

*Sustainable Design Series of  
Delft University of Technology*

A practical  
guide for students,  
designers and  
business managers  
**LCA**



Joost G. Vogtländer

LCA, a practical guide

for students

designers and business managers

Cradle-to-Grave and Cradle-to-Cradle

The cover photo is part of the “Design Cork” book and project ([www. designcork. com](http://www.designcork.com)), directed by Ana Mestre and photographed by Paulo Andrade, for Susdesign, 2008.

The tree is a cork oak tree. Cork is an almost forgotten material, made out of the bark of the tree (the bark is harvested every nine years, without cutting the tree).

Ana Mestre ([www.SUSdesign.org](http://www.SUSdesign.org)) has proven in her research that there are abundant opportunities to apply cork in innovative product designs. LCA and the method of the EVR (see Appendix IV) play an important role in that research, giving guidance on what to do and what to avoid. This is called ‘eco-efficient value creation’ [9].

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# Preface

Life Cycle Assessment (LCA) is a well-defined method to calculate the environmental burden of a product or service. However, LCA has been made (needlessly?) so complex that it seems to be a job for specialists only. The specialists jargon ('functional unit', 'fate analysis', 'midpoints', 'endpoints', 'attributional modelling', etc.) makes it even more impossible for non-specialists to find out what they need to know to make an LCA.

The LCA manual of the International Reference Life Cycle Data System of the EU [3] is an excellent document for those people who like to become expert. The focus is on all the (theoretical) aspects of LCA: 80% of the text is on how to make an LCI (Life Cycle Inventory) and perform the Life Cycle Interpretation, including data quality checks and formalities on the reporting. However, the vast majority of students, designers, architects and business managers (and their consultants) never make LCI emission lists, nor write extensive reports on the interpretation. Most of them apply LCIs of databases of other parties (like the Ecoinvent database), apply existing single indicator systems (like eco-costs, carbon footprint, CED, BEES, Recipe, etc.), and draw simple conclusions on what seems to be the best solution in terms of environmental burden.

Students tend to make LCAs by using computer software. They quickly learn how the input works, regard the calculation as a black box, and watch how the output varies with the input. Basically, they make the LCA by instinct and common sense. However, not all students are equal: some appear to have a much better instinct and common sense than others. Some issues in LCA are too complex to be tackled by common sense only. So these people need a little help and practical guidance.

When I realized the abovementioned situation, I decided to write this Practical Guide to LCA, starting with the common sense, and build on it with practical solutions for, sometimes, complex issues (like recycling). The examples are given in eco-costs; however, most of the examples are identical for other single indicators, like BEES, Traci, Environmental Footprint, ReCiPe, Carbon Footprint, etc.

After two years of intensive use of the First Edition, the Second Edition was published, with two extra issues: how to define the Functional Unit and the Declared Unit, and how to structure recycling calculations. The Sixth Edition is based on the eco-costs 2023, and has some minor changes in Section 5.3 (combustion of wood) and 5.5 (paper recycling)

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The Netherlands, 2023



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# 1 Introduction

## 1.1 For whom is this guide?

This guide has been written to assist anyone who is interested in the environmental burden of their design:

- students who must design products and services which are better for the future in terms of environmental burden
- designers of products who are interested in selecting better materials, or who design innovative products (or product systems) with minimum use of materials and energy
- architects who are interested in optimizing the use of materials and minimizing the use of energy
- business managers who want to introduce 'green' products (and wonder how green their products are)
- consultants in the field of business strategy, product innovation, or in the field of government advice

This group of users is not so much interested in all the ins and outs of LCA: they just want to have quantitative guidance in the decisions they have to take. They don't want to spend much time on LCA, since their primary task is the introduction of innovative products and services. They often have no dedicated computer software, no licenses on LCI databases<sup>1</sup>, and no budget available for specialized LCA consultant firms.

They want to do it themselves, but the time they can spend on the issue is limited. They are not interested in formalities and deliberations on accuracy: they just are interested in results.

There are 3 common misunderstandings about LCA:

1. To make an LCA requires a lot of time (at least 2 - 3 months) and a lot of money. This is true for the formal, classical, 'full' LCA according to ISO 14040 and ISO 14044. However the LCA of this guide takes only 2 - 4 hours (when the required input data are available), or a few days when several alternatives are studied. We

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<sup>1</sup> LCI = Life Cycle Inventory. This is a long list of all emissions during the life cycle plus all the natural resources which are required. Making an LCI is often complex and laborious. The subsequent step in LCA is the LCIA (Life Cycle Impact Assessment), where these long lists are compressed to a few category indicators or to one single indicator. See Appendix I and II.



call it the 'Fast Track' LCA<sup>2</sup>. In many cases the accuracy of a Fast Track LCA is not less than a formal LCA (which is explained in Appendix II of this guide).

2. It is supposed by some people that it is not possible to make an LCA of a cradle-to-cradle (C2C) system. This assumption is absolutely nonsense. The only issue here is that it is less easy to make a cradle-to-cradle LCA, since the data of standard databases have to be selected with more care and understanding (which is explained in Chapter 7).
3. Most people assume that LCA can only be applied to products and systems at the end of the design phase. This is true in the sense that a full 'cradle-to-grave' LCA cannot be made in the early design stages (data are not available yet). However, it is advised to select materials from tables, right in the early design stages, just on the basis of their cradle-to-gate as well as End of Life characteristics (e.g. combustion and recycling performance). This is explained further in Section 3.2.

This guide is in compliance with the ISO 14040 and 14044, as well as the formal LCA manual of the ILCD of the EU [3]. This guide, however, is not meant for specialists in the field of LCA ('practitioners' and 'reviewers'), since it does not deal with the special requirements for a full LCI and the formal requirements for reporting of it.

## 1.2 Two groups of LCAs

There are many different types of LCAs. In this guide, LCAs are divided into two groups;

- The classical LCA ('full', 'rigorous'), where the methodological focus is on the LCI and the LCIA (see footnote <sup>1</sup>). These LCAs are often "ex post"
- The 'Fast Track' LCA, where the output of the calculations of the classical LCA is input for the Fast Track calculation, and where the methodological focus is not at all on LCI and LCIA, but on the comparison of design alternatives, "ex ante".

The classical LCA is needed when the environmental burden of the production of plastics, metals, chemicals, energy, etc. has to be determined, starting from scratch. The complex processes of refineries, the heavy metal industry, production of chemicals, electrical power plants, etc. have to be analysed then by means of mass and energy balances, in order to determine the environmental pollution and the required natural resources. All kinds of complex problems arise. Questions like: what are the system boundaries? How do we allocate the environmental burden to the different products which are output of the system (e.g. in the case of a refinery)? How do we deal with

---

<sup>2</sup> 'Fast Track' LCA's have the single indicator as a starting point, which reduces the complexity of the LCA enormously. The word 'Fast Track' has been introduced by the Delft University of Technology to distinguish between the classical, formal, approach and this practical approach. In the essence, the Fast Track LCA method was first introduced by the EcoScan software of Philips Electronics in 1998

Note: 'Fast Track' LCA must not be confused with 'Streamlined' LCA, see Section 2.3

recycling or reuse of products? How do we deal with electricity and heat from combustion of waste?

It is of great importance that these issues are dealt with in a well-structured, well defined and transparent way. That is the importance of the ISO specifications [5] [6], LCA manuals [3] [4], and Product Category Rules for Environmental Product Declarations (EPDs).

Last but not least there is the issue on how to handle the long lists of emissions (comparing apples with oranges). Since there are several ways to tackle this very complex issue (work for scientists rather than practitioners), there is no ‘single solution’, and therefore international consensus on this issue will never be reached. In the ISO 14044 it is stated that “the selection of ... indicators ... shall be consistent with the goal of the study”. This statement acknowledges the fact that the purpose of an LCA dictates the choice of one or more indicators to describe the environmental burden.

The Fast Track LCA is needed in a different situation. When a product is designed (e.g. a car, a house), all kinds of materials and production processes are combined. It is inconceivable that all these materials and processes are analysed by the designer himself on the level of individual emissions and use of natural resources. In practice, the designer will apply the results of LCAs from other people, the so called background processes, available in databases (e.g. the Idemat and Idematapp databases of the Delft University of Technology, or the Ecoinvent database with over 9000 LCIs of different processes).

Since the aim of the study is a comparison of products, the first thing to do is to select a single indicator model (either damage based, prevention based or single issue, see Appendix II). Once this is done, the single indicators of the products and processes can directly be applied to the system. By doing so, the task is much easier. However, the analysis must still be in compliance with the general rules of LCA. This guide explains which relevant rules there are, and how you must apply them to your particular case.

## 1.3 The difference between a costs calculation and a ‘Fast Track’ LCA

People who have heard about the basic principles of the formal LCA, but who do not know the details of it, often get blocked by the complexity of LCA. They know that they have to start with the ‘functional unit’<sup>3</sup> and must go from ‘cradle-to-grave’. In many cases this is not an easy starting point:

---

<sup>3</sup> The ‘functional unit’ in LCA is not a subsystem or system assembly, but the functional specification combined with the unit of the calculation (e.g. per year, per lifespan, per kilometre, per ton.kilometre, per kilogram etc.). See Section 2.4.

- what is the functional unit of an armchair? What kind of arbitrary assumptions do we take for its maintenance and ‘End of Life’?
- what is the functional unit of a single passenger flight from Amsterdam to Barcelona? How do we define cradle-to-grave of such a service? Do we take the trip or the aeroplane as primary system?

Students who start from fresh (i.e. don’t know much about LCA), and want to limit the amount of time which is needed for the calculation, often use their common sense and intuition. They see that the eco-burden (in terms of Points, kg CO<sub>2</sub>, or eco-costs) is known for materials, production processes, energy and transport (in look-up tables and computer databases). They know that the way to calculate those indicators for eco-burden is complex; however, they are not interested in those theoretical aspects: they are only interested in the LCA results of their design. They just add up the eco-burden of all components of their product system, as they would have done in a normal costs calculation. By doing so, they determine what is neglected (kept out of the system), and what subsystems are taken into account (so they define the system boundaries by instinct). During this process they also become aware of the influence of the functional specification on what they have to add up, and the choice of the unit of calculation becomes just a matter of common sense. The quick end result of such an approach is often amazingly good.

Table 1.1 gives an example of the costs as well as the eco-costs of a house, cradle-to-site (excluding the Use phase and the End of Life phase). The approach of using the output of LCA calculations (in this case eco-costs) in tables which have exactly the same structure as costs tables, has considerably reduced the complexity of LCA calculations on housing<sup>4</sup>.

Note that Table 1.1 is the result of LCA calculations (sub-tables) for each building subsystem. The building subsystems of a specific type are assemblies of building materials (the sub-subsystems) which are the basis for these calculations. Example: The type of outer wall, which has been applied, comprises bricks and stone wool for thermal insulation. The type of outer wall openings comprises wooden window frames with double pane units, and wooden doors. Note also that the Use phase and the End of Life phase (with or without recycling) might be added to the table. How that can be done is dealt with in Chapter 4 and 5 of this Guide.

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<sup>4</sup> Eco-costs tables are available on [www.ecocostsvalue.com](http://www.ecocostsvalue.com) (for materials, energy, transport), and on [www.ecoquaestor.nl](http://www.ecoquaestor.nl) (for buildings).

Although it is not difficult to make your own calculation in excel applying the Idemat excel tables, there are many tools to make the calculations even faster: (a) the Idemaat app and IdematLight LCA app on IOS and Andoid (b) the Excel tools at [www.ecocostsvalue.com](http://www.ecocostsvalue.com)



|             |     |
|-------------|-----|
| house:      |     |
| net m2      | 196 |
| volume (m3) | 705 |

Table 1.1

The costs and the eco-costs of a building cradle-to-site

Note: costs adapted to price level 2023

Source  
www.ecoquaestor.nl

| subsystem                | quantity<br>(m2) | costs<br>(€/m2) | costs<br>(€) | eco-costs<br>(€/m2) | eco-costs<br>(€) |
|--------------------------|------------------|-----------------|--------------|---------------------|------------------|
| foundation               | 133              | 337.7           | 44,918       | 94.5                | 12,570           |
| outer walls              | 190              | 554.7           | 105,396      | 124.1               | 23,588           |
| inner walls              | 64               | 374.8           | 23,987       | 64.1                | 4,100            |
| floors                   | 269              | 157.9           | 42,477       | 40.8                | 10,964           |
| roof                     | 180              | 477.1           | 85,872       | 88.8                | 15,984           |
| structure elements       | 294              | 21.1            | 6,207        | 5.8                 | 1,713            |
| heating & electrical     |                  |                 | 32,841       |                     | 4,358            |
| miscellaneous            |                  |                 | 61,673       |                     | 9,363            |
| total construction costs |                  |                 | 403,370      |                     | 82,638           |

It is obvious that the intuitive costs accounting approach is not without problems. Costs accounting in complex production systems is a complex profession as well:

- allocation of costs to a product in a complex production process is not easy at all (the method of Activity Based Costing)
- when the lifespan of a product is long (say longer than 10 years), the so called Life Cycle Costing, LCC, or Whole Life Costing, WLC<sup>5</sup>, is not easy at all (e.g. the Net Present Value must be applied, making choices on the Discount Rate)

The complexities of allocation and long life spans in costs accounting also exist in LCA, and are still under debate. Choices on these issues have been made in this guide, see Chapter 5, in compliance with the EU manual [3].

There are other practical issues, which cannot be resolved just by common sense or instinct. They are hardly described in the ISO, and the manual of the EU gives only some guidance in an indirect way:

<sup>5</sup> LCC and WLC refer to the total (monetary) costs of ownership of an asset. It is also from cradle-to-grave, but should not be confused with LCA (the environmental burden of a product or service). Although some environmentalists propose to bring the environmental damage in LCC and WLC, the common use of LCC and WLC is to add-up monetary 'real life' costs only.  
It is advised to keep LCA and LCC fully separate, see [8] and [9]

- transport of light freight
- choice of ‘energy mix’ for gas and electricity
- combustion of waste at the End of Life
- recycling of materials
- applying data from standard databases in C2C calculations
- calculations on services
- the way carbon sequestration (in wood and other bio-materials) has to be dealt with

These issues are addressed in this guide in Chapters 4, 5, 6, 7, and 8.

## 1.4 The structure of this book

This book starts with the problem of defining the system. It appears in practice that the choice of the system is far from obvious. Many students struggle with it.

Which system concept do we need in which situation (cradle-to-gate, or cradle-to-grave, cradle-to-cradle, streamlined LCA, etc.)?, and what are the boundaries of our system? What is the functionality of the system?

The right choices on these issues appear to be crucial for the quality of the study. These issues are dealt with in Chapter 2.

Life Cycle Assessment in design is an iterative process, like the design process itself. By instinct people start LCA by making lists of materials (especially when they work with computers, since it is the computer input); however they should think about the system first. So it helps when the LCA study is structured step by step.

An important issue in Fast track LCA is that it should start in the early design stages, preferably before the product design starts: the best results in terms of environmental improvements are achieved when the design process starts with the design of the Life Cycles of the materials to be used (‘Life Cycle Design’). The system functionality and the C2C aspects must be tackled at system level. Once the product design has been finalised, it is hard to change the system. These issues are dealt with in Chapter 3 and Section 7.1.

Transport is a dominating factor in some LCAs. But how do you calculate the eco-burden of transport, applying the standard databases? Most people use the ton.kilometer data of these databases, but this is only correct for heavy bulk freight. For toys, domestic appliances, electronics, etc. the ton.kilometer data are the wrong choice: transport should be calculated here per container.kilometer or per m<sup>3</sup>.kilometer.

For road transport and transport per aeroplane, the weight/volume ratio is also very important in the calculation. Section 4.1 gives practical guidance on the issue of transport.

The use phase of the life cycle is important when the product system needs a lot of maintenance or energy during its lifespan. Maintenance is often forgotten in LCA practice. The issue with the use of energy is which data from which databases are to be

applied: is it wise to assume that the energy (electricity or gas) comes from the nearest source, or is it wise to take the average production data of a country or a region (e.g. western Europe), since the electricity grid or gas pipeline grid levels out supply and demand in such a region? Section 4.2 deals with this issue.

The way End of Life should be modeled in LCA is still under discussion. In the ISO 14044 (ISO, 2006) it is hardly defined. In the manual of the EU (ILCD, 2010) some alternative solutions are provided (either 'attributional modelling' or 'consequential modelling'); however, the text is not easy to understand for non-specialists. This guide provides practical choices (applying the 'allocation, cut-off' data of Ecoinvent V3, in combination with 'system expansion', the 'recyclability substitution' and the 'cut-off approach'). These approaches are easy to understand and easy to apply in practice, and are in line with the EN15804. See Chapter 5.

Chapters 6, 7 and 8 deal with special issues:

- How to make LCA calculations on service systems
- How to make calculations for C2C systems
- How to deal with carbon sequestration (the issue of 'biogenic carbon dioxide' in LCA)

In Chapter 9 the fact is discussed that not all sustainability issues can be included in LCA. How to deal with it? When do we need additional calculations (e.g. yield of land)?

Background information is given in the Appendices:

- How is the calculation structure in LCA computer programs?
- How are the leading single indicators determined?
- What are the most important issues in the ISO 14040 and 14044?
- How do we compare 2 products with different quality and/or functionality?
- How to apply Idemat and Ecoinvent data for recycling and re-use?
- How to calculate the eco-costs on the basis of an Environmental Product Declaration (EPD)?



## 2 The system you want to study

### 2.1 Different system concepts

Life Cycle Assessment (LCA) is a well-defined method to calculate the environmental burden of a product or service. The basic calculation structure of LCA is depicted in Fig. 2.1. The calculation is based on a system approach of the chain of production and consumption, analysing the input and the output of the total system:

- input:
  - materials (natural resources and recycled materials)
  - energy
  - transport
- output:
  - the product(s) and/or service
  - emissions to air, water and soil
  - by-products, recycling products, feedstock for electrical power plants
  - waste for landfill, waste incineration, or other types of waste treatment

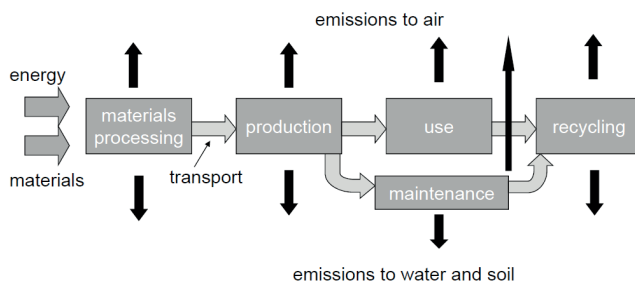


Figure 2.1  
The basic calculation system of LCA

Each LCA starts with the definition of the Processes inside the ‘black boxes’ of Fig. 2.1. Such a process definition is unique for each case. When the definition of the process system is wrong (or not suitable for the goal of the study), the output of the calculation will be wrong. The biggest mistakes in practice are caused by a system definition which is too narrow: sub-processes are not included which appear to be important (and other details are included which have hardly any influence on the output). The definition of the system is often an iterative process as such: by trial and error it is discovered what is important in a certain case.

Some C2C specialists claim that the cradle-to-grave dogma of LCA leads to wrong approach in design. They have a point that the cradle-to-grave dogma may lead to wrong design decisions (i.e. opportunities for recycling are overlooked). However, this

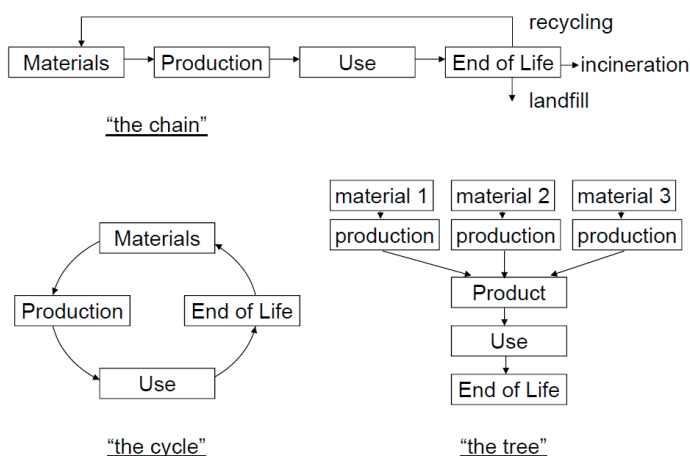


has nothing to do with LCA, but only with the people who apply it. That is the reason that this section gives a lot of attention to the system definition.

There are 3 paradigms in LCA to describe the system to be studied (see Fig. 2.2):

- 'the chain' (from cradle-to-grave)
- 'the cycle' (C2C)
- 'the tree' (often used in computer software)

Figure 2.2  
The 3 system  
paradigms of  
LCA: the chain,  
the cycle and  
the tree



'The chain' (from cradle-to-grave) is the way most product designers and engineers tend to approach the LCA. The advantage of such an approach is that the Use phase and the End of Life phase have a clear focus (as it has in LCC as well). Although recycling is an alternative solution in the End of Life phase, it appears not easy to make analyses on recycling (C2C systems) by means of most of the existing combinations of computer programs and databases. So C2C opportunities are often overlooked by people who describe the system as a chain and use standard computer software for LCA.

'The cycle' (C2C) is the idealist's way of looking at the problem of sustainability. It is "how it should be": if 100% of the products and materials are recycled, all problems of materials depletion and land fill are resolved. Eco-systems in nature recycle everything, so that must be the example for product design and engineering. However, in our 'technosphere' we are far from the level of sophistication of our 'mother nature', the 'biosphere'. So practical issues with regard to the technosphere are often overlooked by people who describe the system as a cycle, like the required need for transport and energy<sup>6</sup>, and the fact that - in real life - recycle loops are 'open' rather than 'closed'<sup>7</sup> in

<sup>6</sup> In the technosphere, systems are required for the conversion of sunlight to energy. These systems require materials that are causing emissions as such.

most cases.

‘The tree’ is the way LCAs are often depicted in computer programs. It is the system approach. It emphasises the fact that product systems are assemblies of subsystems and materials, and that processes have sub-processes and sub sub-processes. The pitfall of the tree is that the production phase is often described in far too much detail, and that broader system concepts are forgotten.

When you make an LCA, you should depict your product system in all the 3 system paradigms. The cycle helps to open up the mind in the early beginning of the design stage (see Sections 3.2 and 7.1). The tree is strong to analyse the production stage. The chain is to be used to analyse alternatives of the Use phase and the End of Life phase. Fig. 2.3 depicts the alternative solutions of the total system.

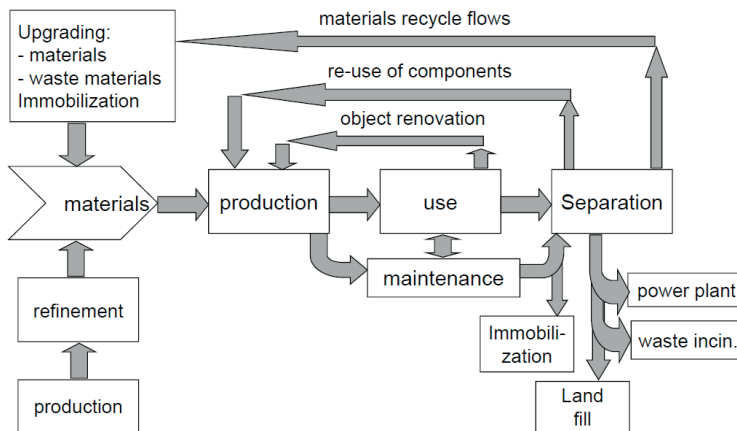


Figure 2.3

The flow of materials in the Life Cycle

Fig. 2.3 depicts the general building blocks of an LCA. For a lot of processes and materials, the LCI data and the single indicators (e.g. eco-costs, carbon footprint, etc.) are provided in standard databases. For processes which are not readily available, the LCI, or an estimation of it, should be made additionally.

Ways to make an estimation of an LCI are:

- take the LCI of a similar process (the ‘surrogate process’)
- take the required energy only (when it is expected that there are not much additional emissions)
- take the major emissions plus the required energy (in case of harmful emissions)

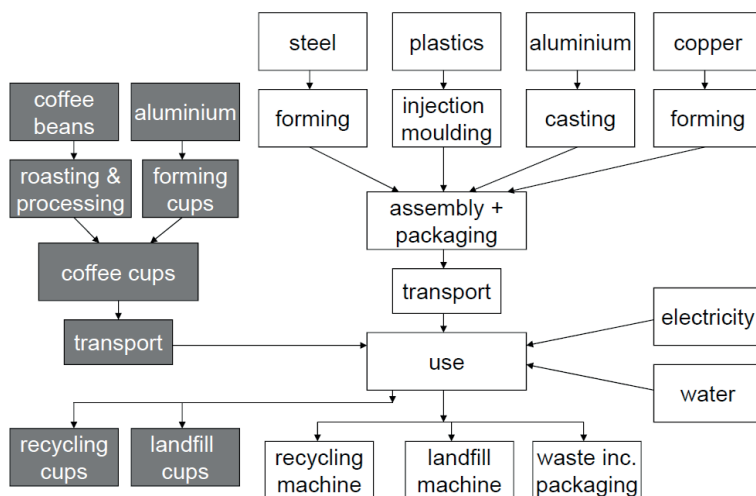
The building blocks of an LCA are not cradle-to-grave. These building blocks are:

<sup>7</sup> A recycle loop is ‘closed’ when 100% of the materials are used to produce the same product again and again. In practice recycle loops are nearly always ‘open’, since there are ‘bleed flows’, and since the materials are used for other products (enter other open recycling loops).

- cradle-to-gate, which is an assessment of the part of the product life cycle from the natural resources (the cradle) to the factory gate (i.e., before it is transported to the consumer). The Use phase and End of Life phase of the product are omitted<sup>8</sup>. Cradle-to-gate assessments are sometimes the basis for environmental product declarations (EPD)
- gate-to-gate, which is a partial LCA looking at only *one* value-adding process of the production chain<sup>9</sup>
- gate-to-grave, which is normally from the end-user to the End of Life (landfill, combustion, etc., including transport, disassembling or demolishing).

Fig. 2.4 depicts the input of computer software in the form of a tree in the case of a coffee machine.

Figure 2.4  
The input of a computer program (simplified), depicted as 'the tree'. Case: a modern coffee machine



Note that the processes in the Use phase and the End of Life phase are nearly always scenarios (assumptions). For consumer goods these scenarios are based on consumer behaviour, which determines the importance of the subsystems.

An example (see Fig. 2.4):

<sup>8</sup> There are two reasons to make a cradle-to-gate analysis:

- The analysis is made to create a building block for cradle-to-grave LCAs
- The Use phase and the End of Life phase of a product are rather unpredictable, or are assumed to be the same for the compared products, or are relatively 'clean' in comparison to the Production phase (e.g. furniture, ceramics, jewels, and other durable products which do not require energy in the use phase)

<sup>9</sup> Especially in the UK the 'carbon footprint approved company' status is quite popular. Be aware that this status is about the gate-to-gate system of the company only, and be aware that this gate-to-gate system is normally a tiny fraction of the carbon footprint of the total life cycles of the products involved.

- When a modern coffee machine (like Senseo or Nespresso) is heavily used, the eco-burden of the coffee pads or cups and the energy is considerably higher than the eco-burden of the coffee machine itself.
- However, when the machine is hardly used it is the other way around.

## 2.2 System Boundaries

The system boundary determines what is included in the system and what is left out.

**Each LCA must have a clear description of what is included and what is excluded**, so that other people who look at the results are well informed about these basic assumptions of the calculations.

The original idea on the issue of system boundary is depicted in Fig. 2.5<sup>10</sup>. The people who developed the LCA method realized that each system is embedded in other systems, so that you have to draw a line on what is included and what is not. Fig. 2.5 is a simple example of transport of goods:

- for the transport of goods you need a truck and fuel (diesel)
- to build a truck you need a manufacturing plant
- to build a manufacturing plant you need trucks
- et cetera
- for the production of diesel, oil platforms, refineries, transport, etc. are required.
- for the construction and operation of oil platforms, refineries, transport, etc. you need diesel
- et cetera

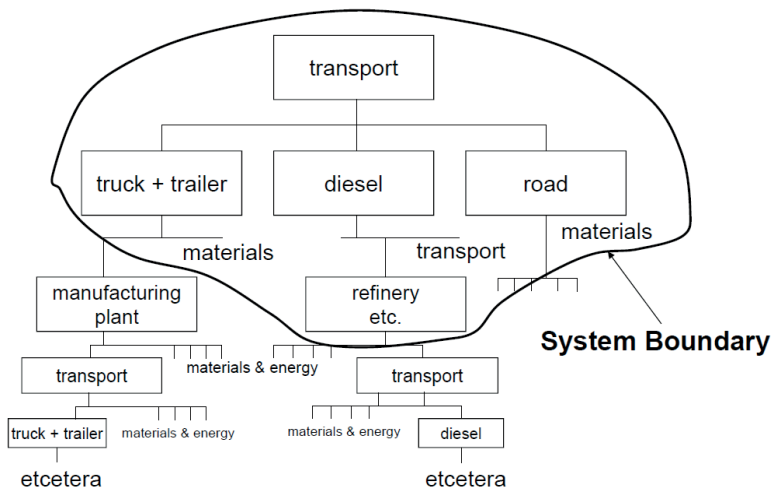


Figure 2.5  
Each LCA system has its system boundary

<sup>10</sup> Note that Fig. 2.5 is also called a 'tree'. The tree is depicted upside down (in comparison to Fig. 2.2 and 2.4), as it is done in computer programs like Simapro.

It is obvious that, for a specific LCA, the amount of work has to be limited, and this chain of systems and subsystems has to be limited to everything above a certain level. A common rule is that something might be neglected when the effect on the total LCA is less than 2%, provided that the sum of the systems which are neglected is not more than 5%. This applies also to subsystems in a process tree which are not cascading, but which are just small<sup>11</sup>.

Table 2.1 is an example of a calculation on bamboo stems, transported to the Netherlands. It is obvious that lines 1, 2 and 6 are small in comparison to 5. In tables like this, they are included to avoid confusion by the reader who might think that something was omitted.

Table 2.1  
The eco-costs  
of a bamboo  
stem in  
Rotterdam.  
Lines 1,2 and 6  
might have  
been left outside  
the system  
boundary  
(Idemat2023)

| Process step                                                                                           | Amount | Unit      | Eco-costs (€/unit)    | Eco-costs (€/FU) | Eco-costs (€/kg) | %       |
|--------------------------------------------------------------------------------------------------------|--------|-----------|-----------------------|------------------|------------------|---------|
| 1. Cultivation and harvesting from plantation. Gasoline consumption                                    | 0.025  | liter/FU  | 0.83 €/liter          | 0.0185           | 0.0024           | 1.88%   |
| 2. Transport to stem processing facility; 5-ton truck (transport 320 FUs)                              | 30     | Km        | 0.31 /km per 5t truck | 0.0146           | 0.0019           | 1.49%   |
| 3. Preservation & drying: Energy consumption                                                           | 1      | kWh/ FU   | 0.084 /kWh            | 0.0847           | 0.0111           | 8.63%   |
| 4. Transport from stem preservation facility to harbor (28-ton truck)                                  | 4.59   | ton.km/FU | 0.022 /ton.km         | 0.10             | 0.013            | 10.42%  |
| 5. Transport from Shanghai to Rotterdam. Volume based; 40 ft container in a trans-oceanic freight ship | 1300   | m3.km/FU  | 0.0006/m3.km          | 0.74             | 0.097            | 75.58%  |
| 6. Transport from harbor to warehouse (28-ton truck)                                                   | 0.88   | ton.km/FU | 0.022 /ton.km         | 0.02             | 0.003            | 2.00%   |
| Total eco-costs (€)                                                                                    |        |           |                       | 0.98             | 0.13             | 100.00% |

Note: FU=functional unit = bamboo stem per piece, 7.65 kg, 5.33 m (diameter 7 cm at the top, 10 cm at the bottom) the volume of a stem is approximately 0.0068 m3 (packed in a container) .

It is common practice that all parts of a list of components of a product are counted in an LCA. However, it is obvious to skip all small items.

In general, one might neglect all items with a weight of less than:

- 1% when the list is < 20 items
- 0.5% when the list is 20 - 40 items
- 0.2% when the list is 40 - 100 items

<sup>11</sup> Note that the cascading as depicted in Fig. 2.5 is no problem in modern computer software for LCA: the computer calculates the cascade at a rather deep level, applying standard LCIs (based on global or regional averages). However, it is the decision of the LCA practitioner which other subsystems are so small that they can be left out anyway.

- 0.1% when the list is 100 - 200 items
- 0.05% when the list is 200 - 500 items

An exception of this rule of thumb is when there are some items in the list which are extreme toxic (which is normally not the case, since toxic materials should be replaced). In general, one must be careful to assume by intuition that subsystems can be neglected. A typical example of this is shown by the LCI of Ecoinvent on the eco-burden of drilling holes in metals ("Drilling, CNC, Steel, RER/U"<sup>12</sup>). The intuition says that the eco-burden of drilling is determined by the electricity which is used. A full LCI, however, shows something else, see Table 2.2. Note that a very large percentage of the total score of this LCI is the eco-burden of the removed material, assuming that the weight of the subassembly in the product is measured as it is in the final stage (i.e. *after* drilling).

The conclusion is: do not take the system boundaries too narrow.

| Subsystem                                                                                    | CED<br>(MJ/kg<br>removed) | CED<br>% | eco-costs<br>(€/kg<br>removed) | eco-costs<br>% |
|----------------------------------------------------------------------------------------------|---------------------------|----------|--------------------------------|----------------|
| 1 Electricity, low voltage {RER}  market group for   Cut-off, U                              | 5.654                     | 12.40%   | 0.058                          | 4.64%          |
| 2 Compressed air, 700 kPa gauge {RER}  market for compressed air, 700 kPa gauge   Cut-off, U | 2.126                     | 4.66%    | 0.023                          | 1.82%          |
| 3 Lubricating oil {RER}  market for lubricating oil   Cut-off, U                             | 0.256                     | 0.56%    | 0.004                          | 0.29%          |
| 4 Energy and auxilliary inputs, metal working factory {RER}                                  | 9.895                     | 21.69%   | 0.258                          | 20.70%         |
| 5 Steel, low-alloyed, hot rolled {GLO}  market for   Cut-off, U                              | 27.677                    | 60.68%   | 0.904                          | 72.46%         |
| 6 Waste mineral oil {Europe without Switzerland}                                             | 0.001                     | 0.00%    | 0.001                          | 0.09%          |
| Total                                                                                        | 45.61                     | 100.00%  | 1.247                          | 100.00%        |

Table 2.2

The subsystem (building block) of drilling a hole in low-alloy steel (Ecoinvent V3)

Note: CED = Cumulative Energy Demand

In LCAs for consumer products (an exception is the Danish Food Database), the following subsystems are normally forgotten, since there are no standard data available in the standard databases<sup>13</sup>:

- sales and marketing activities
- retailer activities

For commodity products these omissions might be acceptable; however, for luxurious products these subsystems should be included.

<sup>12</sup> RER means in this database that the LCI is for the European Region, U means that the primary building blocks ('units') are shown.

<sup>13</sup> One might apply here the EVR data of the Excel tables at [www.ecocostsvalue.com](http://www.ecocostsvalue.com)

A very effective way to reduce the work of LCA benchmarking (= comparison of two or more products) is called ‘Streamlined LCA’. The basic idea of Streamlined LCA is that it does make sense to study only the **differences** between two product systems: neglect all subsystems which are the same. It is a way of carefully defining the boundaries of the systems which have to be studied. This is dealt with in the next section.

## 2.3 Streamlined LCA

It is a wide spread misunderstanding (even under LCA practitioners) that ‘streamlined’ has always to do with less accuracy, since the aim of streamlining is that it reduces the time required to make an LCA. In literature ‘streamlined’ is often used as an equivalent for ‘faster’, and faster is supposed to be less accurate. Streamlined in the original concept, however, has to do with reducing system boundaries in a clever way, fully in line with the formal LCA requirements, and not less accurate (or hardly less accurate)<sup>14</sup>.

There is one specific application of ‘streamlining’ which is very helpful in practice. It is related with the basic aim of LCA: benchmarking two (or more) products (and/or services). The logic of this type of streamlining is that you make your calculation only on the **differences** of the two products: the system boundaries of your calculation include the subsystems which are different, and exclude the subsystems which are the same in both products. The argument is that it doesn’t make sense to spend time on the subsystems which are the same. Two examples are given below.

The first example is on a 3 gang extension socket. The housings of the regular types are made of white or black plastic (mostly polypropylene). Recently an innovative design based on cork was launched on the market, see Fig. 2.6.

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<sup>14</sup> “When the concept of streamlining was first introduced, many LCA practitioners were sceptical, stating that LCA could not be streamlined. Over time, however, there has been growing recognition that ‘full-scale’ LCA and ‘streamlined’ LCA are not 2 separate approaches but rather are points on a continuum. Most LCA studies will fall somewhere along that continuum, in between the 2 extremes. As a result, the process of streamlining can be viewed as an inherent element of the scope-and-goal definition process. For example, as the study team decides what is and what is not to be included in the study, they are engaged in streamlining. In addition to determining what will and will not be included, the study team will determine how to best achieve these requirements. The key is to ensure that the streamlining steps are consistent with the study goals and anticipated uses, and that the information produced will meet the users’ needs. From this perspective, the scope-and-goal definition process involves determination of what needs to be included in the study to support the anticipated application and decision.” From the SETAC North America Report on Streamlined LCA, 1999 (Todd and Curan, 1999)

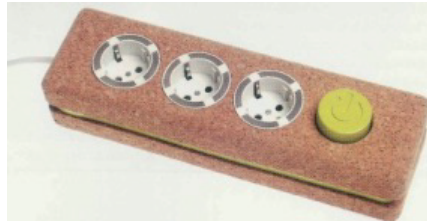


Figure 2.6  
A 3 gang  
extension  
socket out of  
cork

When the question is asked what the environmental benefit is of applying cork instead of polypropylene, it doesn't make sense to make a full LCA on the total product, since the difference is only in the housing. An LCA on the housing only is called a streamlined LCA, see Fig. 2.7.

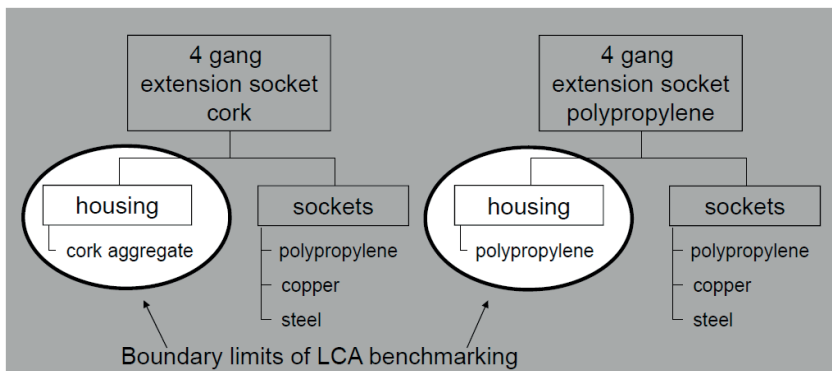


Figure 2.7.  
Streamlined  
LCA: a  
restricted scope  
of study

A practical consequence of the streamlined LCA of Fig. 2.7 is, that it is only allowed when the life span of the two products is identical. When that is not the case, a full LCA must be made, since the other components are discarded together with the housing (note that the eco-burden is calculated per year of use, see the next Section).

In streamlined LCA, the Use phase and the End of Life phase must be taken into account as well, when these phases are different.

The second example is about an innovative design of a prototype electric garbage collection truck, a bit smaller than a normal diesel truck, used for collection of garbage in inner cities and shopping centres. See Fig. 2.8. The primary advantage to make the truck electric is the fact that it produces less pollution and less noise.



Figure 2.8  
Electrical  
garbage  
collection truck



The standard approach in LCA benchmarking is that full LCAs have to be made for the electrical truck as well as the normal diesel truck in terms of collected garbage per year. The disadvantage of such an approach is twofold:

1. The two garbage trucks are not the same in terms of functionality in the broad sense of the word: the small electrical truck is more suitable for garbage collection in the inner cities, the bigger diesel truck is more suitable in the suburbs (it has a wider operational radius).
2. All elements of the innovative design are known (since it is the subject of the design); however, the elements of a standard diesel garbage collection truck are not known so this LCA will require a lot of extra work (it is often not easy to get data from the manufacturer which has no interest in the LCA).

In other words: the LCA benchmarking is not accurate since the functionality is slightly different, and the LCA of the standard diesel truck is a lot of work.

A better approach here is the approach of a streamlined LCA:

- a) make a design of the same innovative truck; however with a diesel power system
- b) do the LCA benchmarking only for the differences between the diesel engine and the electrical power system (cradle-to-grave or cradle-to-cradle)

## 2.4 The Functional Unit

### 2.4.1 The basics of the FU

Defining the right 'Functional Unit' (FU) is an essential step in LCA. However, what is a functional unit, and what can go wrong with it?

The FU of a cradle-to-grave system is a combination of the functionality of the system and the unit in which this functionality is expressed. Examples: number of sockets available per year, collected garbage in kg per year (the first and second example in the previous Section).

For the building blocks (subsystems) of a system (normally cradle-to-gate, gate-to-gate, or gate-to-grave), the FU is simply the unit used for the calculation. Examples: per kg, per year, per kWh, per MJ, per km, per ton.km, per m<sup>3</sup>.km, per piece, et cetera.

Since the FU of a cradle-to-grave system is related to the Use phase and the End of Life phase, it is related to the scenarios which have been chosen for these phases. For this reason, the FU is highly related to the goal and the scope of the study.

Example: The functional unit of drinking a cup of coffee is “per one cup of coffee, for the case of 10 cups of coffee per day”. The reason of the added scenario is that the number of cups of coffee define the allocation of the eco-burden of the coffee machine to one cup of coffee (the coffee machine makes  $\infty$  cups of coffee in its lifespan).

The LCA of this system, already given in Section 2.1 Fig. 2.4, has been summarized in Table 2.3 for 10 cups of coffee per day as well as 1 cup of coffee per day.

LCAs always have scenarios for transport. In the cases of cradle-to-gate LCAs where transport is a major part of the total eco-burden, it is good to add the chosen scenario to the description of the functional unit.

Example 1: The FU of the bamboo stem of Table 2.1 is “bamboo stem per piece, 5.33 m, 7.65 kg (diameter 7 cm at the top, 10 cm at the bottom) in Rotterdam, from China”.

Example 2: the coffee machine of Table 2.3 is assumed to be produced in China and

|                            | 1<br>weight<br>(kg)          | 2<br>material<br>eco-costs<br>(€/kg) | 3<br>processing<br>eco-costs<br>(€/kg) | 4<br>end of Life<br>eco-costs<br>(€/kg) | 5=1(2+3+4)<br>total<br>eco-costs<br>(€) |
|----------------------------|------------------------------|--------------------------------------|----------------------------------------|-----------------------------------------|-----------------------------------------|
| machine components         |                              |                                      |                                        |                                         |                                         |
| steel                      | 0.471                        | 0.18                                 | 0.086                                  | 0.00                                    | 0.13                                    |
| plastics                   | 0.893                        | 1.16                                 | 0.079                                  | 0.15                                    | 1.24                                    |
| aluminium                  | 0.56                         | 2.21                                 | 0.168                                  | 0.00                                    | 1.33                                    |
| copper                     | 0.08                         | 2.41                                 | 0.168                                  | 0.00                                    | 0.21                                    |
| assembly+packaging         | 0.2                          | 0.07                                 | 0.06                                   | -0.10                                   | 0.006                                   |
| transport (china-europe)   | ecocosts=<br>0,0006(€/m3.km) |                                      |                                        |                                         | 0.144   *)                              |
| machine total              |                              |                                      |                                        |                                         | 3.05                                    |
| period 3 years, 1095 days: |                              |                                      |                                        |                                         |                                         |
| per cup, 10 cups per day   |                              |                                      |                                        |                                         | 0.0003                                  |
| per cup, 1 cup per day     |                              |                                      |                                        |                                         | 0.0028                                  |
| cups (excl coffee extract) |                              |                                      |                                        |                                         |                                         |
| aluminium cup not recycled | 0.0012                       | 2.66                                 | 0.17                                   | 0                                       | 0.0034                                  |
| 50% aluminium recycled     | 0.0012                       | 1.53                                 | 0.17                                   | 0                                       | 0.0020                                  |
| plastic cup                | 0.0015                       | 1.16                                 | 0.02                                   | 0.15                                    | 0.0020                                  |
| electricity per cup        |                              |                                      |                                        |                                         |                                         |
| 50 kJ per cup of coffee    | eco-costs = 0,0248 (€/MJ)    |                                      |                                        |                                         | 0.00124   **)                           |

\*)  $0.144 = 0.0006 \cdot 0.2(m) \cdot 0.2(m) \cdot 0.3(m) \cdot 20,000(km)$

\*\*)  $0.00124 = 0.0248 \cdot 50/1000$

Table 2.3

The data of a simplified LCA for design of a modern coffee machine with a lifespan of 3 years

System ref. Figure 2.4

transported to Europe by sea container. It might be considered to add this information to the functional unit.

Although such a short scenario description is not a function, it is good to give the reader this information:

- if it is a key element of the goal and scope of the LCA
- if the eco-burden of the transport is a major part of the total eco-burden

The scenario can also be related to the region of production. In the Ecoinvent database, all processes have letters to describe the region of the LCI: GLO for global average, RER for European average, CH for Switzerland, etc.

In formula:

$$FU = \{\text{system function}\} \text{ per } \{\text{unit of calculation}\} \{\text{plus optional: main scenario}\}$$

It is good to realize that the functional units of many simple items are hard to define. Example: an armchair (the function is that it can carry a certain weight, and will last for 40 years, but does such a kind of definition really help to define the system to base the LCA on?). Products like reading glasses, a necklace, clothes, et cetera, have the same problem.

The issue is, that those products are mainly defined by their quality in the broad sense of the word (important are aesthetics, image, and other intangible elements). This aspect is dealt with in Section 2.5.

## 2.4.2 A wrong choice of FU leads to a wrong conclusion, an example

Choosing the wrong functional unit can lead to wrong conclusions, since it is related to a wrong definition of the system. The example below on transport packaging will illustrate this issue.

Let us assume that we want to study the difference of the environmental burden of a corrugated board box and a plastic crate, both used to carry vegetables and fruit, as shown in Fig. 2.9.



Corrugated box from recycled paper  
for fruit and vegetables  
not reusable



Plastic re-usable crate  
for fruit and vegetables  
reusable: approx. 30 round trips

Figure 2.9

Two types of  
transport  
packaging: a  
corrugated  
board box and a  
plastic re-usable  
crate

The advantage of a corrugated box is that it is made of recycled paper. The advantage of a plastic crate is that it is durable: it can serve 30 round trips in practice (3% of the crates disappear per round trip).

The first idea is to take 'containment of vegetables per litre' as a FU. The summary LCAs for both solutions are given in Table 2.4.

Table 2.4 shows that the best solution in terms of 'containment of vegetables per litre' is the plastic crate.

However, the real FU of the transport packaging is not 'containment', but 'containment and transport'. Here it is important to define the scenario. Take as an example: 'containment and transport of vegetables from the Dutch auction warehouse to a retail warehouse in Frankfurt'. The system has to include now:

- the transport packaging, see Table 2.4
- the truck and trailer, see Table 2.5
- the storage in the warehouses (also the empty crates), see Table 2.6

The eco-costs of 'containment and transport of vegetables from the Dutch auction warehouse to a retail warehouse in Frankfurt' is the sum of the three subsystems of Tables 2.4, 2.5 and 2.6, since all these subsystems are required to fulfil the total functional requirement.

Table 2.4

Summary of an  
LCA of transport  
packaging  
(Idemat2023)

|                     | Corrugated BOX   | Plastic CRATE    |
|---------------------|------------------|------------------|
| Size (L,W,H) (m)    | 0,6 x 0,4 x 0,24 | 0,6 x 0,4 x 0,24 |
| Volume (litres)     | 53.4             | 43.92            |
| Weight (kg)         | 1.086            | 1.95             |
| Eco-costs (€/kg)    | 0.120            | 1.13             |
| Eco-costs (€/unit)  | 0.13             | 2.21             |
| Nr of trips         | 1                | 30               |
| Eco-costs (€/trip)  | 0.131            | 0.074            |
| Eco-costs (€/litre) | 0.0024           | 0.0017           |

FU= containment of vegetables for transport per liter volume

Table 2.5

Summary of an  
LCA of transport  
by truck and  
trailer  
(Idemat2023)

|                                 | Corrugated BOX          | Plastic CRATE      |
|---------------------------------|-------------------------|--------------------|
| Litres per pallet               | 2670                    | 2196               |
| Litres per truck                | 69,420                  | 57,096             |
| Eco-costs of:                   |                         |                    |
| - truck+trailer (€/km)          | 0.3120                  | 0.312              |
| - driver (€/km)                 | 0.015                   | 0.015              |
| - road €/km)                    | 0.135                   | 0.135              |
| Subtotal (€/km)                 | 0.462                   | 0.462              |
| distance full loaded truck (km) | $500 + 500 * 0,3 = 650$ | $500 + 500 = 1000$ |
| Eco-costs (€/trip)              | 300                     | 462                |
| Eco-costs per trip (€/liter)    | 0.0043                  | 0.0081             |

FU= containment and transport of vegetables per liter volume  
from the Dutch auction warehouse to a retail warehouse in Frankfurt

Table 2.6

Summary of an  
LCA of storage  
of boxes and  
crates  
(Idemat2023)

|                                     | Corrugated BOX | Plastic CRATE |
|-------------------------------------|----------------|---------------|
| Litres per pallet                   | 2670           | 2196          |
| days of storage full pallets        | 37             | 67            |
| Eco-costs of storage (€/pallet.day) | 0.043          | 0.043         |
| Eco-costs of storage (€/pallet)     | 1.591          | 2.881         |
| Eco-costs per trip (€/liter)        | 0.00060        | 0.00131       |

FU= containment for transport of vegetables per liter volume in warehouses

When the eco-costs of feeding and distribution are added (this is the transport from the Dutch greenhouses to the warehouse of the auction, plus the transport from the distribution centres to the retail shops), the eco-costs of the total transport chain is found. See Fig. 2.10. See for a full analysis of this case see Section 8 in [8].

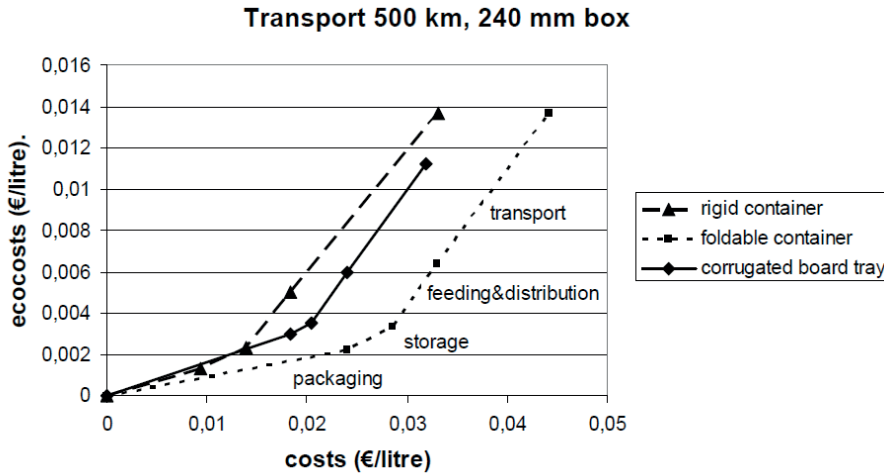


Figure 2.10

The eco-costs of transport of vegetables from Holland to Frankfurt in different types of transport packaging

The corrugated box scores slightly better in the total system (eco-costs of the total chain is 0.011 €/litre<sup>15</sup>) than the plastic crate (eco-costs of the total chain is 0.014 €/litre). The reason is simple: the empty crates require the extra return transport and storage in the transport system.

The conclusion of this example is that the wrong definition of the FU leads to the wrong conclusion.

A wrong FU is related to a wrong system description and very often to a wrong system boundary.

### 2.4.3 The interrelation of the FU, the system boundaries and the goal and scope

In most LCA manuals the following sequence of steps is proposed, following the theoretical top-down approach for LCA benchmarking:

- step 1. definition of goal and scope of the study
- step 2. definition of functional unit
- step 3. description of the system with system boundaries

These three steps are an iterative process in practice.

In the case of a total new design, it seems more practical to turn the sequence of thinking around to a bottom-up approach:

- step A. the system with system boundaries
- step B. the functional unit
- step C. the goal and scope

<sup>15</sup> The assumption is that the empty truck in the transport system of the corrugated boxes can be filled for 70% with other freight on the trip back to Holland. The empty 30% is allocated to the main trip of vegetables to Frankfurt, hence the distance of  $500 + 500 \times 0.3 = 650$  km in Table 2.5. This is in line with the common practice of cost calculations in the transport sector. In LCA it is called 'economic allocation', see Appendix III.

The reason of this bottom-up approach is that, in practice, people become aware of the problem to be solved by thinking about the system. Steps B and C are concluding this process of thinking about the system in step A. In reporting, the formal top-down sequence should be applied.

## 2.5 Choice of Functional Unit and the Declared Unit

In the previous section, the Functional Unit (FU) has been described (what it is, and how you define it). This section will deal with the choice of the FU in a specific design situation. The issue is that the FU determines the degree of freedom in a design. For examples, see Table 2.7.

Table 2.7  
The definition of the Functional Unit and the degree of freedom in the design

| <i>Product</i>   | <i>Functional Unit, high degree of design freedom</i>                                                           | <i>Functional Unit, low degree of design freedom</i>                                                  | <i>Remarks</i>                                                                                                   |
|------------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|
| car              | Satisfy the need of people (functionally specified) for transport, per person.km                                | The function of a car (with a certain functional specification), per km                               | The second FU requires a redesign of a car.<br>The first FU enables system solutions without cars                |
| cup of coffee    | Satisfy people with a coffee based drink to facilitate social contacts in a pleasant way, per 10 drinks per day | The function of a coffee machine (with a certain functional specification), 10 cups of coffee per day | The second FU requires a coffee machine.<br>The first FU allows a cold coffee based drink (less energy required) |
| drilling machine | Enabling the attachment of subjects to a wall, per attachment                                                   | Drilling holes to be able to attach subjects to a wall, with a screw or bolt, per hole                | The second FU requires a redesign of the drill driver.<br>The first FU allows solutions with adhesives           |

It depends on the aim and the goal of the study, which level of design freedom is to be applied:

- In the classical paradigm of LCA practitioners, a functional unit at the start of a redesign should give the designer the maximum degree of freedom, to be able to design new systems with a radical change of user behaviour, in order to achieve minimum environmental impact.
- In practice, however, designers are often asked to redesign the product, i.e. designers are not allowed to design a new system (without the product). So the degree of design freedom is restricted by the aim of a company: selling (physical) products.

Note that a functional unit with a high degree of freedom for the fuzzy front end might be changed in later stages of the design process to a FU with a lower degree of freedom, to focus better on the selected design alternatives. In this way the LCA benchmarking activity is made as accurate and reliable as possible for each design stage.

The high degree of freedom in a Functional Unit may provide the designer with the freedom of designing systems with broad system boundaries. In practice, however, it has disadvantages as well:

- It is less easy, sometimes impossible, to compare (benchmark) the designs, because they are too different: you cannot compare apples and oranges. The more complex model of the EVR should be applied then [9]
- Parties involved tend to focus on the fulfillment of the FU, rather than discuss other important system aspects of the LCA such as end-of-life solutions (like recycling systems). Note that the choice of recycling system is hardly described by the FU.

Companies are tempted to define the FU in a way which generates the best results for their own products.

For this, and other, reasons LCA practitioners have decided that, **in the case of a specific product redesign (e.g. 1 chair, 1 shoe), it is better to abandon the complex and subjective definition of a Functional Unit, and introduce the idea of the Declared Unit. Declared units are also used when a material can fulfill many functions (e.g. 1 kg steel, wood, plastic).**

The Declared Unit is a description of the product characteristics (either ‘open’ specified or with detailed restrictions) plus the unit of calculation you would select when you use your common sense (not knowing about the FU theories). It is a normal SI unit, plus a description of the product characteristics, plus a description of the main scenario.

The difference with a FU (as defined at page 19) is that the *function* of a product is not the core of the definition, but the *specification* of the product (note the difference: a product with a specification can often fulfill more functional demands, and, a functional demand can often be delivered by more specific product systems)

The unit of calculation is not related to the *output* of the function fulfillment (the result), but the *input* of a future function fulfillment (the input quantity like weight, volume, time, etc.).

The declared unit in formula:

$$\text{Declared Unit} = \{\text{specification of product or service}\} \text{ per } \{\text{unit of calculation}\} \{\text{plus optional: main scenario}\}$$

Example 1. The drill driver in Table 2.7 is calculated “per hole”. The unit “per hole” (= output for the function fulfilment) does make sense, but is not more accurate than “per hour” (=input for the function fulfilment). In both cases a test protocol as scenario is required to make the definition more accurate. “Per hour” is straight forward, easy to understand, and leaves not much room for manipulating the results in the case that the



main characteristics of the drilling machine is specified. According to the formulas of the Functional Unit (page 19) and the Declared Unit (this page), the drill driver is characterised as follows:

Functional Unit = Drilling holes to be able to attach two subjects, per hole; to withstand a certain force, for concrete walls as well, 1000 holes in 10 years.

Declared Unit = Drill driver (drills < 10 mm; 500 W, hammer), per hour; lifespan 10 years, 3 hours per year

Example 2. An electrical hedge trimmer. The Functional Unit might be “per m<sup>2</sup> hedge”; however, it makes more sense to have a Declared Unit “per hour”, under the condition that the length of the blade is specified:

Functional Unit = Trimming hedges, per m<sup>2</sup> hedge; branches < 3 mm; lifespan 200 m<sup>2</sup> in 10 years

Declared Unit = Electrical hedge trimmer (blade 50 cm, 500 W), per hour; lifespan 40 hours

The ILCD manual “general guide for LCA, detailed guidance” [3], Section 6.4.6, gives the following explanation on the use of the Declared Unit:

“It is important to note that not all systems have clear or unique functional units: For application-unspecific materials such as steel, gypsum, etc. but also for multiple use machines such as trucks, waste incinerators, etc. the number of possible applications and hence functional units is often extremely large to virtually indefinite. In such cases where one or few, relevant functional units cannot be given, it is crucial to clearly and both quantitatively and qualitatively identify the reference flow as the detailed name of the product plus further information that identifies its relevant characteristics ..... This is also called 'declared unit', as a general functional unit cannot be given, and a simpler mass, volume, area, pieces, or similar unit is used instead.”

Note: in some cases it is unavoidable to have a declared unit “per piece”. Examples are shoes, jewels, skates, etcetera (products with a highly unpredictable life span, and a variety of quality attributes). Here the specification and the scenario of the declared unit become utterly important. For these products it is recommended to consider “per euro”, as suggested in [8] and [9].

## 2.6 Quality aspects and the functional unit

A prerequisite for a comparison in LCA (LCA benchmarking) is that the functionality ('functional unit') and the quality of the alternative product(s) are the same (you cannot compare apples and oranges). In cases of product design and architecture, however, this prerequisite seems to be a fundamental flaw in the application of LCA: the designer or architect is aiming at a better quality (in the broad sense of the word: including intangible aspects like beauty and image), so the new design never has the same quality as the old solution. As an example we look at an armchair: different types of armchairs differ in terms of comfort, aesthetics, etc. rather than in terms of functionality.

Many practitioners of LCA-study struggle with quality aspects of LCA benchmarking. Basically there are 3 ways to deal with differences in quality:

- Option 1. For technical items: take the most important quality aspect, and if it is measurable, use it in the unit (e.g. "per lumen", "per decibel", etc.)
- Option 2. For technical products: take the lifespan as the most important quality criterion, use "per year" as unit
- Option 3. For general products and services: use the market value as a proxy for the sum of all quality aspects (tangible as well as non-tangible), use "per euro" or "per US\$" as unit

The first option does only make sense, if the goal of the LCA study is to determine the best solution in terms of the prime quality aspect.

An example is provided in Fig. 2.11, which is the output LCA benchmarking by means of CES (Cambridge Engineering Selector). The graph is showing the eco-costs (in euro per m<sup>3</sup>) and their quality in terms of tensile strength (N/m<sup>2</sup> = Pascal). The goal of the analysis is "which is the greenest material in terms of tensile strength?". The eco-costs of the materials are cradle-to-gate. The tensile strength is here a quality aspect of the materials.

Note that this way of presenting the eco-burden in terms of its technical performance is very powerful in the selection of materials for a product design in the early design stages (Section 3.2 and Section 7). More examples and applications of the CES software are given in [1] and [11].

The second option is widely applied. It follows the instinct that one should divide the eco-burden of a product by the years it is used.

However it is good to realize that:

- The lifespan of a product is an important quality aspect, but it is not the only quality aspect (other quality aspects are performance, reliability, the non-tangible aspects like aesthetics and image, etc).
- The lifespan is something which must be guessed, and this guess has an enormous impact on the output of the LCA. The 'technical lifespan' is often easier to guess

than the economical or emotional lifespan (many products are sooner discarded than their maximum technical service limit).

- The lifespan can be extended by good care and good maintenance, which is an aspect that cannot easily be modelled using LCA, since it is related to the behaviour of the user. Products like houses (of good quality) seem even to have an eternal lifespan, since they are renovated each time they fail to fulfil the quality criterions set by the owner.

The third option is dealt with by the model of the Eco-costs/Value Ratio (EVR). It links the LCA with aspects of customer preference and customer behaviour, and it provides a key solution to incorporate the quality aspects (tangible as well as non-tangible) in LCA. It enables a comparison between solutions which are different in terms of quality. See Appendix IV.

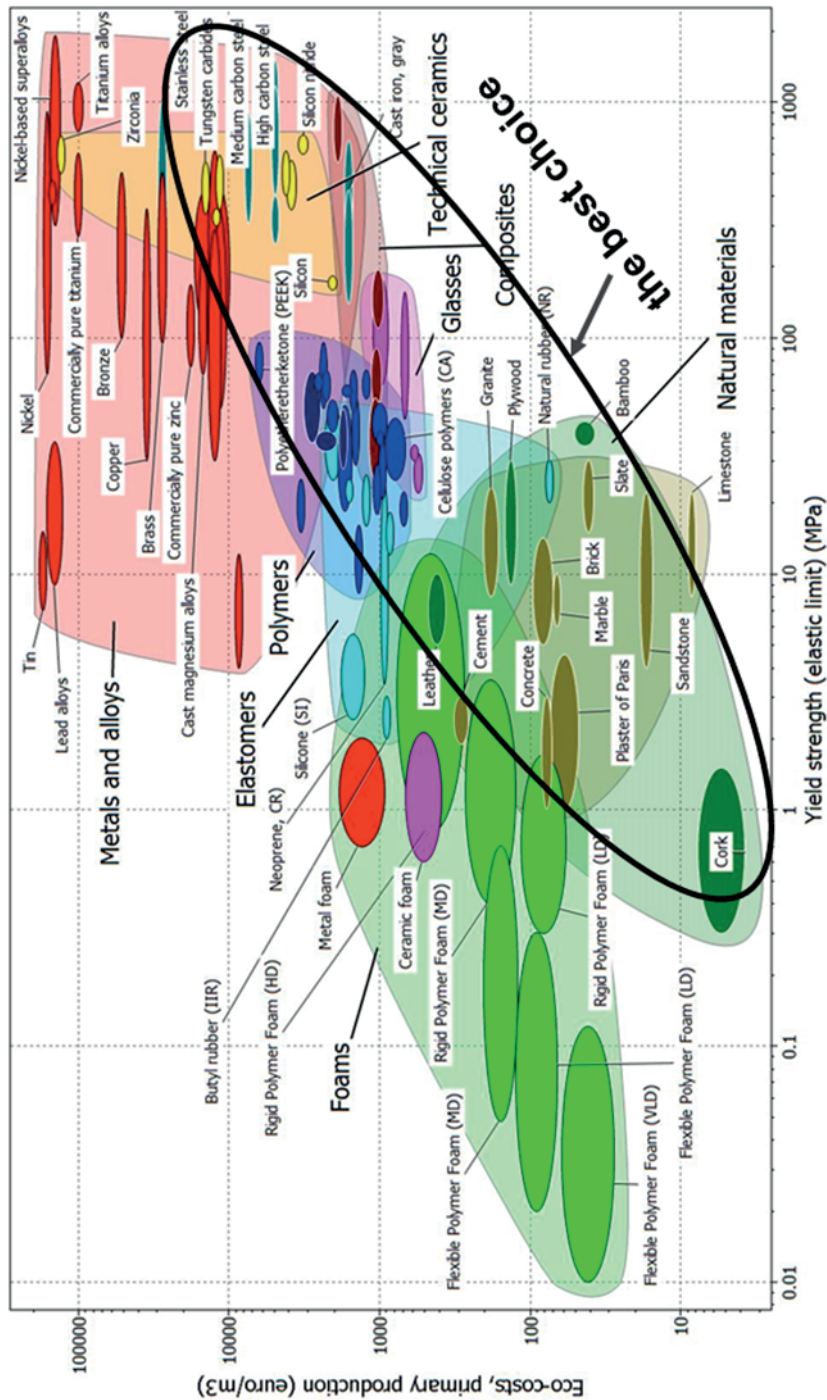


Figure 2.11. LCA benchmarking: the eco-costs/kg of materials and their quality in terms of yield strength. Software: CES



## 3 The step by step approach and LCA as an iterative process

### 3.1 The Fast Track method, step by step

'Fast Track' refers to an LCA which is made by means of look-up tables (e.g. in Excel). This is in contrast with the 'Rigorous' LCA as described in the Handbook of LCA [3]. The basic idea is, that the easiest way to make an LCA is to multiply the inputs and outputs of the Life Cycle Inventory (= list of emissions, required materials and required energy) directly by factors for the single indicators, and build look-up tables (by means of computer systems like Simapro and LCI databases like Ecoinvent) for the most common materials (cradle-to-gate) and processes (gate-to-gate or gate-to-grave). See Fig. 3.1 and 3.2.

| A  | B             | C                                             | D                                              | E           | F                       | G | H | I                | J | K          |
|----|---------------|-----------------------------------------------|------------------------------------------------|-------------|-------------------------|---|---|------------------|---|------------|
|    |               |                                               |                                                |             | weighting factor        |   |   | eco-costs (euro) |   | multiplier |
| 66 | 5 Impact cat. | Global Warming Potential 100 years, IPPC 2013 |                                                |             |                         |   |   |                  |   |            |
| 67 | 6 Air         | (E)-1-Chloro-3,3,3-trifluoroprop-1-ene        |                                                | 102687-65   | 1.49 kg CO2 eq / kg     |   |   | 0.20             |   | 0.135      |
| 68 | 7 Air         | (E)-1,2,3,3,3-Pentafluoroprop-1-ene           |                                                | 0.5595-10   | 0.079 kg CO2 eq / kg    |   |   | 0.01             |   |            |
| 69 | 8 Air         | (Perfluorobutyl)ethylene                      |                                                | 0.19430-93  | 1.36E-01 kg CO2 eq / kg |   |   | 0.02             |   |            |
| 70 | 9 Air         | (Perfluorooctyl)ethylene                      |                                                | 0.21652-56  | 9.29E-02 kg CO2 eq / kg |   |   | 0.01             |   |            |
| 71 | 10 Air        | (Perfluorohexyl)ethylene                      |                                                | 0.25291-17  | 0.108 kg CO2 eq / kg    |   |   | 0.015            |   |            |
| 72 | 11 Air        | (Z)-1,1,1,4,4,4-Hexafluorobut-2-ene           |                                                | 0.00692-45  | 1.08 kg CO2 eq / kg     |   |   | 0.227            |   |            |
| 73 | 12 Air        | (Z)-1,2,3,3,3-Pentafluoroprop-1-ene           |                                                | 0.05528-43  | 0.233 kg CO2 eq / kg    |   |   | 0.031            |   |            |
| 74 | 13 Air        | (Z)-1,3,3,3-Tetrafluoroprop-1-ene             |                                                | 0.29118-25  | 0.285 kg CO2 eq / kg    |   |   | 0.04             |   |            |
| 75 | 14 Air        | 1-Undecanol                                   | 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,11     | 0.87017-97  | 0.69 kg CO2 eq / kg     |   |   | 0.09             |   |            |
| 76 | 15 Air        | (unspecified)                                 | 1,1,1,3,3,3-Hexafluoropropan-2-ol              | 0.00920-66  | 182 kg CO2 eq / kg      |   |   | 24.57            |   |            |
| 77 | 16 Air        | (unspecified)                                 | 1,2,2-Trichloro-1,1-difluoroethane             | 0.00354-21  | 5.92E+01 kg CO2 eq / kg |   |   | 7.99             |   |            |
| 78 | 17 Air        | (unspecified)                                 | 2,3,3,3-Tetrafluoropropene                     | 0.00754-12  | 0.352 kg CO2 eq / kg    |   |   | 0.05             |   |            |
| 79 | 18 Air        | (unspecified)                                 | Acetate, 1,1-difluoroethyl 2,2,2-trifluoro-    |             | 30.84 kg CO2 eq / kg    |   |   | 4.16             |   |            |
| 80 | 19 Air        | (unspecified)                                 | Acetate, 2,2,2-trifluoroethyl 2,2,2-trifluoro- | 0.00407-38  | 6.84 kg CO2 eq / kg     |   |   | 0.92             |   |            |
| 81 | 20 Air        | (unspecified)                                 | Acetate, difluoromethyl 2,2,2-trifluoro-       | 0.02024-86  | 27.06 kg CO2 eq / kg    |   |   | 3.65             |   |            |
| 82 | 21 Air        | (unspecified)                                 | Acetate, methyl 2,2-difluoro-                  | 0.00433-53  | 3.27E+00 kg CO2 eq / kg |   |   | 0.44             |   |            |
| 83 | 22 Air        | (unspecified)                                 | Acetate, methyl 2,2,2-trifluoro-               | 0.00431-47  | 5.24E+01 kg CO2 eq / kg |   |   | 7.07             |   |            |
| 84 | 23 Air        | (unspecified)                                 | Acetate, perfluorobutyl-                       | 0.209597-26 | 1.66E+00 kg CO2 eq / kg |   |   | 0.22             |   |            |
| 85 | 24 Air        | (unspecified)                                 | Acetate, perfluoroethyl-                       | 0.343269-97 | 2.06 kg CO2 eq / kg     |   |   | 0.28             |   |            |

Figure 3.1  
Screenshot of part of the look-up table for eco-costs of pure emissions<sup>16</sup>

It isn't necessary then to bother about classification, characterisation, normalisation, etc. (which are steps in the formal rigorous LCA process), and it has the advantage that the designer or engineer sees immediately which materials or processes are causing the most eco-burden.

<sup>16</sup> See [www.ecocostsvalue.com](http://www.ecocostsvalue.com) tab data Excel file  
Ecocosts2012\_LCA\_data\_on\_emissions\_and\_resource\_depletion

Figure 3.2

Screenshot of part of the look-up table for products, services and energy<sup>17</sup>

|     | Process      | unit | Total eco-costs | eco-costs of human health | eco-costs of eco-toxicity | eco-costs of resource depletion | eco-costs of carbon footprint | Carbon footprint | CED [Total] | Total Recipe |
|-----|--------------|------|-----------------|---------------------------|---------------------------|---------------------------------|-------------------------------|------------------|-------------|--------------|
|     |              |      | €               | €                         | €                         | €                               | €                             | kg CO2 eq        | kg          | kg           |
| 487 | A 100 03 109 | kg   | 1.51            | 0.10                      | 0.02                      | 0.76                            | 0.57                          | 4.2              | 95.5        | 0.445        |
| 488 | A 100 03 103 | kg   | 0.97            | 0.03                      | 0.07                      | 0.60                            | 0.28                          | 2.0              | 87.4        | 0.308        |
| 4   | A 100 03 101 | kg   | 0.96            | 0.10                      | 0.14                      | 0.28                            | 0.43                          | 3.2              | 55.3        | 0.336        |
| 500 | A 100 04     |      |                 |                           |                           |                                 |                               |                  |             |              |
| 501 | A 100 04 101 | kg   | 124             | 0.02                      | 0.05                      | 0.71                            | 0.46                          | 3.4              | 100.2       | 0.463        |
| 502 | A 100 04 102 | kg   | 0.89            | 0.01                      | 0.04                      | 0.50                            | 0.34                          | 2.5              | 72.7        | 0.339        |
| 503 | A 100 04 103 | kg   | 1.48            | 0.06                      | 0.13                      | 0.72                            | 0.56                          | 4.1              | 130.9       | 0.464        |
| 504 | A 100 04 104 | kg   | 2.23            | 0.16                      | 0.24                      | 0.56                            | 1.27                          | 9.4              | 123.2       | 0.748        |
| 505 | A 100 04 105 | kg   | 1.58            | 0.11                      | 0.17                      | 0.39                            | 0.91                          | 6.7              | 68.8        | 0.539        |
| 506 | A 100 04 106 | kg   | 2.10            | 0.13                      | 0.24                      | 0.64                            | 1.10                          | 8.1              | 137.5       | 0.705        |
| 507 | A 100 04 107 | kg   | 1.50            | 0.09                      | 0.17                      | 0.45                            | 0.79                          | 5.8              | 96.9        | 0.509        |
| 508 | A 100 04 108 | kg   | 1.04            | 0.00                      | 0.06                      | 0.89                            | 0.19                          | 1.3              | 60.8        | 0.255        |
| 509 | A 100 04 109 | kg   | 2.17            | 0.24                      | 0.20                      | 0.66                            | 1.07                          | 7.9              | 108.7       | 0.695        |
| 510 | A 100 04 110 | kg   | 1.54            | 0.17                      | 0.14                      | 0.46                            | 0.77                          | 5.7              | 78.7        | 0.480        |
| 511 | A 100 04 111 | kg   | 1.09            | 0.06                      | 0.06                      | 0.70                            | 0.27                          | 2.8              | 78.0        | 0.280        |
| 512 | A 100 04 112 | kg   | 1.13            | 0.07                      | 0.07                      | 0.70                            | 0.30                          | 2.2              | 79.9        | 0.287        |
| 513 | A 100 04 113 | kg   | 1.07            | 0.05                      | 0.05                      | 0.70                            | 0.26                          | 2.0              | 75.7        | 0.274        |
| 514 | A 100 04 114 | kg   | 1.14            | 0.07                      | 0.07                      | 0.70                            | 0.30                          | 2.2              | 84.2        | 0.296        |
| 515 | A 100 04 115 | kg   | 3.11            | 0.21                      | 0.42                      | 0.70                            | 1.79                          | 13.2             | 370.5       | 1.223        |
| 516 | A 100 04 116 | kg   | 0.90            | 0.08                      | 0.10                      | 0.38                            | 0.34                          | 2.5              | 58.8        | 0.285        |
| 517 | A 100 04 117 | kg   | 1.17            | 0.10                      | 0.12                      | 0.54                            | 0.42                          | 3.1              | 77.6        | 0.396        |
| 518 | A 100 04 118 | kg   | 1.28            | 0.11                      | 0.13                      | 0.54                            | 0.45                          | 3.4              | 81.7        | 0.385        |
| 519 | A 100 04 119 | kg   | 1.95            | 0.17                      | 0.21                      | 0.50                            | 0.80                          | 7.2              | 129.5       | 0.670        |
| 520 | A 100 04 120 | kg   | 1.07            | 0.06                      | 0.13                      | 0.35                            | 0.54                          | 4.0              | 103.0       | 0.390        |
| 521 | A 100 04 121 | kg   | 1.09            | 0.06                      | 0.06                      | 0.70                            | 0.28                          | 2.1              | 76.9        | 0.279        |

This approach is also called the ‘Philips method’, since Philips Electronics was the first company which did LCAs in this way in 1998-1999 (the EcoScan software).

The ‘Fast Track LCA’ method must not be confused with ‘Streamlined’ LCAs: the Fast Track method has exactly the same output (accuracy) as the Rigorous, formal, LCA, since it applies the same LCIs and calculation methods for a single indicator (eco-costs, carbon footprint, CED, Recipe, and Environmental Footprint). Only the calculation **sequence** is different. For a summary description of the rigorous and formal way to calculate, see Appendix II.

The Fast Track LCA method has the following step by step procedure:

- **Step 1 Establish the scope and the goal of your analysis (this step might be done after step 2 in the case that it is a total new design)**
  - is it a comparison of two or more products?
  - is it an attempt to improve the environmental characteristics of a typical design?
    - less, or less harmful, materials?
    - less energy in the use phase?
    - less transport?
    - better recycling or better incineration of waste for electricity?
    - cradle-to-cradle solution?
    - better durability?
- **Step 2 Establish the System, Functional Unit (or declared unit) and System Boundaries**
  - Describe the function of your product or service:

<sup>17</sup> For these kind of tables see [www.ecocostsvalue.com](http://www.ecocostsvalue.com) tab data Excel file Idematapp2017.xlsx and Idemat2017+EI\_V3-3.xlsx. This last file is updated each time when the Ecoinvent data is updated. The V3-3 refers to the version of the Ecoinvent data.

- example for a coffee machine: 1000 cups of coffee per year (or: ... cups over the life time)
- example for a transport system: 50 m<sup>3</sup> freight over a distance of 300 km, no payload back
- Make a drawing of your product system (from cradle-to-grave, or from cradle-to-cradle). See the examples of Fig. 2.2, 2.3 and 2.4.
- Determine the life time of the system components.
- Establish one or more transport scenarios (e.g. bamboo from China or Latin America).
- Establish the system boundaries (what do you include and what do you neglect in your system?).
- **Step 3 Quantify materials, use of energy, etc. in your system**
  - Collect (measure) data (e.g. weight, material, energy consumption).
  - Determine accuracy and relevance; establish allocation rules (or scenarios) and cut-off criteria.
- **Step 4 Enter the data into an Excel calculation sheet or a computer program**
  - If an indicator value for a material or process is missing in the look-up table, this can be resolved as follows:
    - check whether the missing material or process could make a significant contribution to the total environmental impact, if not neglect it (if it is expected under the cut-off criterion)
    - substitute a known process for the unknown one which has the same characteristics (take a surrogate process). For example: If you miss an indicator value for a certain type of plastics, find out which known plastic is similar
    - search in EPD databases (e.g. of Germany or France) and apply Appendix VII
    - take the required energy for the process, calculate the eco-burden of it, and add the eco-costs of the toxic emissions and materials depletion (if any); see for the eco-costs of emissions and materials depletion the excel file with emissions at [www.ecocostsvalue.com](http://www.ecocostsvalue.com), tab data
- **Step 5 Interpret the results and draw your conclusions**
  - When you have entered everything in your computer program or calculation sheet, you can add up the total eco-costs of your product (and/or service). However, it is not the aim of an LCA to have the total eco-costs only. The aim of LCA is always a comparison with other products and/or alternative designs or processes. So, the last step of LCA is an analysis of the total output, including relevant details.
  - Note: it might be that you conclude in this last step that you have to (partly) redo your calculation, since elements are missing or are not accurate enough.



## 3.2 Applying LCA data in the early design stages

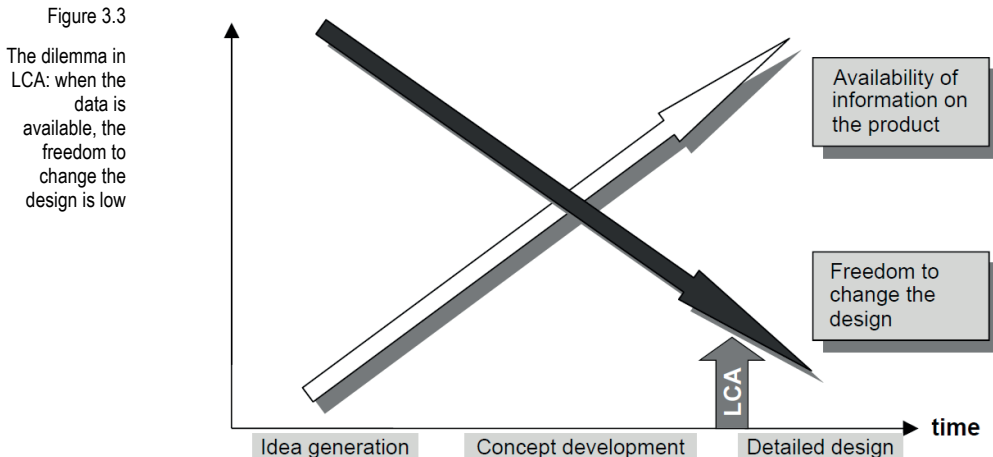
The classical paradigm in LCA is, that you can do an LCA only when the design of your product is finished. The logic behind this paradigm is supported by the following aspects:

- the step by step procedure of the previous section suggest that you know the end result of the design
- the tree of Fig. 2.4, used in most of the computer manuals, suggests that you need to have a lot of detailed information prior to your calculation, especially when you aim at a stringent cut-off criterion for your system boundary (e.g. 2%)
- the rigorous, full, LCA calculation sequence is a lot of work, so you want to do it only once
- in many computer programs (like Simapro) the calculation as such is a black box, with the fact of “rubbish in, rubbish out”, generating the normal reaction of people that the input must be as comprehensive and accurate as possible

The drawback of this classical paradigm is, that the LCA is made when the design is considered to be ready. Only minor changes can be realised at that stage.

This leads to the basic dilemma of Fig. 3.3:

- in order to make an LCA, a lot of information is needed
- at the moment the information is available; however, there is little freedom left to change the design



The logic question is now how to resolve this dilemma. How can we shift the LCA towards the fuzzy front end of the design process? See Fig. 3.4. The solution to this dilemma is to do the LCA *parallel* to the design process. So LCA is not the last step of

the design process, but it is part of the optimization loops during a normal design process.

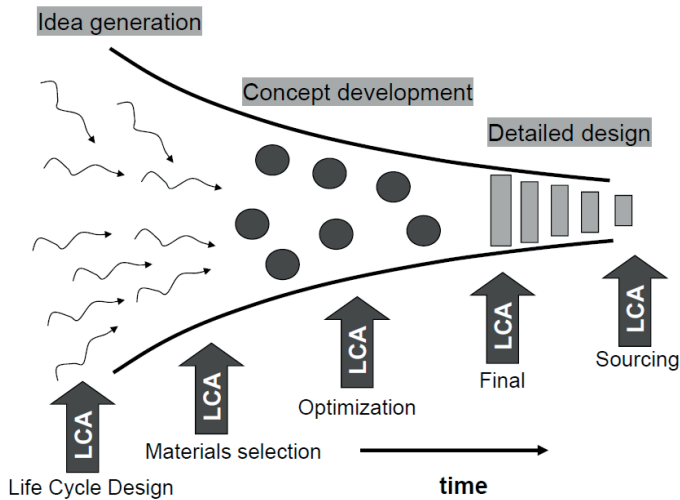


Figure 3.4

The start of Life Cycle Assessment must be shifted to the start of the design: the LCA must be done in parallel to the design process

It is even advised to start the design process with step 2 (and 1) of the Fast Track LCA of the previous section, prior to the design itself. This is even more important when we try to apply the philosophy of cradle-to-cradle to the design.

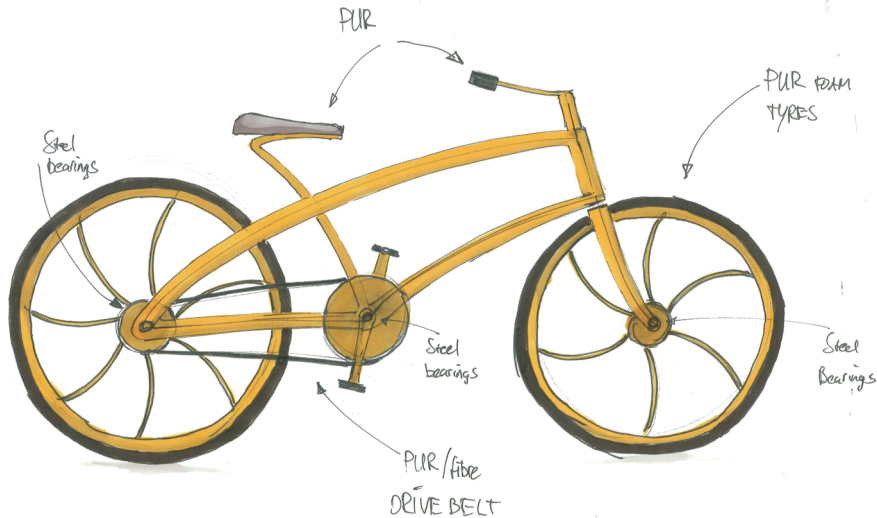
An example of such an application of LCA right at the start of the design process is the design of an innovative production method for a bicycle. This bicycle, the 'Rebicycle', is depicted in Fig. 3.5.

The issue is here that the bicycle is not just a wooden bicycle, but a bicycle which has the lowest LCA score possible, cradle-to-cradle. This is not only achieved by the choice of materials, but also the choice of production methods, applying the cradle-to cradle philosophy (i.e. taking advantage of opportunities of recycling, and trying to incorporate the biosphere in the production method).

In such a situation is it wrong to design the bike first, and then try to select the materials for the design. It is a must to analyse first the opportunities of different recycle loops. In terms of cradle-to cradle, the first issue is to make a choice on the materials to be used. The possibilities are:

- steel for the frame, since steel can be upcycled (open loop as well as closed loop), or
- wood for the frame, since wood is recycled by our nature itself (the question is then: must the wood be biodegraded, with capture of the methane for heat and electricity, or can the wood directly be burned for heat and electricity?)
- steel for the chain and the bearings, or
- bio-plastics for the chain, the bearings, and the other parts (like the tires)

Figure 3.5  
The Rebicycle,  
a cradle-to-  
cradle design of  
a bike



It is needless to say that the design follows from the choice of the cradle-to cradle materials, and not the other way around.

Steel has good C2C characteristics; however, wood (as a renewable material) scores better in LCA. The issue is which wood species score well in terms of strength, and can be grown in the Dutch climate (to avoid the eco-burden of transport). Such an analysis leads to a choice of specific materials, and the design follows the selected materials.

The LCA analysis of such cradle-to-cradle loops is a little less straight forward than the standard, simple, LCAs. More details are explained in Chapters 5 and 7.

Note that the accuracy of such calculations is not high in the beginning of the design process (30% -50%), since a lot of details are not known. However, accuracy in this stage of the design is not an issue: the difference in eco-costs (or other single indicators for LCA) of the different systems is normally a factor 2 - 10.

Note also that the time required for such analyses is very limited for Fast Track LCAs, since the number of lines which are required from the look-up tables is very limited (data on production of the material, processing, transport, maintenance and/or energy in the use phase, and recycling, resulting in 5 - 10 lines in practice).

## 4 Transport and the Use Phase

### 4.1 Transport

Transport is an important issue in LCA, so it requires extra attention. The relative importance of transport follows from the eco-costs of transport (Idematapp):

- 0.026 €/ton.km for a European standard truck + trailer
- 0.022 €/ton.km for a European truck + container
- 0.0014 €/ton.km for long distance sea transport by container

This means that you can transport 1 kg of bulk materials by a truck + trailer over a distance of 1000 km in Europe for 0.026 € eco-costs. For bulk plastics this is negligible, since the eco-costs of production of plastics is about 1 €/kg (ranging from 0.4 €/kg for some bio-plastics to 2.3 €/kg for Nylon). However, the eco-costs of wood (600 kg/m<sup>3</sup>) “at the forest road” ranges from 0.003 - 0.004 €/kg. So the eco-costs of wood are determined by the transport of it.

The cradle-to-gate<sup>18</sup> LCIs of most standard databases (Ecoinvent, Idemat, etc.) include the transport of the material. Even it includes the transport of the materials required to build the manufacturing facilities (see Fig. 2.5). So the transport we need to add is the transport from the manufacturing plant to the user, the transport by the user, and the transport related with the End of Life.

A lot of consumer products have the factory gate in China. It is wrong then to apply ton.km data to the transport to Europe, since the weight/volume ratio of a box with a product is rather low. Transport must be calculated then based on m<sup>3</sup>.km, which is explained at the next two pages.

LCIs of long distance road transport in the Ecoinvent and Idemat databases are calculated on the basis of a full load of the truck and an empty trip back, divided by the maximum load of the truck. The so called (overall) load factor is then 50%, and the functional unit is “per km” (one way distance). The eco-costs are based on a load factor of 50% for road transport, 70% for air freight, and 80% for sea freight (per km, one way distance).

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<sup>18</sup> The gate is here the gate of the manufacturing plant. The transport from cradle-to-gate is based on global averages (a free global trade of the product is assumed), and the gate is assumed to be in Europe for most cases of the Ecoinvent and Idemat databases.

One might make a correction for special transport legs. When a sea freight leg has an overall load factor of 60%, the eco-costs of this transport leg is a factor 80/60 higher than the data in the Idemat and Idematapp database.

A 'euro 6' truck<sup>19</sup> has 0.31 €/km eco-costs (LCI data from Idemat and Ecoinvent). The eco-costs per ton or per m<sup>3</sup> are calculated as follows:

- A standard European truck + trailer, 40 tons, can carry a total weight of 24 tons or a total volume of 75 m<sup>3</sup>.
  - When the weight/volume ratio is more than  $24/75 = 320 \text{ kg/m}^3$  (the break-even weight/volume ratio), the eco-costs of the transport is determined by the weight<sup>20</sup>:  $(1/0.50) \times 0.31/24 = 0.026 \text{ €/ton.km}$ .
  - When the weight/volume ratio is less than  $24/75 = 320 \text{ kg/m}^3$ , the eco-costs of the transport is determined by the volume:  $(1/0.50) \times 0.31/75 = 0.0083 \text{ €/m}^3\text{.km}$ .
- A standard European truck with container (40 ft), can carry a total weight of 28 tons or a total volume of 67.7 m<sup>3</sup>.
  - When the weight/volume ratio is more than  $28/67.7 = 414 \text{ kg/m}^3$ , the eco-costs of the transport is determined by the weight:  $(1/0.50) \times 0.31/28 = 0.022 \text{ €/ton.km}$ .
  - When the weight/volume ratio is less than  $28/67.6 = 414 \text{ kg/m}^3$ , the eco-costs of the transport is determined by the volume:  $(1/0.50) \times 0.31/67.7 = 0.0091 \text{ €/m}^3\text{.km}$ .

A standard 40 ft sea container (TEU) on a modern container ship has 0.031 €/km eco-costs with an average load factor of 0.80. The eco-costs per ton or per m<sup>3</sup> are calculated as follows:

- A standard 40 ft container, can carry a total weight of 28 tons or a total volume of 67.7 m<sup>3</sup>.
  - When the weight/volume ratio is more than  $28./67.7 = 414 \text{ kg/m}^3$  (the break-even weight/volume ratio), the eco-costs of the transport is determined by the weight:  $1/0.8 * 0.031/28 = 0.0014 \text{ €/ton.km}$
  - When the weight/volume ratio is less than  $28.1/67.7 = 414 \text{ kg/m}^3$ , the eco-costs of the transport is determined by the volume:  $1/0.8 * 0.031/67.7 = 0.00057 \text{ €/m}^3\text{.km}$ .
  - For a bulk sea freight container of 20 ft, the break-even weight is 846 kg/m<sup>3</sup>

For intercontinental air freight, the same kind of reasoning applies, resulting in:

- the eco-costs = 0.17 €/ton.km for a weight/volume ratio is more than 167 kg/m<sup>3</sup>
- the eco-costs = 0.028 €/m<sup>3</sup>.km for a weight/volume ratio is less than 167 kg/m<sup>3</sup>

<sup>19</sup> 'Euro 6' is an European classification of the emissions of a truck.

<sup>20</sup> Note that the factor 0.50 is caused by the empty trip back: the so called average is 50%.

**When databases have ton.km LCI data only**, a correction factor must be applied to convert these data to ton.m<sup>3</sup>. This correction factor is:

$$[\text{break-even weight/volume ratio}] / [\text{actual weight/volume ratio}]$$

under the condition that this factor is more than 1.

The break-even weight/volume ratio is (as explained above):

- 320 kg/m<sup>3</sup> for freight in a European standard truck + trailer
- 414 kg/m<sup>3</sup> for freight in a standard truck + 40 ft container

The same formula is to be applied to sea freight by container and air freight:

- 414 kg/m<sup>3</sup> for freight in a standard 40 ft sea container (take the weight/volume ratio of 846 for 20 ft containers and other sea freight by bulk vessels)
- 167 kg/m<sup>3</sup> for airfreight

Example: when 24 tons has to be transported by a standard European truck and trailer (24 tons = a full truck load for high densities), and the actual weight/volume ratio is 160 kg/m<sup>3</sup>, the correction factor is 2. This means that the truck must drive two times to transport this freight. The eco-burden per ton.km of this transport is 2 times the eco-burden per ton.km of high density freight.

Note.

- For trucks, the assumption is an average load factor (=occupancy rate) of 50% (the truck is full, but returns empty, on average) which appears realistic in practice. For air freight and sea freight, occupancy rates are 70% and 80%, included in the data.
- If the truck is not fully loaded at the trip, a multiplier (bigger than 1) must be applied in LCA to cope with the partly loaded truck.
- If, in special cases, the trip of the truck can be combined with other freight on the trip back, the so called 'economic allocation' of the eco-burden of the round trip of the truck should be applied. Economic allocation means that each consignment must carry a percentage of the eco-costs of the full trip which is in line with the percentage of the total economic costs of the round trip. Example: when costs of the return freight equals 40% of the total costs of the round trip, the eco-costs which are to be allocated to this return freight are also 40% of the total eco-costs.
- Do not apply the ton.km data to transport of freight and weight carried by cars, motors and scooters. The eco-costs must be calculated from the following data on extra fuel:
  - Cars and motors  
0.3 liter gasoline (0.25 liter diesel) per 10.000 kg.km
  - Scooters  
see Idemat data per 100.000 kg.km

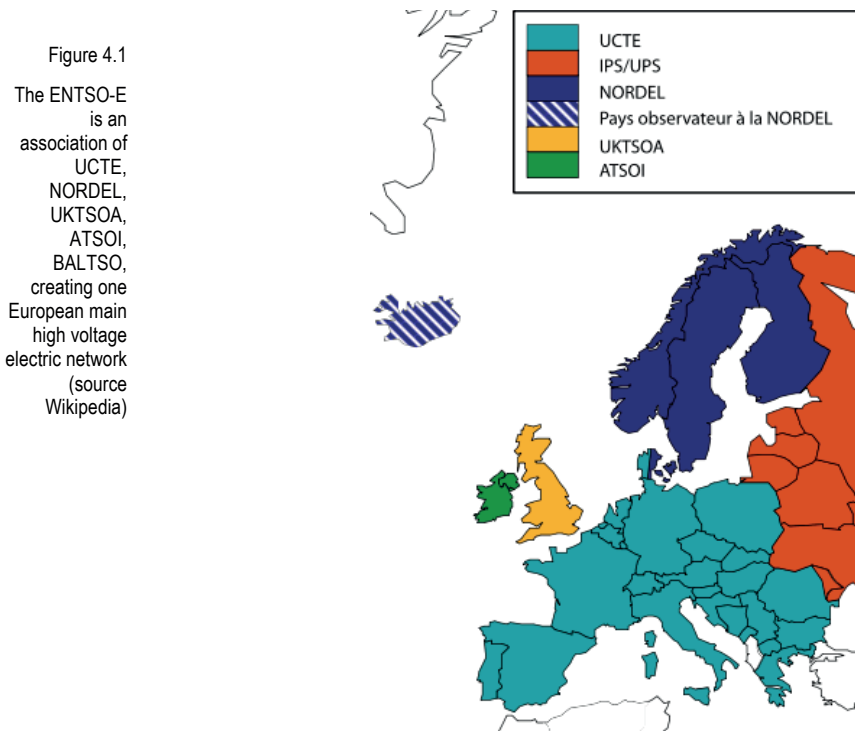
## 4.2 Energy

One of the major aspects of the production phase as well as the use phase is the consumption of energy (electricity, heat and fuels for transport). Databases provide a lot of data for energy, and the energy consumption is just a matter of straightforward calculations in the classical LCA. Only when discounting of delayed pollution is applied (e.g. in calculations on the use phase of a house), calculations become more complex, see Section 5.6.

Two remarks:

1. The data for fuels in databases like Ecoinvent is provided for the production phase only. The eco-burden of combustion depends on the combustion system, and must be calculated additionally.
2. The eco-burden of the production of electricity is different for each country. In Europe it is recommended to take the eco-burden of the average of the ENTSO-E group of 34 countries, since these countries are connected in one power grid, see Fig. 4.1.

The same approach is recommended for gas: take the European average, rather than the local production.



## 4.3 Maintenance

In most of the systems in practice, maintenance does not play an important role. The eco-burden of normal maintenance in most cases is negligible. Examples:

- conservation of wood:  
The eco-costs of 1 kg white acrylic varnish is 1.85 €/kg (for 12 - 15 m<sup>2</sup>), and the eco-costs of the van of the house painter is 0.105 €/km. In normal cases this is negligible in comparison with the eco-costs of the object which is painted.
- maintenance of a car or truck:  
The main eco-costs of scheduled maintenance are the eco-costs of the tires, the oil, replacements of small parts, and the use of the garage. The tires are quite important (for a car 3 extra sets for a lifespan of 300.000 km; for a truck 4 extra sets for a lifespan of 1.000.000 km). The eco-costs of the tires of a truck are approximately 5% of the eco-costs of the diesel in the use phase. The use of the garage is approximately 5% as well.

An important aspect of maintenance in LCA is that it can enhance the lifespan of a product. In nearly all cases, the reduction of eco-burden per year (because of the longer lifespan) is much more than the eco-burden of the maintenance as such. So here is an opportunity for designers and engineers.

The maintenance of houses and offices is more complex in LCA. Refurbishing, replacement of heating equipment, kitchens and bathrooms are important factors. Total renovations of floors, walls, etc. inside and outside the building require a special approach in LCA. In fact, a house with a good quality at a good location does not have a fixed point of End of Life: it lives virtually for ever. See Fig. 4.2.

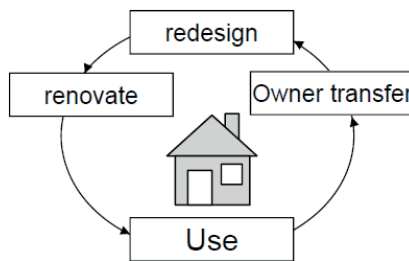


Figure 4.2  
The endless  
maintenance  
circle of a house

A simple approach in LCA is to give separate life spans to the different objects of a house, e.g.:



- the interior (painting, decorating, furniture, etc.) 10-15 years
- the heating systems 15-20 years
- window frames 30-50 years
- the house 75 years

The problem of this simple approach is that the eco-burden of the house is determined by the guess of its lifespan of 75 years. With such a fixed guess, the quality aspect of the design is not taken into account, which results in unsatisfactory results of LCA benchmarking calculations.

Moreover, comparisons of the 2 different scenarios 'demolishing and building new' versus 'renovation' cannot be analysed in this way.

In Section 5.6 a different approach for houses and office buildings is proposed, which is a bit more complex, but far more powerful in terms of benchmarking.

# 5 By-products, Waste and Recycling

## 5.1 By-products and waste

The way by-products and waste are dealt with in LCA is discussed for the last 15 years. The reason is that there is no 'one truth' for these calculations: more solutions are possible. This LCA guide will not describe and discuss all possibilities; however, it will describe the practical and logical solutions for designers and engineers. The approach of this manual is to keep the LCA calculation in line with the technical structure of the product system, and in line with the requirements of ISO 14040, 14044, and EN 15804. The issue is related with the so-called 'allocation' of eco-burden in LCA.

The basic structure of an LCA calculation is depicted in Fig. 5.1. The basic idea is that all inputs (materials, energy, and transport) and emissions (to air, water, and soil) of a product system cause eco-burden.

Outputs are the products and services which are delivered by the system, as well as by-products, energy, waste, and materials to be recycled.

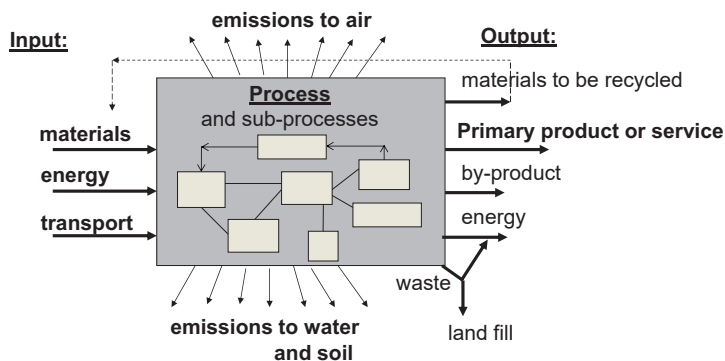


Figure 5.1  
The basic structure of a system in LCA

In this guide we use the following practical definitions for output flows:

- By-products are products which can be used directly in other product systems (e.g. wood chips from saw mills can directly be applied in chipboard, saw dust can directly be applied in MDF plates)
- Energy is electricity or heat which is used by another system. This is also a form of by-product. (e.g. heat and/or electricity from combustion of wood chips and saw dust).

- Waste<sup>21</sup> is material that goes either to land-fill or waste incineration, or requires waste treatment (sorting, shredding, etc.) and recycling (up- as well as downcycling<sup>22</sup>). Post-consumer waste stems from products at the end-of-life (the moment the original function of the product stops, and the product is discarded). Production-waste is defined as material from the input that is no longer useful or required in the production process, and is discarded.

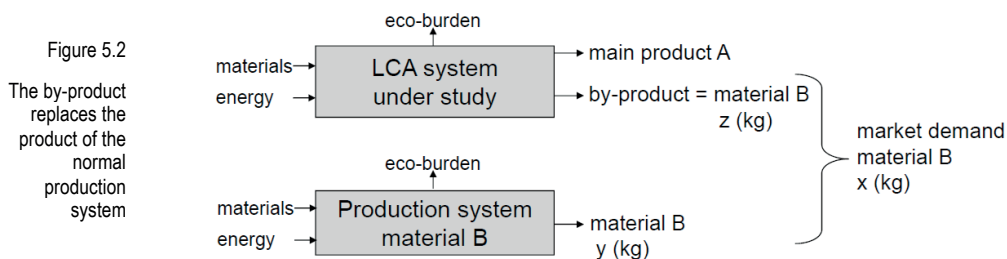
The most consistent way to handle by-products in LCAs for product design is via so called ‘credits’. A credit is a negative eco-burden, caused by the effect that the by-product causes the avoidance of the eco-burden of the production of that product elsewhere in the market. This is explained in Sections 5.2 and 5.3.

The way to handle waste in LCA is dealt with in Sections 5.4 and 5.5. Both solutions, for by-products and waste, are in line with each other, so there is no need to make a formal distinction between both types of outputs.

## 5.2 Credits and system expansion

The basic system approach of ‘credits’ (also called ‘system expansion’, ‘substitution’, or ‘avoided burden’) is depicted in Fig. 5.2.

The basic idea is that the by-product replaces the product of the normal production system in the market place. This results in a reduced normal production. So, on global level, the by-product results in the avoidance of the eco-burden which is related to the normal production.



<sup>21</sup> This definition differs from a general definition used in science, where by-products are products with a positive market value, and waste is a product with negative market value. Such a definition, however, is impractical for designers and engineers, since the market value of waste depends on the time, the place, and the quantity of the waste: some types of waste like waste paper and waste from buildings can have a negative as well as a positive market value.

<sup>22</sup> In upcycling, the material is recycled to the quality of the virgin material, or to other materials with a high value (e.g. stainless steel). In downcycling the waste material ends up in an application of lower value (e.g. recycled paper from waste paper). In practice, however, the line is rather blurred between upcycling and downcycling.

In the LCA system which is under study, it is counted as a ‘credit’ (a negative eco-burden), equal to the eco-burden of the normal production.

In the example of Fig. 5.2, the reasoning is as follows:

- a) the market demand of the material B is  $x$  kilograms
- b) without the system under study, this demand is produced by the normal production system  $y = x$
- c) when the system under study is introduced, the normal production system only has to produce  $y = x - z$
- d) so the total eco-burden of the production of the material B is reduced with the eco-burden of  $z$  kilograms, the so called avoided eco-burden, the credit
- e) this credit is allocated to the main product of the system under study
- f) concluding: when the total eco-costs of the system under study is 2.4 euro, and the credit of the by-product is 0.5 euro, the total eco-costs of the main product is  $2.4 - 0.5 = 1.9$  euro

This approach of applying credits to the main product is an approach of a so called marginal calculation. The assumption is that the amount of  $z$  kilograms is very small (less than 10-20%) compared to the total market demand of  $x$  kilograms. This is normally the case in design and engineering<sup>23</sup>.

In cases where the by-product doesn’t have the right quality compared to the same material on the market (e.g. in case of a lower grade), there are two solutions in LCA:

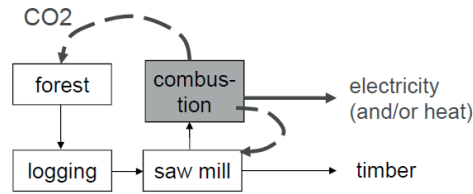
- to expand the system with a process which will bring the by-product in line with the market requirements (e.g. a purification step)
- to apply the so-called **economic allocation instead of crediting**, according to the rules of ISO 14044. In economic allocation, the eco-burden of a system is assigned to the co-products in proportion to the economic value of the products (“the strongest shoulders carry the most eco-costs”). See also Section 6.2.

Heat can also be a by-product of a production system. Either the heat is a direct outcome of the production process, or the heat can be generated by combustion of materials which can be used as fuel. The second case is an example of system expansion. The ISO 14044 (Section 4.3.3.1) has a practical statement on this issue: “Inputs and Outputs related to a combustible material (e.g. oil, gas or coal) can be transformed into an energy input or output by multiplying them by the relevant heat of combustion” (The lower heating value, LHV, is advised in this guide, often converted to electricity, taking the right production efficiency into account, see Section 5.3).

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<sup>23</sup> When macro-economic scenarios for the future are studied, a by-product might have a considerable impact on the total market. The system under study must be expanded then, including the normal production system of the same type of material as the by-product. Material B (Fig. 5.2) is then a **co-product** of the total system. Such studies on **future** changes in a total market require the so called consequential allocation, which is outside the scope of this LCA guide.

Figure 5.3  
Combustion of  
waste in LCA



The consequence of this rule in the ISO is that the saw dust and wood chips of saw mills can be converted to heat, applying the system expansion as depicted in Fig. 5.3. Part of the heat can replace the oil required for drying, the rest can be exported in the form of electricity. This is a relatively simple solution in comparison with the system expansion with production of chipboard and/or MDF.

Note that Fig. 5.3 depicts a theoretical situation: it can also be applied to situations when the wood chips and the saw dust is used in particle board and MDF. So the combustion is a surrogate process for the production of particle board. This is allowed in LCA, since it is often not known exactly what happens in reality (how much is used in particle board, how much in MDF and how much is combusted?).

It is obvious that this approach is only allowed when it is certain that the saw dust and the chips are applied in a useful output (e.g. in European timber production). If the excess of saw dust and chips are discarded to landfill, so there is no export of electricity (e.g. typical Chinese production of bamboo), this flow must be defined as landfill. The approach in LCA is always to describe the total system as closely as possible to reality. System expansions are used only to make an LCA doable in practice.

Table 5.1 provides data for the combustion of wood: the heat (LHV), and the credits in terms of the eco-costs at 100% as well as 90% thermal efficiency.

Table 5.1  
Credits of  
combustion of  
wood, using the  
heat in other  
processes

| heat of wood    | LHV (MJ/kg) | eco-costs<br>(€/kg) |                |
|-----------------|-------------|---------------------|----------------|
|                 |             | 100% efficiency     | 90% efficiency |
| hardwood 0% MC  | 20.5        | -0.22               | -0.20          |
| hardwood 12% MC | 17.7        | -0.19               | -0.17          |
| hardwood 50% MC | 9           | -0.09               | -0.08          |
| softwood 0% MC  | 21.4        | -0.23               | -0.21          |
| softwood 12% MC | 18.5        | -0.19               | -0.17          |
| softwood 50% MC | 9.4         | -0.09               | -0.08          |

The credits for wood in Table 5.1 are high since the CO<sub>2</sub> emissions are not counted in LCA (the CO<sub>2</sub> is of bio-origin). Combustion of plastics from fossil fuels gives hardly any credits because of the CO<sub>2</sub> emissions (for some plastics the eco-costs of CO<sub>2</sub> are even higher than the eco-benefits of the delivered heat). See next Section 5.3.

Table 5.1 is only valid for clean and pure materials, i.e. by-products from the production phase. However, most materials from the End of Life phase are not clean and

pure. As waste they are mixed with other materials, and cannot be burned as efficient as the materials from the production phase. The next section deals with this issue.

## 5.3 Combustion of waste with production of heat or electricity

Fully in line with the calculation on heat in the previous section, end-consumer waste that can be burned is dealt with in LCA by the same type of system expansion. See Fig. 5.4 for the case of wood waste.

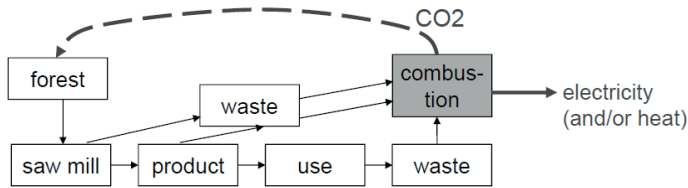


Figure 5.4  
System expansion in LCA to deal with waste incineration of wood

The extra step, added to the chain, is the gray step in Fig. 5.3, where the waste is burned and converted to electricity, either in an electrical power plant or in a municipal waste incinerator.

To calculate the electricity, the Lower Heating Value of the waste has to be applied (ISO 14044). The following efficiencies are to be applied in the eco-costs system (the best practice in Western Europe):

- 45% to convert the LHV to electricity in a power plant (medium voltage, i.e. 1 KV to 35 kV, power supply in the range of 160 kWh to 40.000 kWh)
- 25% (= 55% of 45%) to convert the LHV to electricity in a municipal waste incinerator, medium voltage
- 95% to convert the LHV to heat output.

**Since wood is a natural product, the CO<sub>2</sub> emissions of combustion are not counted in the eco-costs system (biogenic CO<sub>2</sub> is not counted according the calculation rules of the IPCC),** see Fig. 5.3 and 5.4: these emissions are part of a closed loop in mother nature *if the trees are replanted or regrown* (which is the case for European wood types, and FSC wood that is rotational harvested, but not for non-FSC tropical hardwood). The resulting credits for some types of wood are provided in Table 5.2. For further explanation, and the time span issue (the period required for the growth of the tree), see Section 8, page 82, on carbon sequestration in wood.

The basis for the approach of the system expansion is the fact that LCA calculations of designers and engineers are ‘marginal’ calculations in most of the cases, as explained in Section 5.2. At a macro-economic level, these marginal calculations are not fully correct, as stated before in footnote 23. However, the marginal approach fully supports system expansion in LCA (as in Fig.5.4) to deal with incineration of waste wood, in line

with the common sense of designers, engineers and students<sup>24</sup>, and avoids complex calculations with a lot of underlying assumptions.

| Table 5.2                                                                                                                           | electricity from waste                                     | eco-costs (€/kg)<br>electr. power plant | eco-costs (€/kg)<br>waste incinerator |
|-------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------|-----------------------------------------|---------------------------------------|
|                                                                                                                                     |                                                            |                                         |                                       |
| Credits or debits of electricity production in electrical power plants and municipal waste incinerators with electricity production | hardwood 0% MC                                             | -0.22                                   | -0.11                                 |
|                                                                                                                                     | hardwood 12% MC                                            | -0.19                                   | -0.10                                 |
|                                                                                                                                     | hardwood 50% MC                                            | -0.09                                   | -0.04                                 |
|                                                                                                                                     | softwood 0% MC                                             | -0.23                                   | -0.12                                 |
|                                                                                                                                     | softwood 12% MC                                            | -0.20                                   | -0.10                                 |
|                                                                                                                                     | softwood 50% MC                                            | -0.09                                   | -0.04                                 |
|                                                                                                                                     | paper and board, dry                                       | -0.21                                   | -0.11                                 |
|                                                                                                                                     | PLA                                                        | -0.21                                   | -0.11                                 |
|                                                                                                                                     | starch based plastics                                      | -0.18                                   | -0.09                                 |
|                                                                                                                                     | PA 66                                                      | -0.01                                   | 0.14                                  |
|                                                                                                                                     | PC                                                         | 0.04                                    | 0.19                                  |
|                                                                                                                                     | PE                                                         | -0.09                                   | 0.14                                  |
|                                                                                                                                     | PET                                                        | 0.03                                    | 0.16                                  |
|                                                                                                                                     | POM                                                        | 0.01                                    | 0.09                                  |
|                                                                                                                                     | PP                                                         | -0.07                                   | 0.15                                  |
|                                                                                                                                     | PVC                                                        | 0.87                                    | 0.97                                  |
|                                                                                                                                     | efficiency waste incinerator 55% of electrical power plant |                                         |                                       |

For combustion of plastics, the situation is basically the same, see Fig. 5.5. The difference with wood is that most of the plastics which are applied in products are based on fossil fuels. Therefore the eco-costs of CO<sub>2</sub> must be counted. The result is that the positive effect of the generation of electricity (or heat) is counteracted by the CO<sub>2</sub> emissions. The net result for electrical power plants is slightly positive for some plastics, but negative for many others. See Table 5.2. For more materials see the LCIs of Idemat in the Excel tables on [www.ecocostsvalue.com](http://www.ecocostsvalue.com).

For municipal waste incineration, the result for oil based plastics is always negative, because of the lower efficiency. So burning of oil based plastics in a municipal waste incinerator is not a good solution for the environment: plastics should be recycled.

<sup>24</sup> Ecoinvent has the point of view that the benefit of combustion of wood cannot be taken at End of Life. The debate is that this would result in double counting, since biomass is already taken into account at the “market mix” of electricity. From macro-ecologic point of view this is right. However, the issue is that LCA is normally applied to micro-ecologic issues: when a designer decides on wood since it can be burned at the EoL, it is a good decision as such, regardless of the fact what happens on average in Europe. It is an issue of applying marginal instead of integral mass-balances.

The Idemat database (build on Ecoinvent data) is meant to be for designers, purchasers, business people and consumers who have to take their marginal decisions. Therefore, the Idemat database incorporates the positive effect of combustion of wood and bio-plastics. These Idemat LCIs can be applied to the Eco-costs as well as the latest Simapro versions (higher than version 7.2.3) of Recipe.

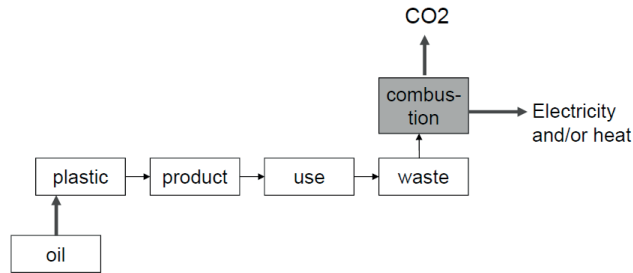


Figure 5.5  
Waste  
incineration of  
plastics from  
fossil fuels

For plastics made from renewable resources ('bio-plastics'), combustion is a good option (since the  $\text{CO}_2$  is not counted, like the wood system in Fig. 5.4).

For these types of plastics, as well as for wood, combustion is a better solution than uncontrolled bio-degrading in nature: bio-degrading in nature has not the positive credit of generating electricity and/or heat of combustion with heat recovery, and has the risk of  $\text{CH}_4$  emissions (30 times stronger than  $\text{CO}_2$  as greenhouse gas).

Controlled bio-degrading, however, is okay. There are two types of it:

- Controlled bio-degrading by anaerobic bacteria in a closed storage tank, where the  $\text{CH}_4$  is collected and burned. This can be applied to wet farmyard manure. For small rural communities in the third world, it seems to be a good local solution to generate methane for cooking. For wood and bio-plastics, however, it seems to be not the best solution, since the overall eco-efficiency is lower than combustion in an electrical power plant or a modern waste incineration plant.
- Controlled bio-degrading by aerobic bacteria in a closed building to produce compost, where the  $\text{CH}_4$  emissions are minimized and captured. This method is applied in Western Europe (The Netherlands, UK, Germany, etc.) for waste from gardens and agriculture. In countries like The Netherlands, there is an increasing appreciation for compost (to replace chemical fertiliser), leading to an increasing demand of compost. In LCA, however, it is not easy to model the credit of compost, since the credit of compost is more than the avoided chemical fertilizer: compost results in better quality of the agricultural products. Therefore the data in the Idemat database is a slight underestimation of the credit of composting.

Note that composting of bio-plastics does not make sense, since the bio-plastics do not contain fertilizers.

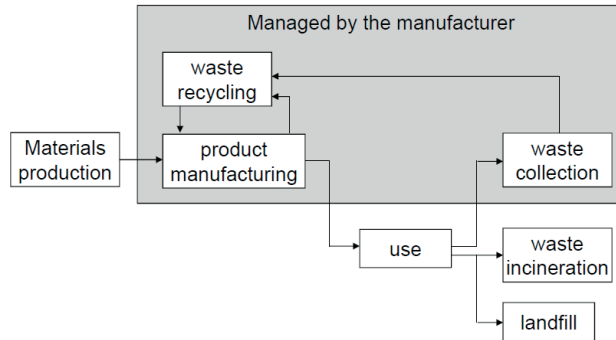
## 5.4 Open Loop and Closed Loop Recycling

Next section will deal with recycling of plastics and metals. To understand the complex issues, however, first a short explanation is given on open loop and closed loop recycling.



Figure 5.6

Closed loop recycling: the waste materials are replacing input of earlier process steps in the same system



The simplest form of recycling is closed-loop recycling: the waste material is shunted back to an earlier process in the same system where it directly replaces input from primary production of the same material<sup>25</sup>. This is depicted in Fig. 5.6.

Closed loop recycling is not only about recycling of waste materials, but also about remanufacturing and re-use of products and parts. In the cases of process-internal recycling this may even happen without any environmentally relevant recycling process (i.e. without additional eco-burden).

In Europe, closed loop recycling in industry is nearly always organised and managed by the manufacturer (or group of companies in the same production sector). Examples are:

- the recycling of aluminium Nespresso cups by Nestlé in countries like Switzerland, Germany, France and Portugal
- the recycling of PVC building materials (piping, etc.) by Wavin (leading manufacturer in the EU)
- the recycling of glass by the Dutch glass industry
- the recycling of electric and electronic equipment in the EU

In the EU, directives are introduced which impose the responsibility for the recycling of disposed products on the manufacturers of such products. By doing so, open loop recycling is replaced by closed loop recycling, leading to less waste incineration and less landfill.

Calculating the effect of closed loop recycling in LCA is quite straightforward:

- the reduction of the input of the system (the actual input of the virgin material, which is reduced by recycling)
- the addition of the environmental burden of the recycling

<sup>25</sup> This definition of closed loop recycling is from the European general guide for LCA [3]

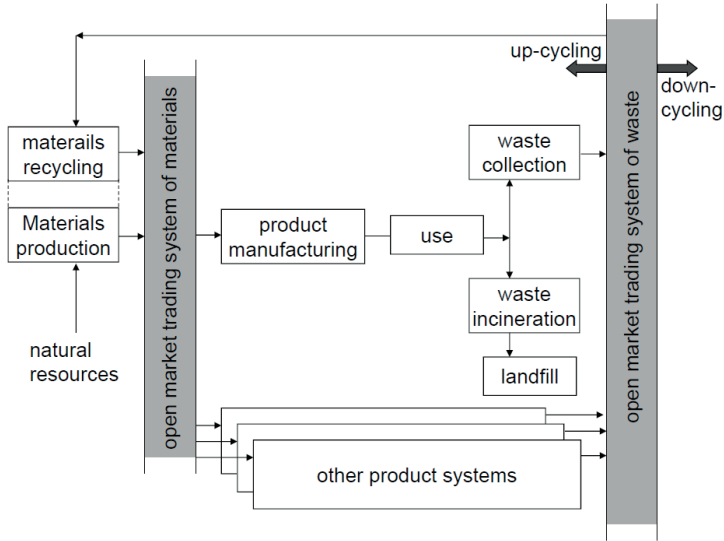


Figure 5.7

Open loop recycling: the waste materials are replacing input of other systems as well

In Open loop recycling, the waste of the system is recycled to other (different) systems via open market trading of the waste. This is common practice for metals and plastics, as well as for materials which are down-cycled, such as paper and concrete aggregate. See Fig. 5.7.

The way the effect of open loop recycling is calculated in LCA, is different from the way it is done in closed loop recycling. In open loop recycling, both for up- and downcycling, the ‘credits’ of recycling of waste are calculated<sup>26</sup>. This approach is fully in line with the approach in Sections 5.2 and 5.3, where ‘credits’ have been applied to model the environmental benefits of by-products and energy as system outputs in LCA. The way these calculations are structured is explained in the next section.

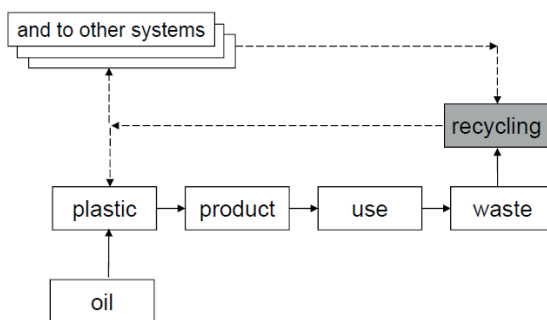
## 5.5 Open Loop Recycling of Plastics, Metals and other materials

### 5.5.1 Plastics

Most of the thermoplastics can be recycled. This can be dealt with by ‘system expansion’ in the End of Life stage, like it is done with combustion of waste in Section 5.3. See Fig. 5.8.

<sup>26</sup> In the European guide for LCA [3], Annex C, this is called the ‘recyclability substitution approach’.

Figure 5.8  
Open loop  
recycling of  
Plastics



The Life Cycle Chain is expanded with the recycling step, and the production of recycled ('up-cycled') plastic is output to the general market for plastics ('open loop recycling', see Fig. 5.8). The recycled plastics will replace the 'virgin' plastics, so overall less plastic will be made out of fossil oil. In the eco-costs system we call that the 'recycling credit' = (eco-costs of recycled plastics) – (eco-costs of virgin plastics). These eco-costs are negative (having a reducing effect on the total eco-costs of the chain).

A list of the eco-costs of recycling credits of plastics is provided at the tables at the [ecocostsvalue.com](http://ecocostsvalue.com) website.

Some remarks on recycling of plastics:

- Recycling of plastics at the end of the use phase can only be done efficiently in big volumes. Therefore, a closed loop system, where the plastics at the End of Life are used for the same product system (don't enter the open waste market) is not a realistic option for the vast majority of the design cases.
- 'Mechanical' recycling (downcycling) without severe loss of quality is only possible when a plastic is not contaminated with another type of plastic and when the material has no colour. Upcycling is possible for the full range of plastics by 'chemical recycling'; however, this is energy intensive and more expensive than mechanical recycling (melting).
- A way to deal with loss of quality ('grade') of the secondary material is to multiply the credit with the market-price ratio (lower grade secondary material)/(virgin material). However, this way is not fully in line with the formal LCA method.
- A better way is the approach of dealing with recycling at the beginning of the production chain, as is described at the text below. In this approach, the eco-burden of the specific recycling process is calculated, and becomes part of the main cradle-to-gate, cradle-to-grave or cradle-to-cradle calculation of the new product. See for more details Appendix IX of [9].

The paradigm of the classical LCA expert is that recycling is part of the End of Life stage. However, another modern approach is to be preferred: dealing with recycling at the beginning of the chain, see Fig. 5.9. The issue is that recycling is forming a loop, and it is a matter of choice where to cut the loop: at the point where the recycled material is still waste, or at the point where the waste has been recycled.

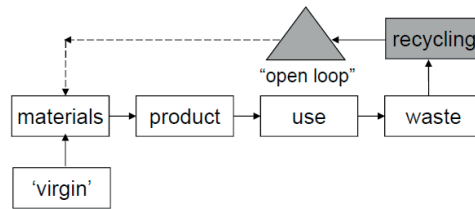
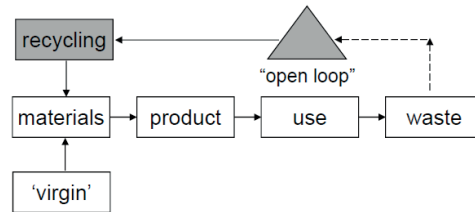
The old paradigm: recycling as part of End of LifeThe new approach: recycling as part the beginning of the chain

Figure 5.9

The old paradigm and the new approach: shift the recycling to the beginning of the chain. The "cut-off" point is at the triangle "open loop"

In the example of the plastics of Fig. 5.9, the shift of paradigm can be explained by the following two equations, describing the total eco-costs of a chain for the case of 100% recycling:

- equation 1:  

$$(\text{eco-costs of virgin plastics}) + (\text{eco-costs of production}) + (\text{eco-costs of use phase}) + \{(\text{eco-costs of recycling}) - (\text{eco-costs of virgin plastics})\}$$
- equation 2:  

$$(\text{eco-costs of recycling}) + (\text{eco-costs of production}) + (\text{eco-costs of use phase}) + 0 \quad (\text{i.e. no recycling credit})$$

Equations 1 and 2 have the same result. The difference is that equation 1 has the benefit of recycling at the end of the chain (assigned to the old product), and equation 2 has the benefit at the beginning of the chain (assigned to the new product).

The advantage of the new approach (called "cut-off" approach) is:

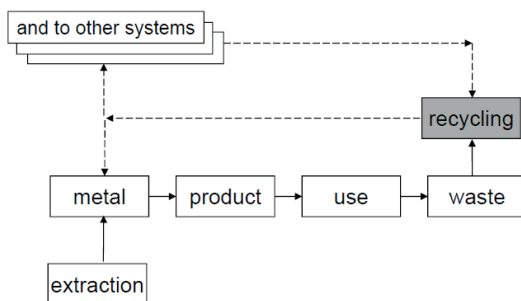
- it fits better to the responsibility of the designer or purchaser: their choice has a direct effect, instead of shifting responsibilities to the end-users in future
- it is a better solution for systems with considerable hold-up in the use phase, or other complex situations (see the 'market mix' issue of metals Section 5.5.2)
- it is in line with the basic approach of the EN15804 (a detailed norm for calculations of Environmental Product Declarations – EPDs - in the building industry)

Note 1. It should be clear to the reader that the above mentioned two calculation systems have nothing to do with the choice between a "linear system" and a "circular system". It has only to do with how calculate a circular C2C system in practice.

Note 2. Be aware that the difference between "open loop" and "closed loop" vanishes in the new "cut-off" approach !!

Figure 5.10

Open loop  
recycling of  
Metals



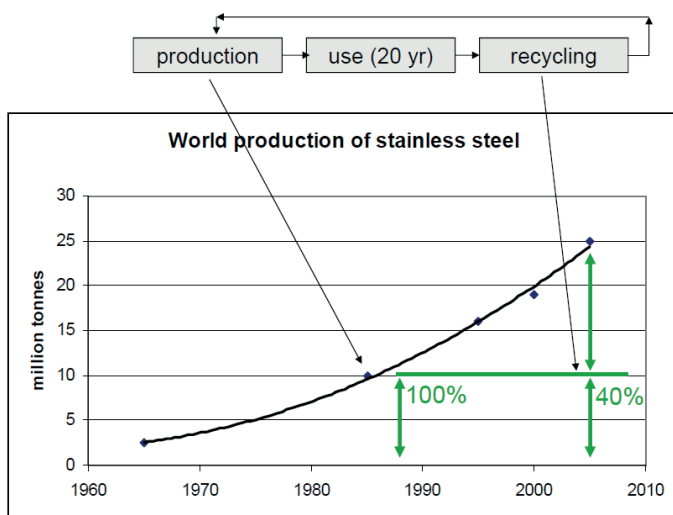
## 5.5.2 Metals

The situation for metals seems on the first sight similar to the situation for plastics, see Fig. 5.10.

However, there is a complicating factor. Since the lifespan of metal products is rather long, the hold-up of materials in the use phase of the system must be taken into account. See Fig. 5.11.

Figure 5.11

Recycling of  
stainless steel  
and the system  
hold-up



The issue is that the demand of metals has been growing for the last decades, and is expected to grow further. Take the example of stainless steel of Fig. 5.11:

- the average residence time of the steel in the use phase is approximately 20 years
- nearly 100% of the stainless steel is being recycled (since it is an expensive material)
- however, 100% of the production of the stainless steel (of 20 years ago), is about 40% of the current demand

It is therefore far from realistic to state that “100% is recycled, so we take only the eco-costs of recycled stainless steel”. A far more realistic approach is that we take the current ‘market mix’ (40% recycled, 60% virgin), and apply the eco-costs of that mix.

There is, however, a logic exception on the rule to take the market mix for open loop recycling: in cases where the manufacturer of the product tries to become a bit more closed loop, like Nestlé with the Nespresso cups. The actual system mix of virgin and recycled materials has to be calculated then (as input for the production), since it has become a combination of open loop and closed loop recycling<sup>27</sup>.

### 5.5.3 Waste Paper based products, and other secondary products

Waste paper based products are a typical example of downcycling. In practice, paper can be recycled approximately 3 - 4 times on average. After 4 times on average, some batches have fibres that are too short to have sufficient value for strength.

The source of waste paper is virgin paper. The source of virgin paper is pulp. The quality of pulp is more than a factor 3.5 higher than the quality of mixed waste paper, as is shown by the price of it (2023):

- woodpulp 250 €/ton
- white paper, without colour (waste paper) 150 €/ton
- mixed municipal waste paper 50-70 €/ton

There is an on-going debate on how to deal with such examples of downcycling in LCA, partly because of the interests of the industry, partly because of the challenge to model it in science<sup>28</sup>.

In this LCA guide a practical approach is proposed, following the rule in ISO 14044 that output of combustible material may be transformed into an energy output. In the case of paper and paper products it does make sense to take the electricity output of a municipal waste incinerator as a norm. Such a chain is shown in Fig. 5.12.

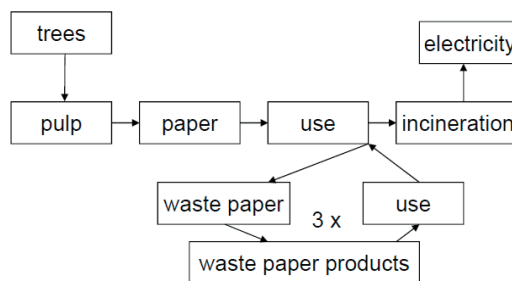


Figure 5.12  
Waste paper products as part of the paper chain  
Note: recycling rates (2022) are:  
2.5x in EU  
2.1x in USA  
3.8x in NL  
(Milieu Centraal)

<sup>27</sup> In Switzerland 60% of the Nespresso cups are recycled. So 40% of Aluminium is bought at the market. In the market mix, 65% is primary material. So the primary Aluminium at the production input is 40% of 65% is 26%.

<sup>28</sup> This is the field of ‘attribitional modelling’, where the debate is focussed on economic allocation methods down the recycling cascade, see for details the European guide for LCA [3], Annex C.

The waste paper products are ‘additional applications’ in the paper chain. It does make sense to give: (a) this additional application no eco-burden of its material source (e.g. apply the cut-off at the stockpile of waste, like it is done in EN 15804), (b) allocate 1/3 of the credits for End of Life (incineration) to the waste paper when the waste paper is 3x recycled (as in Fig. 5.12)<sup>29</sup>. The eco-burden of such a secondary product is only its transport, processing, use, waste processing, and part of the EoL credit.

The same principle may be applied to other examples of real downcycling such as:

- mechanical recycling (re-melting) of clean and pure plastics (e.g. PET)
- street furniture pressed from different kind of coloured plastics
- hardboard plates made from old, discarded, wooden planks
- consumer products directly made from waste, like bags and garments made of discarded clothing
- aggregate from concrete

**Note 1. In such an approach, the grade of the waste - not to be confused with the grade of the secondary (recycled) material - is not relevant for the eco-costs of the waste (the eco-costs of waste to be recycled is 0, regardless of its quality, see also Appendix V). The quality of the grade becomes part of the value of the new product, and/or causes more or less activities in the upgrading process of the recycling step, but the quality of the waste is not affecting the eco-costs of the waste as such.** This approach is similar to the approach of virgin materials in the ground (iron ore, copper ore, coal, oil, gas, etc.). These materials start also with no eco-costs (“eco-costs = 0”) in LCA, regardless of the specific economic value (the grade).

Note 2. In some situations, there are different scenarios for the waste (e.g. wood waste burned in an electrical power plant, versus the end-of-life of a downcycled product in a municipal waste incinerator with heat recovery). The different end-of-life credits should be mentioned then as different cases in the system description of the LCA.

Note 3. Guidance for applying specific Idemat and Ecoinvent LCI data for recycling is given in Appendix V.

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<sup>29</sup> Any other allocation rule (allocation part of the eco-burden of the primary product to the secondary product) seems to be arbitrary. Complex allocation formulas in the ILCD Handbook Annex C [3], for attributional modelling are laborious and do not add much to the analyses, since the effect on the outcome of the LCA is rather limited.

#### 5.5.4 Time aspects in 'delayed' recycling or combustion of products with a long lifespan

In the example of metals in the previous section, we saw the effect of growing market demand on the issue of hold-up in the use phase of the system.

There is, however, another aspect related with a long lifespan. The issue is whether a (negative) eco-burden today should be counted in the same way as a (negative) eco-burden many decades in the future, or a discounting system for eco-burden in that far future must be applied.

Discounting the effects of expected eco-burden in the far future has been subject of heavy debates over the last 15 years. It is still a choice to be made by the LCA practitioner, whether or not to apply any discounting system.

In the European guide for LCA [3], Section 7.4.3.7.3, a linear discount is proposed of 1% per year as 'optional'. Example: the effect in year 60 (from now) is discounted by 60%, resulting in a factor 0.4 contribution of the credit for the End of Life. This choice of 1% originates from a widely accepted practical approach in the classical LCA: the time span of LCA is 100 years after the manufacturing of the product. The 1% linear discount should prevent a sudden cut-off (an abrupt discontinuity) after 100 years, and has scientific background of the characterisation factors of the 'GWP 100' [10].

However, in this practical LCA guide, we advise to:

- either refrain from any discounting system (ignore the fact that the credit is delayed)
- or apply non-linear rules for discounting of future eco-burden, as it is done in financial calculations (i.e. the standard rules for discounting cash flow calculations)

The first option is advised for a lifespan of less than 10 years. The last option is advised for systems with a lifespan of more than 10 years, or systems without End of Life (when the lifespan is very long and unpredictable).

This last option is explained in the next section. It is applicable to monetized single indicators (damage based as well as prevention based, such as eco-costs) as well as carbon footprint calculations.

## 5.6 Houses and office buildings, without End-of-Life

Houses and offices of good quality and at good locations seem to stay forever and have no End of Life in the foreseeable future, as it was explained in Section 4.3. These objects tend to be kept in good shape by repetitive refurbishing and renovation. They



have an endless life, certainly within the normal LCA time horizon of 100 years (see Fig. 4.2) which results in a special situation in LCA<sup>30</sup>.

The key to the solution of these types of LCAs is:

- set an end to the LCA calculation at the first point in the continuous cycle where the real estate is likely to change of ownership
- allocate part of the eco-burden of the building activities to the next owner<sup>31</sup>
- apply discounting when the time span of the LCA is more than 10 years (which is normally the case for real estate), to recognise that scenarios in the near future are more certain than scenarios in the far future (the proposed discounting rules are in line with the standard rules for financial Discounting Cash Flow calculations)

The proposed calculation procedure is explained by the case of the classic Dutch house of Table 1.1. The assumptions are:

- the house is built in 'year 0'
- the yearly demand of natural gas is 3500 Nm<sup>3</sup>, required for heating (note that this is likely to be less in future because of energy savings)
- the house is transferred to a new owner after 25 years
- the value of the house after 25 years is 75% of the value of the new house<sup>32</sup>, and therefore 75% of the eco-costs are allocated to the next 'life' of the house
- maintenance of the wooden parts outside is not taken into account (low eco-costs)
- inside decorating en furniture is not taken into account

The results of these assumptions on the calculation of eco-costs are shown in Table 5.3.

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<sup>30</sup> It is a fact that such an LCA is:

- not from-cradle-grave, since it is a continuous loop
- neither cradle-to-cradle (see Section 7), since there is no specific point in the loop where “waste becomes food” for the next pass of the loop

<sup>31</sup> Here it makes sense to apply economic allocation (for details, see Section 6.2): when the second owner pays x% of the original price of the building to the first owner, x% of the eco-burden of the production of the house is allocated to the second owner as well. Note that such an allocation rule does make sense for all kinds of second hand products.

<sup>32</sup> In this case, the net value of the new house is approximately € 400.000,- (see Table 1.1). 75% value after 25 years is in line with an assumption that, after renovation of the kitchen, the bathroom plus a new heating unit for a total price of 100.000,- (= 25%), the old house (renovated by the new owner) has got the same value as the new house (current price level).

| year  |        | eco-costs house (€) | eco-costs energy (€) | discounting factor | eco-costs discounted house (€) | eco-costs discounted energy (€) |
|-------|--------|---------------------|----------------------|--------------------|--------------------------------|---------------------------------|
| 0     | house  | 82,638              |                      | 1.000              | 82,638                         |                                 |
| 1     | energy |                     | 1,400                | 0.980              |                                | 1,373                           |
| 2     | energy |                     | 1,400                | 0.961              |                                | 1,346                           |
| 3     | energy |                     | 1,400                | 0.942              |                                | 1,319                           |
| 4     | energy |                     | 1,400                | 0.924              |                                | 1,293                           |
| 5     | energy |                     | 1,400                | 0.906              |                                | 1,268                           |
| 6     | energy |                     | 1,400                | 0.888              |                                | 1,243                           |
| 7     | energy |                     | 1,400                | 0.871              |                                | 1,219                           |
| 8     | energy |                     | 1,400                | 0.853              |                                | 1,195                           |
| 9     | energy |                     | 1,400                | 0.837              |                                | 1,171                           |
| 10    | energy |                     | 1,400                | 0.820              |                                | 1,148                           |
| 11    | energy |                     | 1,400                | 0.804              |                                | 1,126                           |
| 12    | energy |                     | 1,400                | 0.788              |                                | 1,104                           |
| 13    | energy |                     | 1,400                | 0.773              |                                | 1,082                           |
| 14    | energy |                     | 1,400                | 0.758              |                                | 1,061                           |
| 15    | energy |                     | 1,400                | 0.743              |                                | 1,040                           |
| 16    | energy |                     | 1,400                | 0.728              |                                | 1,020                           |
| 17    | energy |                     | 1,400                | 0.714              |                                | 1,000                           |
| 18    | energy |                     | 1,400                | 0.700              |                                | 980                             |
| 19    | energy |                     | 1,400                | 0.686              |                                | 961                             |
| 20    | energy |                     | 1,400                | 0.673              |                                | 942                             |
| 21    | energy |                     | 1,400                | 0.660              |                                | 924                             |
| 22    | energy |                     | 1,400                | 0.647              |                                | 906                             |
| 23    | energy |                     | 1,400                | 0.634              |                                | 888                             |
| 24    | energy |                     | 1,400                | 0.622              |                                | 870                             |
| 25    | energy |                     | 1,400                | 0.610              |                                | 853                             |
| 25    | house  | -61,979             |                      | 0.610              | -37,778                        |                                 |
| Total |        | 20,660              | 35,000               |                    | 44,860                         | 27,333                          |

Table 5.3

The first 25 years of the house of Table 1.1, until the moment of switch of ownership (maintenance of outside painting neglected, inside refurbishments excluded), discounted with 2% (=real interest)

The effect of discounting can clearly be seen in this table. Without discounting, the eco-costs of the house are less than the eco-costs of the energy. With discounting it is the other way around. The reason is twofold:

- The credit of the house at the end of the 25 years is quite much, leading to low eco-costs of the house, but is this realistic (is it sure that there is no external reason that the value of the house is much lower at that time)?
- The use of energy is adding up to an enormous amount, but does the energy consumption not change in future (better insulation and higher efficiencies)?

In general, the future is less certain when we estimate further in future, so discounting is advised. But the arguments for discounting of eco-costs (eco-burden) are different from the arguments for discounting of financial costs. Hence, both discounting rates might be different (the EVR is likely to become lower in future) Table 5.4 shows the effect of discounting factors for each year in future.

Table 5.4

Discounting  
factors for a  
year in future as  
function of the  
real interest  
(2%, 1.5%, 1%)

| year | 2%    | 1.50% | 1%    | year | 2%    | 1.50% | 1%    | year | 2%    | 1.50% | 1%    |
|------|-------|-------|-------|------|-------|-------|-------|------|-------|-------|-------|
| 0    | 1     | 1     | 1     | 34   | 0.510 | 0.603 | 0.713 | 67   | 0.265 | 0.369 | 0.513 |
| 1    | 0.980 | 0.985 | 0.990 | 35   | 0.500 | 0.594 | 0.706 | 68   | 0.260 | 0.363 | 0.508 |
| 2    | 0.961 | 0.971 | 0.980 | 36   | 0.490 | 0.585 | 0.699 | 69   | 0.255 | 0.358 | 0.503 |
| 3    | 0.942 | 0.956 | 0.971 | 37   | 0.481 | 0.576 | 0.692 | 70   | 0.250 | 0.353 | 0.498 |
| 4    | 0.924 | 0.942 | 0.961 | 38   | 0.471 | 0.568 | 0.685 | 71   | 0.245 | 0.347 | 0.493 |
| 5    | 0.906 | 0.928 | 0.951 | 39   | 0.462 | 0.560 | 0.678 | 72   | 0.240 | 0.342 | 0.488 |
| 6    | 0.888 | 0.915 | 0.942 | 40   | 0.453 | 0.551 | 0.672 | 73   | 0.236 | 0.337 | 0.484 |
| 7    | 0.871 | 0.901 | 0.933 | 41   | 0.444 | 0.543 | 0.665 | 74   | 0.231 | 0.332 | 0.479 |
| 8    | 0.853 | 0.888 | 0.923 | 42   | 0.435 | 0.535 | 0.658 | 75   | 0.226 | 0.327 | 0.474 |
| 9    | 0.837 | 0.875 | 0.914 | 43   | 0.427 | 0.527 | 0.652 | 76   | 0.222 | 0.323 | 0.469 |
| 10   | 0.820 | 0.862 | 0.905 | 44   | 0.418 | 0.519 | 0.645 | 77   | 0.218 | 0.318 | 0.465 |
| 11   | 0.804 | 0.849 | 0.896 | 45   | 0.410 | 0.512 | 0.639 | 78   | 0.213 | 0.313 | 0.460 |
| 12   | 0.788 | 0.836 | 0.887 | 46   | 0.402 | 0.504 | 0.633 | 79   | 0.209 | 0.308 | 0.456 |
| 13   | 0.773 | 0.824 | 0.879 | 47   | 0.394 | 0.497 | 0.626 | 80   | 0.205 | 0.304 | 0.451 |
| 14   | 0.758 | 0.812 | 0.870 | 48   | 0.387 | 0.489 | 0.620 | 81   | 0.201 | 0.299 | 0.447 |
| 15   | 0.743 | 0.800 | 0.861 | 49   | 0.379 | 0.482 | 0.614 | 82   | 0.197 | 0.295 | 0.442 |
| 16   | 0.728 | 0.788 | 0.853 | 50   | 0.372 | 0.475 | 0.608 | 83   | 0.193 | 0.291 | 0.438 |
| 17   | 0.714 | 0.776 | 0.844 | 51   | 0.364 | 0.468 | 0.602 | 84   | 0.189 | 0.286 | 0.434 |
| 18   | 0.700 | 0.765 | 0.836 | 52   | 0.357 | 0.461 | 0.596 | 85   | 0.186 | 0.282 | 0.429 |
| 19   | 0.686 | 0.754 | 0.828 | 53   | 0.350 | 0.454 | 0.590 | 86   | 0.182 | 0.278 | 0.425 |
| 20   | 0.673 | 0.742 | 0.820 | 54   | 0.343 | 0.448 | 0.584 | 87   | 0.179 | 0.274 | 0.421 |
| 21   | 0.660 | 0.731 | 0.811 | 55   | 0.337 | 0.441 | 0.579 | 88   | 0.175 | 0.270 | 0.417 |
| 22   | 0.647 | 0.721 | 0.803 | 56   | 0.330 | 0.434 | 0.573 | 89   | 0.172 | 0.266 | 0.412 |
| 23   | 0.634 | 0.710 | 0.795 | 57   | 0.323 | 0.428 | 0.567 | 90   | 0.168 | 0.262 | 0.408 |
| 24   | 0.622 | 0.700 | 0.788 | 58   | 0.317 | 0.422 | 0.562 | 91   | 0.165 | 0.258 | 0.404 |
| 25   | 0.610 | 0.689 | 0.780 | 59   | 0.311 | 0.415 | 0.556 | 92   | 0.162 | 0.254 | 0.400 |
| 26   | 0.598 | 0.679 | 0.772 | 60   | 0.305 | 0.409 | 0.550 | 93   | 0.159 | 0.250 | 0.396 |
| 27   | 0.586 | 0.669 | 0.764 | 61   | 0.299 | 0.403 | 0.545 | 94   | 0.155 | 0.247 | 0.392 |
| 28   | 0.574 | 0.659 | 0.757 | 62   | 0.293 | 0.397 | 0.540 | 95   | 0.152 | 0.243 | 0.389 |
| 29   | 0.563 | 0.649 | 0.749 | 63   | 0.287 | 0.391 | 0.534 | 96   | 0.149 | 0.239 | 0.385 |
| 30   | 0.552 | 0.640 | 0.742 | 64   | 0.282 | 0.386 | 0.529 | 97   | 0.146 | 0.236 | 0.381 |
| 31   | 0.541 | 0.630 | 0.735 | 65   | 0.276 | 0.380 | 0.524 | 98   | 0.144 | 0.232 | 0.377 |
| 32   | 0.531 | 0.621 | 0.727 | 66   | 0.271 | 0.374 | 0.519 | 99   | 0.141 | 0.229 | 0.373 |
| 33   | 0.520 | 0.612 | 0.720 |      |       |       |       | 100  | 0.138 | 0.226 | 0.370 |

A discounting percentage of 1% - 2% for eco-costs as well as costs seems to be a good choice in practice.

There are three arguments that clearly support the use of discounting for eco-costs (resulting in lower eco-costs in future):

- The future shift towards renewable energy (governmental planning to become less dependent on fossil fuels)
- The future shift towards more recycling (the circular economy)
- The future shift towards renewable bio-based materials (the circular economy)

These three arguments are completely different from the arguments in environmental science to apply discounting, or refrain from it.<sup>33</sup>

These three arguments are also completely different from the reasons to apply discounting in finance<sup>34</sup>.

The situation for offices is similar to that for houses, except from the fact that the most common scenario is different: office buildings tend to have a drastic renovation every 40 years on average, where only the main structure (with floors) stays intact. The value of the 40 year office before such a drastic renovation is normally approximately 30% of the original value of the office.

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<sup>33</sup> For a detailed analysis of the issue see [10]. In this paper it is made clear that the so called “discounting of the delayed pulse” must be regarded as an aberration in science. The confusion is caused by the fact that the systems to calculate weighting factors for LCIA indicators (like the Global Warming Potential CO2 equivalent list of the IPCC) are blurred with the calculations in LCI itself (as dealt with in this LCA Guide).

<sup>34</sup> A simplified explanation of financial discounting is given in the following example:  
When you want to renovate your kitchen for € 10.000 euro which will take place in year 10, you need to put now € 8.200 on a bank account (see Table 11). This € 8.200 will increase each year by the interest; however, its real value will increase less because of inflation of money. The yearly net increase in value is the called the ‘real interest’ (=interest minus inflation). The € 8.200 is the ‘Net Present Value’ of the € 10.000 which is required later. A ‘real interest’ of 1% - 2% is common for discounting calculations on macro-economic level.

On the level of individual projects, the real interest can be much higher, since - in finance - interest is higher in cases where the uncertainty is higher. In LCA scenarios with an extreme uncertainty, such as the introduction of new technologies, discount rates higher than 2% might be applied.



## 6 LCA of Services

### 6.1 Characteristics of an LCA of Services

Although there is no distinct line between products and services, the characteristics of calculations on LCAs of services are different from the classical LCA calculations on products:

- services are (not strictly) cradle-to-cradle nor cradle-to-grave, since services have a gate-to-gate character
- services share physical systems (products) with other services

Examples of services are:

- internet providers (facilitating flow of information)
- banks (facilitating flow of money)
- shops (facilitating flow of goods)
- hotels (facilitating tourists and travelling business people)
- restaurants
- etc.

In each of these examples it is possible to define the system boundaries, see Fig. 6.1. Note the difference in system structure compared with the system structure of products (see Fig. 2.4).

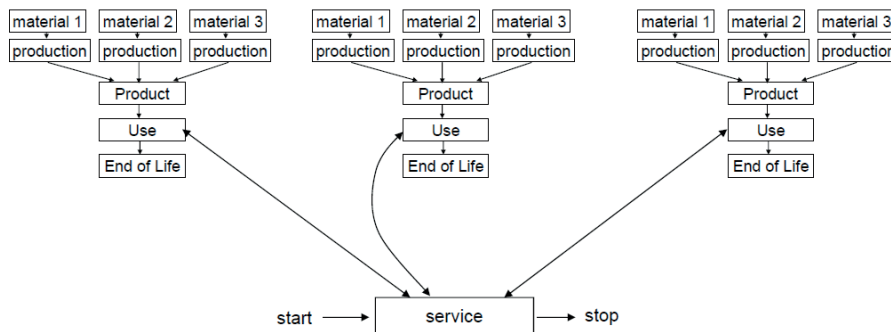


Figure 6.1  
A service in LCA comprises the partial use of several product systems

Every type of service has its specific function. However, in most cases it is not easy to define the functional unit of a service in the strict way as it is described in Section 2.4, because of the non-tangible quality aspects of services (see Section 2.6).

The best way to tackle services in LCA is applying economic allocation. This means that the eco-burden of a physical sub-system, which is partly used by the service, is

allocated to the service in proportion to their economic value. Some background information on economic allocation is given in the next section.

The principle, however, can easily be explained by the following example.

Example: a shop (“the service function of a shop”).

A clothes shop is a good example of a service. The system is a combination of the following subsystems:

- building (partially used)
- interior decoration and furniture
- gas or oil for the heating in winter
- electricity for the air conditioning in summer, lighting, computers, etc.
- personnel

The function of the shop is to sell clothes (transfer of clothes from the manufacturer to the user). The issue is the unit of the calculation: is it per kg, per m<sup>3</sup>, per piece of clothing, per client? This problem of the choice of unit is caused by the variety of products which are handled by the service system: clothes are big or small, heavy or light, expensive or cheap, etc. The issue is typical for service systems in general.

**A general approach is to take the price as a basis, and do the LCA calculations per euro** (per US\$, or any other currency), see also Appendix IV.

In financial calculations it is common to take a percentage of the price to cover the costs of the building, a percentage for the interior, a percentage for the gas and the electricity, and a percentage for the costs of the personnel. When the eco-costs per euro (the so called the ecocosts/value ratio = EVR) is known for each subsystem (building, interior, gas, electricity, personnel), the eco-costs of the service can easily be calculated.

Such a calculation is given in Table 6.1. This Table gives an estimate of a shop in a city centre. The EVR data of the building and the interior are from a European database on eco-burden/price ratios<sup>35</sup>, the EVR of heat (gas) and electricity are calculated from the price levels of these products (summer 2010) and the EVR of the personnel is estimated for average commuters in the city of Amsterdam.

The service can be defined as “the selling of clothing, per jacket of 300 €” (= the ‘functional unit’ of the product-service combination).

The aim is to calculate the eco-costs of the ‘service’ function of the shop for the jacket. Note that the eco-costs of the production of the jacket must be calculated via a normal LCA.

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<sup>35</sup> The data are from the EIPRO study database, derived from so called macroeconomic Input-Output Tables of the EU countries. Input-Output Tables are tables which describe inputs and outputs of macroeconomic systems. They are used by environmental economists to describe inputs and outputs of countries or groups of countries (e.g. the EU). The source is statistical data on these countries. Such data is available for the EU (the EIPRO study), The Netherlands (statistical data of the manufacturing industry), Denmark (products and services), and the US (products and industrial processes). Data are cradle-to-gate or gate-to-gate.

|                         | (1)<br>structure of<br>costs<br>(€/year) | (2)<br>percentage | (3)<br>per<br>jacket<br>of € 300<br>(€) | (4)<br>EVR<br>(€/€) | (5)<br>eco-costs<br>per<br>jacket of €<br>300<br>(€) |
|-------------------------|------------------------------------------|-------------------|-----------------------------------------|---------------------|------------------------------------------------------|
| building                | 200,000                                  | 11%               | 33.33                                   | 0.25                | 8.33                                                 |
| interior                | 100,000                                  | 6%                | 16.67                                   | 0.25                | 4.17                                                 |
| heating                 | 60,000                                   | 3%                | 10.00                                   | 1                   | 10.00                                                |
| electricity             | 40,000                                   | 2%                | 6.67                                    | 0.8                 | 5.33                                                 |
| personnel               | 400,000                                  | 22%               | 66.67                                   | 0.1                 | 6.67                                                 |
| profit                  | 200,000                                  | 11%               | 33.33                                   | 0                   | 0                                                    |
| total 'service' of shop | 1000000                                  | 56%               | 166.67                                  |                     | 34.50                                                |
| purchase costs          |                                          |                   |                                         |                     |                                                      |
| clothing                | 800,000                                  | 44%               | 133.33                                  |                     |                                                      |
| total sales             | 1,800,000                                | 100%              | 300.00                                  |                     |                                                      |

Table 6.1

Example of a service system:  
A clothes shop  
in a city centre

The step by step technique of calculations on services is:

1. determine the cost components of the service (make a so called 'costs breakdown')
2. calculate the percentages
3. calculate the costs breakdown of the product-service combination
4. try to find the EVR (ecocosts/value ratio) of these cost components in readily available tables (some data are provided in Table 6.2, more data can be found on the [ecocostsvalue.com](http://ecocostsvalue.com) website tab data)
5. when the EVR cannot be found in tables, then calculate it by calculating the eco-costs as well as the costs (= value) of the total subsystem <sup>36</sup>
6. calculate the eco-costs of each subsystem by multiplying each costs component by its EVR and add up the eco-costs of all subsystems

<sup>36</sup> In general: an EVR which has been calculated by a classical LCA and a classical LCC, is much more accurate than an EVR calculated via Input-Output Tables.



Table 6.2

|                                                                                        | Description of service and [CEDA number]                                                | EVR (€/€) |
|----------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|-----------|
| EVR (eco-costs per price in euro); data from the European EIPRO study (cradle-to-gate) | [A20] Landscape and horticultural services                                              | 0.10      |
|                                                                                        | [A458] Doctors and dentists                                                             | 0.11      |
| More data available on the ecocostsvalue website                                       | [A416] Banking                                                                          | 0.12      |
|                                                                                        | [A420] Insurance agents, brokers, and services                                          | 0.13      |
|                                                                                        | [A461] Other medical and health services                                                | 0.16      |
|                                                                                        | [A443] Legal services                                                                   | 0.17      |
|                                                                                        | [A465] Colleges, universities, and professional schools                                 | 0.19      |
|                                                                                        | [A407] Telephone, telegraph communications, and communications services n.e.c.          | 0.19      |
|                                                                                        | [A421] Owner-occupied dwellings                                                         | 0.19      |
|                                                                                        | [A433] Services to dwellings and other buildings                                        | 0.20      |
|                                                                                        | [A415] Retail trade, except eating and drinking                                         | 0.20      |
|                                                                                        | [A464] Elementary and secondary schools                                                 | 0.20      |
|                                                                                        | [A45] Other repair and maintenance construction                                         | 0.22      |
|                                                                                        | [A414] Wholesale trade                                                                  | 0.22      |
|                                                                                        | [A452] Theatrical producers (except motion picture), bands, orchestras and entertainers | 0.22      |
|                                                                                        | [A460] Nursing and personal care facilities                                             | 0.22      |
|                                                                                        | [A317] (use of) Electronic computers                                                    | 0.23      |
|                                                                                        | [A162] Newspapers                                                                       | 0.23      |
|                                                                                        | [A445] Accounting, auditing and bookkeeping, and miscellaneous services, n.e.c.         | 0.23      |
|                                                                                        | [A43] Maintenance and repair of highways & streets                                      | 0.24      |
|                                                                                        | [A440] Management and public relations services                                         | 0.25      |
|                                                                                        | [A164] Book publishing                                                                  | 0.25      |
|                                                                                        | [A432] Miscellaneous repair shops                                                       | 0.25      |
|                                                                                        | [A408] Cable and other pay television services                                          | 0.26      |
|                                                                                        | [A151] Furniture and fixtures, n.e.c.                                                   | 0.26      |
|                                                                                        | [A40] New office, industrial and commercial buildings construction                      | 0.26      |
|                                                                                        | [A31] New residential 1 unit structures, nonfarm                                        | 0.27      |
|                                                                                        | [A41] Other new construction                                                            | 0.28      |
|                                                                                        | [A34] New residential garden and high-rise apartments construction                      | 0.29      |
|                                                                                        | [A448] Automotive repair shops and services                                             | 0.30      |
|                                                                                        | [A139] Wood household furniture, except upholstered                                     | 0.32      |
|                                                                                        | [A35] New highways, bridges, and other horizontal construction                          | 0.32      |
|                                                                                        | [A145] Wood office furniture                                                            | 0.32      |
|                                                                                        | [A32] New residential 2-4 unit structures, nonfarm                                      | 0.35      |
|                                                                                        | [A447] Automotive rental and leasing, without drivers                                   | 0.38      |
|                                                                                        | [A167] Commercial printing                                                              | 0.40      |
|                                                                                        | [A146] Office furniture, except wood                                                    | 0.41      |
|                                                                                        | [A446] Eating and drinking places                                                       | 0.48      |
|                                                                                        | [A354] (Driving with) motor vehicles and passenger car bodies                           | 0.81      |

## 6.2 Background on economic allocation, and the EVR

A lot of students apply economic allocation by instinct in a correct way. They realize that you can calculate eco-burden per euro (or US\$) just as it can be done per kilogram or any other unit.

Many environmentalist, however, are not used to thinking in terms of euros instead of kilograms. They wonder whether the calculations made in the previous section are in accordance with the ISO 14044. These calculations are, however, fully in line with this ISO specification. The link to the common LCA is the acceptance of ‘economic allocation’ throughout the entire calculation system.

This section explains economic allocation in more detail.

The basic methodology for allocation in LCAs is dealt with in ISO 14044 (see Appendix III):

*"Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and the functions in a way that reflects other relationships between them. For example, environmental input and output data might be allocated between co-products in proportion to the economic value of the products"*

This methodology can be explained by an example: the indirect environmental impact of building an air plane, allocated to a single trip<sup>37</sup>. The main parameters are:

- the value of a ticket for the single trip,  $W$ , of which a part of that value,  $X$ , is related to the depreciation (or leasing costs) of the plane
- the value of a plane,  $Y$
- the eco-costs of a plane,  $Z$  (calculated from LCA data).

The question is now which part of the indirect environmental impact of building a plane,  $Z$ , has to be allocated to the trip. Applying economic allocation:

$$EI = (X/Y) \times Z = \text{'the economic proportion'} \times \text{'eco-costs of a plane'}$$

Where  $EI$  is the indirect environmental impact (eco-costs) allocated to the ticket.

The formula can be written as  $(Z/Y = \text{Eco-costs/Value Ratio} = \text{EVR})$ :

---

<sup>37</sup> There is no simple physical relationship to base the allocation on for many reasons. The major two reasons are:

- Planes transport passengers as well as freight (in the same plane on the same trip). How to allocate (split) between passengers and freight? Based on volume or on weight or any combination of both?
- One plane will make many trips during its lifetime, all over the world. There are trips ('legs') with high occupancy rates and trips with low occupancy rates. How to cope with these differences?

$$EI = (Z/Y) \times X = \text{EVR} \times \text{'part of the value of the ticket related to the depreciation of the plane'}$$

This Equation shows how the EVR (eco-costs/value ratio) can be used for economic allocation in a complex LCA, starting with a 'cost-breakdown structure', e.g. from Activity Based Costing. Especially in cases when proportions of weight are not known directly, which is often the case for services, the EVR model is a powerful tool.

In the example, the first equation is applied to an 'indirect' environmental impact. The second equation can also be applied to situations of 'direct' impact (e.g. for allocation of the fuel to one passenger). In most of the situations of 'direct' impact, however, the physical relationship is known as well, in which cases the eco-costs have to be determined on that direct physical relationship, according to ISO 14044.

Although the ISO 14044 define economic allocation as a 'last option' (to be avoided, if possible) there is no need to avoid economic allocation in cases *where the ratio between 'value' and 'kilograms' is fixed*<sup>38</sup>, since the ratio between eco-costs and value, the EVR, is fixed then as well.

So it is a prerequisite for applying the EVR in LCA calculations that a specific EVR has to be independent of the size (weight, volume, time, etc.). Under this condition, the EVR can be used for direct impacts as well, instead of the eco-costs/weight ratio, which appears extremely practical in many cases. An example is given in Table 6.3.

Table 6.3

An example of using the EVR for economic allocation in a transport chain

| Chain element          | LCA subsystem            | Value (Euro) | EVR  | Eco-costs (Euro) |
|------------------------|--------------------------|--------------|------|------------------|
| Packaging              | (one way boxes)          | 61           | 0.16 | 9.8              |
| Transport              | Truck, fuel, road        | 23           | 0.58 | 13.3             |
| Distribution & feeding | Truck, fuel, road        | 10           | 0.49 | 4.9              |
| Storage                | Building, forklift truck | 6            | 0.29 | 1.7              |
| End-of-life            | (packaging)              | 0            | 0    | 0.0              |
| Total chain            |                          | 100          |      | 29.7             |

The functional unit is: "transport of 1 litre net volume of tomatoes from Holland to Frankfurt" (EVR data from the [ecocostsvalue.com](http://ecocostsvalue.com) website, tab data)

Although economic allocation is a very powerful method to resolve problems in LCA, the requirement that the price must be known might give some problems in practice (the price might be not known or might be unstable). Table 6.4 provides strategies to find prices of products with missing or distorted markets, from [4].

<sup>38</sup> Under such conditions, the 'economic proportion' in the first equation equals the 'physical proportion'.

| Problem                                                     | Solution                                                                                    |
|-------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| 1. Market prices not known                                  | Look for public sources, preferably FOB (Free On Board) prices                              |
| 2. Fluctuating prices                                       | Use three-year averages, or use prices at futures market                                    |
| 3. Inflation                                                | No problem, as long as the same base year is used in each process                           |
| 4. Trends in real prices                                    | No problem, as long as the same base year is used in each process                           |
| 5. Different currencies in different processes              | No problem, as long as the same currency is used in each process                            |
| 6. Locally diverging prices                                 | Choose prices at relevant process locations or calculate averages for the relevant region   |
| 7. Market prices available only further downstream          | Use gross sales value method                                                                |
| 8. Partially missing prices                                 | Construct prices from costs and known prices                                                |
| 9. Economically based market distortions (e.g., Monopolies) | Use actual market prices, correct in very exceptional cases only                            |
| 10. Regulations-based market distortions                    | Accept prices as they are, use value or cost of close alternative for missing market prices |
| 11. Tax-like financing of activity (e.g., Sewer systems)    | Treat as 'missing market, public provision'                                                 |
| 12. Taxes and subsidies on products                         | Use the price the seller actually receives                                                  |
| 13. Taxes and subsidies on activities                       | Do not correct for taxes and subsidies on activities.                                       |
| 14. In-firm prices not known                                | Use gross sales value method                                                                |
| 15. Missing markets with public provision                   | Construct prices based on costs                                                             |
| 16. Developing markets for recycling products               | Use current prices of similar products to specify the price of future recycled products     |
| 17. Markets not yet in existence                            | Use expected future market prices                                                           |

Table 6.4 Strategies to find prices of products with missing or distorted markets [4]



# 7 Cradle-to-Cradle in LCA

## 7.1 Life Cycle Design: LCA in early design stages

Cradle-to-Cradle is a design philosophy with the primary focus on ‘closing the loop’ of recycling (i.e. ‘waste = food’). It is obvious that an LCA can be made of a C2C system; however, there are two special issues:

- If the LCA is made at the end of the design stage, it is too late to decide on total different product(ion) systems in order to close the recycle loop in a better way.
- If the product system is designed as a combination of the biosphere and the technosphere (since mother nature is more efficient and effective in recycling than out technical world), data from existing LCI databases must be applied with great care.

In Section 3.2, the first issue has already been dealt with in terms of the selection of materials. It is, however, not only a matter of materials selection: it is also a matter of system design. We call this Life Cycle Design, and will elaborate on this issue in this section.

The second issue will be dealt with in the next section, Section 7.2.

### **Life Cycle Design**

The basic idea of Life Cycle Design is that a product design should start with a quick study on the product system, prior to the design of the product itself. This is in line with the C2C design philosophy that real environmental improvements can be found by starting from a different design perspective: not our current system infrastructure of the technosphere is point of departure, but the belief that product systems can be improved by recycling (‘upcycling’) of its components. The design must then start with an analysis of the opportunities of recycling, and exploring the possibilities of including the biosphere in the product system, since the biosphere is more efficient and effective in upcycling than the technosphere.

In LCA, the eco-burden of both transport and the energy required for recycling plays an important role. In the C2C philosophy, energy (the sun) and transport are not

counted as eco-burden, so there might be some differences between the optimal choice of the recycling system in C2C and LCA<sup>39</sup>.

Natural products (wood, bamboo and cork) as such score very good in LCA, as they do in C2C, so the positive appraisal of the biosphere is in both systems.

Life Cycle Design is explained best by examples.

A classical dilemma is the choice on packaging systems. Take the example of milk or other beverages: which form of packaging is the best for the environment? Is a glass bottle better than a plastic bottle, or is a carton container better? What is the advantage of a bottle made out of bio-plastics?<sup>40</sup>

Some alternative recycle loops of bottles are shown in the following figures:

- Fig. 7.1: glass bottles for milk (re-use of the bottles or recycling of the glass)
- Fig. 7.2: recycling of PET bottles or combustion of PLA bottles

Figure 7.1  
Glass bottles  
for milk: re-use  
or recycle

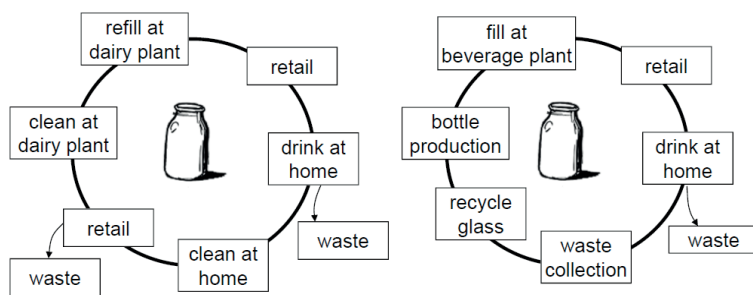
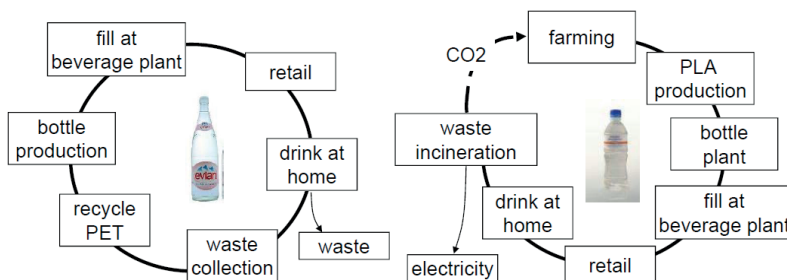


Figure 7.2  
Recycling of  
PET bottles and  
waste  
incineration of  
PLA bottles



Before the sixties, the re-use of milk bottles was widespread in Western Europe. The re-use rate was high (higher than 90%) and it was doable because of the short distance consumer - dairy factory and the small scale of the operation. It was by far the best solution. When the distance between the factory and the consumer became bigger and

<sup>39</sup> In the system of the eco-costs it is technically feasible to set, quite easily, the eco-costs of energy and the energy for transport at zero. See Section 7.2. This can be done by setting the eco-costs of CO<sub>2</sub> and fossil fuels to zero. However this is **not** advised, since it is related with the assumption that greenhouse gasses and depletion of fossil fuels are no problem in regard to sustainability (!)

<sup>40</sup> It is not the purpose of this LCA guide to give the answers on above questions (there is not one best solution: the best solution depends on the type of beverage and the specific consumer market with its logistic system). The purpose of this manual is to show the different system choices and its consequences for the choice on materials in the early design stages.

the scale of operations got bigger, the hassle of return flow became a problem, and the glass bottle system was replaced by carton containers (with a thin plastic liner). The eco-burden of the carton box system was not more than the glass bottle re-use system (the cleansing of the bottles at home and in the factory plus the increased transport had a relative high eco-burden).

A recent development is the PE bottle for milk, which solution is less attractive from the environmental point of view. It is also less attractive than PET, since PE has a higher eco-burden for recycling.

PET bottles for beverages are still re-used in some countries; however, they are more and more recycled (approx. 50% of the PET bottles in Europe).

Wine bottles are recycled in some countries (approx. 70% in The Netherlands).

PLA bottles (bio-degradable and made from bio-products) are still rather scarce.

Table 7.1 gives some general information on eco-costs. It is quite easy to sort out which system is the best in terms of the environment, when the general design requirements (e.g. expected realistic recycling rates, expected waste incineration, transport distances, etc.) are known.

|           | approx.<br>weight<br>per litre<br>(grams) | eco-costs<br>virgin material<br>production<br>(euro/kg) | eco-costs<br>virgin material<br>production<br>(euro/litre) | eco-costs<br>recycled<br>production<br>(euro/kg) | eco-costs<br>recycled<br>production<br>(euro/litre) | eco-costs<br>munic.<br>waste<br>incineration<br>(euro/kg) | eco-costs<br>munic. waste<br>incineration<br>(euro/litre) |
|-----------|-------------------------------------------|---------------------------------------------------------|------------------------------------------------------------|--------------------------------------------------|-----------------------------------------------------|-----------------------------------------------------------|-----------------------------------------------------------|
| glass     | 400                                       | 0.24                                                    | 0.096                                                      | 0.20                                             | 0.080                                               | -                                                         | -                                                         |
| PET       | 30                                        | 1.03                                                    | 0.031                                                      | 0.09                                             | 0.003                                               | 0.16                                                      | 0.005                                                     |
| PE        | 40                                        | 1.16                                                    | 0.046                                                      | 0.09                                             | 0.004                                               | 0.14                                                      | 0.006                                                     |
| aluminium | 40                                        | 2.21                                                    | 0.088                                                      | 0.40                                             | 0.016                                               | -                                                         | -                                                         |
| steel     | 90                                        | 0.21                                                    | 0.019                                                      | 0.11                                             | 0.010                                               | -                                                         | -                                                         |
| carton    | 30                                        | 0.10                                                    | 0.003                                                      | 0.10                                             | 0.003                                               | -0.11                                                     | -0.003                                                    |
| PLA       | 30                                        | 0.50                                                    | 0.015                                                      | 0.50                                             | 0.015                                               | -0.11                                                     | -0.003                                                    |

Table 7.1 Key data on recycling systems for containers of beverages, 1 litre (Idematapp 2023)

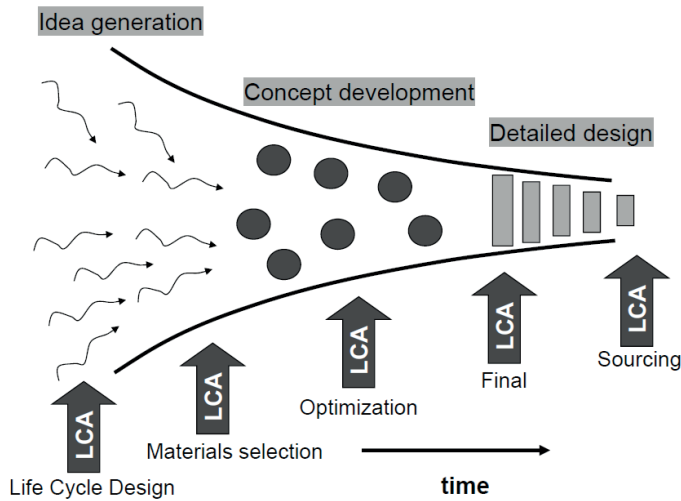
It is obvious from the table that such an analysis of the total system must be made in the early design stages: the choice on the system must be made prior to the design of the product itself. See Fig. 7.3.

LCA (Fast Track) is to be used throughout the total design process, right from the start:

- First, the Life Cycle Design is made to determine the best product-service system
- Then the (other) materials are selected
- In the subsequent period, LCA is applied in the process of design optimization
- At the end, LCA used to select the best suppliers of the materials



Figure 7.3  
LCA applied throughout the design process, starting at the early design stage



## 7.2 Pitfalls in LCA calculations on C2C systems

As we saw in the previous sections, LCA can be made on systems with recycling (C2C). However, there are some pitfalls in LCA calculations: in some cases the standard LCI databases and the standard Fast Track databases cannot be used. In these cases, new LCIs have to be made. The reason is that the standard LCI databases are based on the existing production systems of our technosphere.

In successful innovative C2C designs, the biosphere plays an important role, and the system design minimizes the use of products from the existing technosphere. This issue is explained by an example: the system of the Rebicycle (the bike of Fig. 3.5).

The Rebicycle is a bicycle, made of natural materials: wood and bio-plastics (strong engineering plastics). Steel was avoided. A prototype of the bicycle has been built. The innovative production system is hypothetical: the wood and oil-seeds are supposed to be cultivated at a 40 ha farm with a farmhouse. The production is in the old farmhouse. So Rebicycle is not only a bike, it is a real C2C production system, where the biosphere plays an important role<sup>41</sup>. An essential element of this system is that there is no input to the system, so polluting transport is eliminated. Electricity is generated in a small wood-fired co-generating plant. The heat and the electricity are used for the production of the bike, and the surplus of electricity is exported as a by-product of the bike. Leaves of the trees are composted, to be used as fertilizer for the oil-seed production.

<sup>41</sup> Note that steel can be recycled in the technosphere, but this recycling causes a lot of environmental pollution. Applying wood from the biosphere is much cleaner.

The example shows that it is not enough to apply materials with can be recycled (all metals can be recycled in the technosphere). Incorporation of the biosphere is essential to create a system with a good score in LCA. In such a way most of the emissions are recycled by mother nature.

The system is depicted in Fig. 7.4.

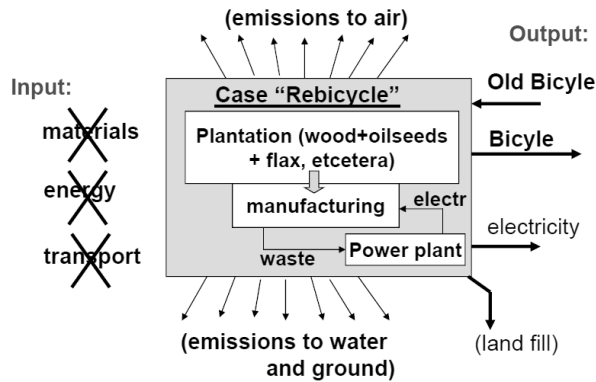


Figure 7.4.

The production system of the Rebicycle is characterised by using the biosphere and eliminating imports of materials, energy and transport

The LCA of such a system cannot directly be made from the LCIs from the Ecoinvent database (nor from Idemat or other LCI databases). The reason is that these data are derived from current subsystems in the technosphere, so these standard LCIs contain inputs of materials, energy and transport (See also Appendix II).

This problem can be resolved in four ways:

1. The **emissions** of the primary production processes are listed, and converted with the table “eco-costs 2023 LCA data on emissions and materials depletion” on the [ecocostsvalue.com](http://ecocostsvalue.com) website.

The **energy balance** is calculated to assess the surplus of electricity, to be converted to the corresponding credit of this by-product in as explained in Section 5.3.

The eco-costs of the required equipment is added, applying the normal eco-costs databases (since the equipment is made in the technosphere).

2. The **Ecoinvent** data (“unit” type) are copied in **Simapro**, the lines of transport and energy in the subsystems are set to zero, and the calculations are made in Simapro.

The energy balance is calculated to assess the surplus of electricity, and the credits of this by-product are calculated in Simapro (apply the LCIs for “avoided products”, see Section 5.2).

The standard Ecoinvent subsystems are used to add up the production equipment (from the technosphere).

3. Apply the classical **rigorous LCA** method (create the full LCI by analysing the total system). This solution, however, is much more laborious than the methods described in point 1 and 2.
4. **Fast Track:** Apply the eco-costs data in the Ecoinvent lines for “wood at the forest road” and “soya been oil” as surrogate processes (this causes a slight overestimation of the eco-burden, but the main eco-burdens of the bike are caused by making the equipment and the co-generation unit). Calculate the energy balance,

and use the eco-costs of “Idemat Electricity General Industry” (negative, since it is the credit of a by-product). Calculate the eco-costs of the equipment and the co-generating unit in the standard Fast Track way.

This solution is by far the fastest way, and the error caused by the use of surrogate processes is negligible.

In practice, systems to be studied are not as extreme as the Rebicycle system, so a bit of common sense is normally enough to avoid the pitfalls in LCA calculations on C2C systems.

## 8 Carbon Sequestration in wood

### 8.1 Carbon Sequestration in LCA

Sequestration (= capture and storage) of CO<sub>2</sub> in wood is an important issue in sustainability. However, it is also a confusing subject, leading to many discussions.

After many years of discussions among LCA experts, there seems to be finally consensus on the way “biogenic CO<sub>2</sub>” (=CO<sub>2</sub> which is captured in wood during the growth of a tree) is to be handled in LCA: it is simply not counted. The reasoning behind is that:

- this biogenic CO<sub>2</sub> is released back to the atmosphere at the End of Life (it is recycled), so it doesn't make sense to follow its way through the system
- incorporating biogenic CO<sub>2</sub> results in more complexity of the LCA calculations, leading to many mistakes in practice
- it is only a matter of a different system boundary (the result of the LCA calculations is the same), so it doesn't make sense to do it the complex way, see Fig. 8.1.

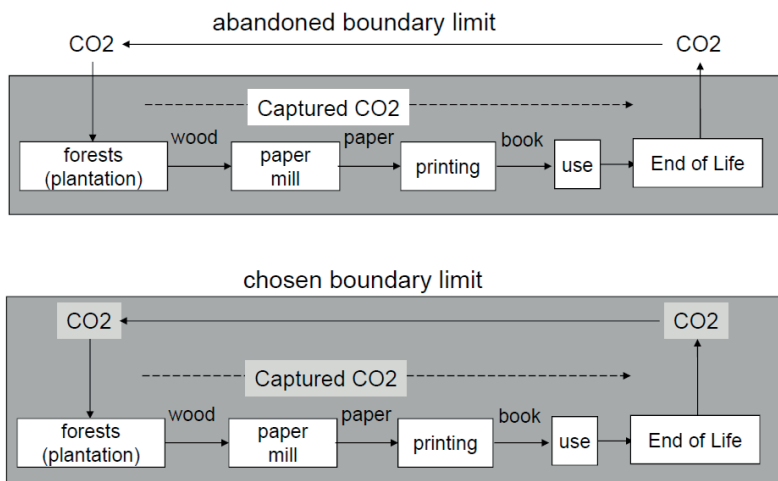


Figure 8.1

With the chosen system boundary, the recycling of biogenic CO<sub>2</sub> stays within the system, so there is no need to take it into account as import or export in the subsystems of the LCA

It is important to understand that the issue of carbon sequestration in wood is different from the issue of the credits of burning wood at the End of Life when the heat is used (for electricity or other purposes), as dealt with in Sections 5.2 and 5.3.

The widespread confusion comes from the fact that carbon sequestration as such, even temporary, is good for the environment, so “it has to be incorporated in some way in LCA”.

However, there are more issues which are not (fully) dealt with in LCA, as it is explained in Chapter 9. Carbon sequestration in wood is such an issue. It is rather complex to model it in LCA, because of two reasons:

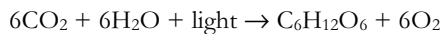
- LCA is basically only about material flows (inputs, emissions, outputs) of a system: it doesn't deal with temporary storage
- LCA is done on the level of product systems (not on global systems)

The effects of carbon sequestration in wood can only be analysed at a global system level. For designers it is important to understand the global system, and how the global system is influenced by product design. Therefore a short explanation on carbon sequestration in wood is given in the next section.

## 8.2 The global carbon cycle and biogenic CO<sub>2</sub> in wood

### 8.2.1 Chemical background

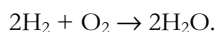
The carbon sequestration stems from the photosynthesis in growing plants. The biochemical reaction of photosynthesis is:



Note: C<sub>6</sub>H<sub>12</sub>O<sub>6</sub> is sugar, transferred to cellulose (C<sub>6</sub>H<sub>10</sub>O<sub>5</sub>) in further reactions

In this equation, carbon is stored in the plant, releasing part of the oxygen, and H<sub>2</sub>O is split in H<sub>2</sub> (stored in the plant) and O<sub>2</sub> (released to the air).

When the plant is burned, it releases the CO<sub>2</sub> again, and heat is produced by



### 8.2.2 The global carbon cycle and the role of carbon sequestration in forests

A good overview of the global carbon cycle and sequestration of carbon in forests is depicted in Fig. 8.2 (source NASA Earth Science Enterprise). A short explanation of this figure is given at the website of the NASA:

<https://earthobservatory.nasa.gov/Features/CarbonCycle/?src=features-fromthearchives>

The issue is that the human role of the CO<sub>2</sub> emissions is three-fold:

- 5.5 Gt carbon emissions per year caused by burning of fossil fuels
- 1.6 Gt carbon emissions per year caused by deforestation in tropical and sub-tropical areas
- 0.5 Gt carbon sequestration per year by re-growth of forests on the Northern Hemisphere.

So it can be concluded that the global carbon cycle can significantly be improved in the short term by:

- less burning of fossil fuels
- stopping deforestation
- forest conservation by better management and wood production in plantations
- afforestation (planting of trees on soils that have not supported forests in the recent past)

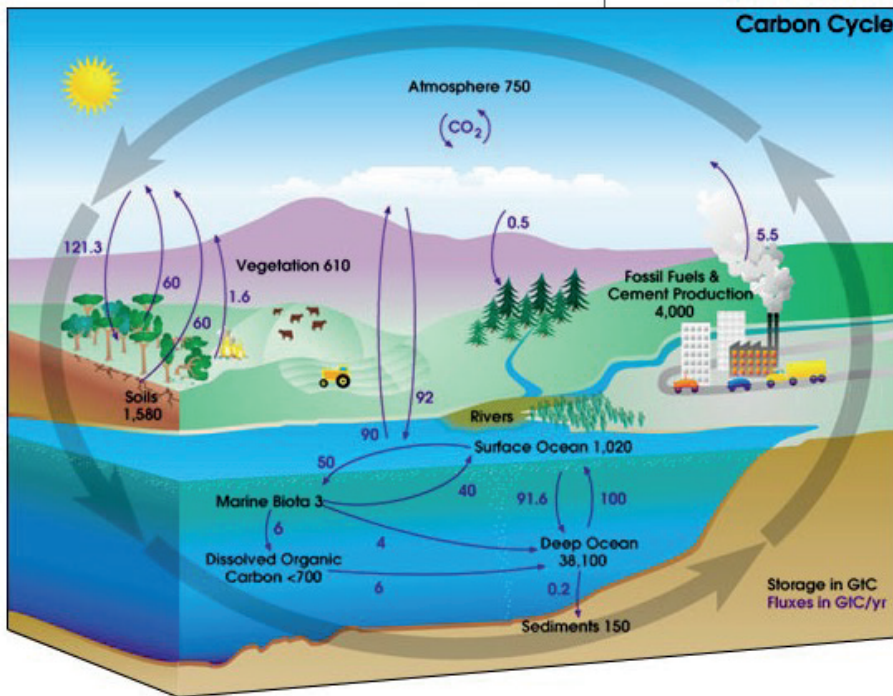


Figure 8.2

The global carbon cycle  
(Source NASA)

### 8.2.3 Carbon sequestration in wood from the perspective of designers, architects and engineers

Carbon sequestration is a hot issue in LCA [10]. The designer, architect and engineer might take the positive consequences of carbon sequestration into account by selecting natural bio-based materials.

It is far too simple to say that “application of wood in design and construction will lead to carbon sequestration, and therefore it will counteract global warming”. It depends on the type of wood, which is explained in this section.

There are two issues:

- carbon sequestration of wood in the forests
- carbon sequestration of wood in the houses, offices, etc. during the life time

One should realise that, if there is *no change* in the area of forests and *no change* in the volume of wood in houses, offices, etc., there is *no change* in sequestered carbon. Then, there is no effect on carbon emissions. So, the issue is related with the *global growth* of production and demand of wood.

Only when the global area of forests is increasing, and when the total volume of wood in houses, offices, etc. is increasing, there will be extra carbon sequestration. This is the situation for European wood: extra market demand of wood leads to afforestation. See Fig. 8.3. The situation is different for tropical hardwood, where extra demand of wood is not leading to afforestation, but deforestation, see Fig. 8.4.

Figure 8.3

More demand of European wood leads to afforestation (extra forests) in Europe and more carbon sequestration

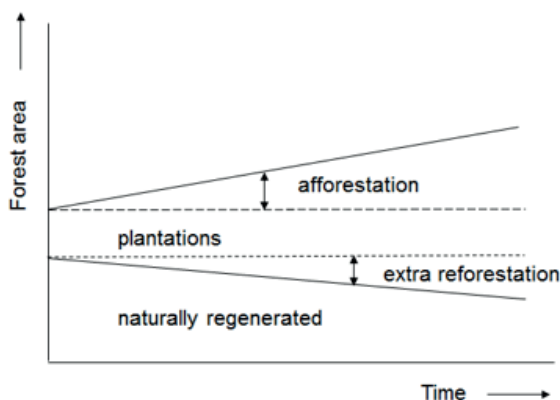
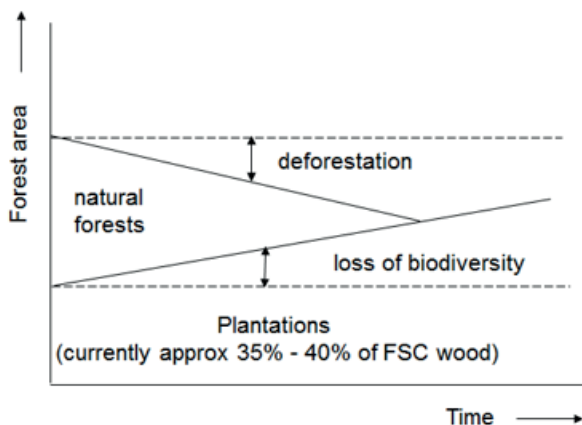


Figure 8.4

More demand of tropical hardwood leads to deforestation on the short term, and less carbon sequestration



In Fig. 8.4 the demand for tropical hardwood is more than the supply from plantations (only 40% of FSC-wood is from plantations). This deforestation leads to carbon emissions caused by less carbon sequestration.

The conclusion for the production side of wood is:

- extra demand of European wood leads to an increase in forest area, so more sequestered carbon
- (extra) demand of tropical hardwood leads to a decrease in forest area, so less sequestered carbon
- extra demand of bamboo, however, leads to an increase in forest area, since bamboo is not harvested from areas with natural forests

The volume of wood in houses, offices, etc. is slowly rising on a global scale (because of increasing population), which is positive in terms of extra carbon sequestration. See Fig. 8.5. This volume, however, is generally low in comparison with the volume of standing trees in the forests (less than 25% of the wood ends up in housing).

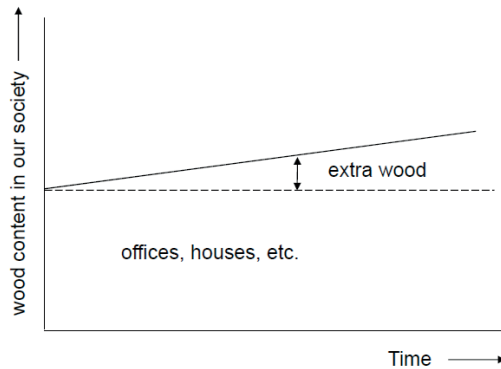


Figure 8.5  
More applications of wood in the building industry leads to more carbon sequestration

The conclusion for designers, architects and engineers is that carbon sequestration is enhanced whenever more European wood and/or bamboo is applied. The application of tropical hardwood, however, is damaging carbon sequestration.

Note that carbon sequestration is not increasing per house which is built, but per extra house that is built above the number of houses that are required to replace discarded, old, houses (this is the reason that carbon sequestration is not easy to model in LCA).

#### 8.2.4 The negative eco-costs of carbon sequestration

For detailed LCA calculations on carbon sequestration, see [10].

A simplified calculation is given below.

The negative eco-costs of (additional) carbon sequestration can be calculated as follows:

- 1 kg dry wood stores 0.47 kg C (ranging from 0.42 to 0.50)
- 0.47 kg C is equivalent to 1.72 kg CO<sub>2</sub>



- the benefit of storing 1.72 kg CO<sub>2</sub> is - 0.21 €.

So the eco-costs of carbon sequestration in wood is - 0.21 € per kg wood

These negative eco-costs apply to the *extra* wood which is “brought into the system” on a continuous, everlasting basis (as explained in Section 8.2.3). One could argue that such a simple calculation holds also for wooden construction parts (e.g. beams) in a house that last longer than 100 years (since more than 100 years is ‘forever’ in LCA), but most of the wood does not fulfill this 100 year criterion.

For softwood from the Northern Hemisphere it is calculated that the carbon sequestration in forests plus houses is **0,19 kg CO<sub>2</sub> (equivalent to -0.023 euro eco-costs) per kilogram dry planed timber** brought into the system on average (Fig 8.3 and 8.5), whereas it is 0.68 kg CO<sub>2</sub> (- 0.084 euro eco-costs) per kilogram dry matter bamboo plywood [10]. These data are **not** applied in the Idemat data on wood and wood products.

The carbon sequestration per kilogram planed timber (dry matter) is negative for tropical hardwood from the rain forest (see Fig. 8.4) as estimated below:

- - 3.88 kg CO<sub>2</sub> or 0.477 euro eco-costs per kilogram dry planed timber extracted from natural forests (based on the assumption that a tree from the natural forest will not grow back within 100 years)
- 0.00 kg CO<sub>2</sub> per kilogram planed timber from existing plantations and FSC wood (based on the assumption of RIL - reduced impact logging - plus rotational harvesting of FSC wood), see below.

These estimates are applied in the Idemat data on tropical hard wood.

Note 1. FCS wood is harvested according to two principles: (a) Reduced Impact Logging (RIL), where only trees are harvested that have a sufficient stem diameter (b) Rotational logging, which means the area will be untouched for several decades before harvesting the next time; this means that every year a different section of the total area is logged, resulting in a "steady state" for the total area. For more information see [www.ecocostsvalue.com/lca/wood-lca-issues/](http://www.ecocostsvalue.com/lca/wood-lca-issues/) .

Note 2. Boreal forest in the Scandinavian countries contain more wood than a decade ago, so these forests are growing in terms of sequestered carbon: they are carbon sinks. The main threat to the carbon sinks are the increase of wildfires in Canada and Russia. In countries with a strong forest management, like Finland, Sweden, and Estonia, wildfires are not a major problem, but here is an issue of a sudden increase of production of wood logs, because of less imports from Russia.

Remark: In contrast to many stories in internet bubbles, the combustion of wood pellets in power plants plays a negligible role in the global statistics on boreal wood: these pellets stem predominantly from wood waste that cannot be sold in the form of particle board, MDF, or pulp..

## 9 Land-use, Water and other issues

### 9.1 Land-use: yield of land as an indicator for scarcity

In the previous section, we saw that carbon sequestration has led to many discussions among LCA experts and practitioners. The same applies to Land-use, Water, and People (of the third world). It are issues of sustainability, but how to cope with it in LCA? Or is it better to analyse it outside LCA?

#### 9.1.1 LCA and Ecological Footprint

The main discussions on Land-use in LCA are focused on the choice how to model it<sup>42</sup>. This LCA manual is not the place to discuss these deliberations. For the non-specialists it is important, however, to realize that **LCA copes with carbon sequestration as well as the loss of species**, but that this is another issue than the issue of **scarcity** of land as such (the fact that there might be a shortage of land in future for agricultural production).

The idea of scarcity of land is compelling to many environmentalists, hence the popularity of the system of the Ecological Footprint<sup>43</sup>.

The Ecological Footprint takes five aspects into account:

- land required for production of food (m<sup>2</sup> per inhabitant)
- land required for production of wood (m<sup>2</sup> per inhabitant)
- build-up area (m<sup>2</sup> per inhabitant)
- sea required for food production (m<sup>2</sup> sea per inhabitant)
- forests required to sequester the CO<sub>2</sub> from energy production (m<sup>2</sup> per inhabitant)

It is clear from these 5 aspects that the Ecological Footprint has little to do with the main aspects LCA (human health, eco-toxicity and resource depletion). So, Ecological

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<sup>42</sup> See [8] and further the J. of Cleaner Production in the period 1995 - 2005, in which leading articles on this issue were published. The model of the eco-costs takes conversion of land and the loss of biodiversity (scarcity of biodiversity) as point of departure (unit: euro per m<sup>2</sup>). In practice it has a high impact on the eco-costs of wood from tropical areas.

The Recipe model takes occupation of land as a point of departure (unit: species.yr/m<sup>2</sup>.yr, after weighting Pt per m<sup>2</sup>.yr). Conversion of land is formally included as well, but plays in practice a minor role in terms of overall output.

<sup>43</sup> Definition ([www.footprintnetwork.org](http://www.footprintnetwork.org)): The Ecological Footprint measures how much land and water area a human population requires to produce the resource it consumes and to absorb its wastes, using prevailing technology.

Footprint must not be confused with the LCA method according to ISO 14040 and 14044. Furthermore, it must be mentioned here that the calculation method of the Ecological Footprint is still not defined very well, and lacks standardisation, especially with regard to import and export of countries. Although the basic idea is simple, the calculation is rather complex, triggering a lot of discussion<sup>44</sup>.

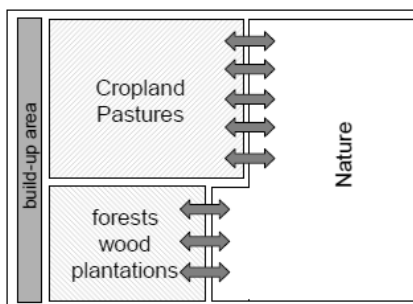
The conclusion is that LCA lacks the aspect of **scarcity** of land, and the ecological footprint is not well enough defined and standardised to cover this aspect.

### 9.1.2 Yield of land: a sustainability issue for designers, architects and engineers

For designers, architects and engineers yield of land is an additional sustainability issue, apart from LCA, to cope with the **scarcity** of land. The importance of the yield of land is fully in line with the philosophy of the ecological footprint. This is the notion that the consumption of people is supported by the production of land: more consumption leads to less nature, unless the yield is higher. See Fig. 9.1.

Figure 9.1

Yield of cropland, pastures and forests for wood production is important, especially in areas where nature has a high biodiversity (more yield = less pressure on nature)



Yield is important in the selection of the type of wood, since every type of wood has its own yield in forestry. Yield is also important in the selection of the type of biosphere system in C2C, as well as in the selection of agricultural systems.

For wood from European forests, the eco-costs are rather low. So yield might be taken here as the major sustainability aspect for selection, when one has the opinion that European land for forestry will become scarce in the near future.

For wood from tropical **plantations**, yield is a very important issue for selection. The reason is that the **adjacent** nature has a high biodiversity (see Fig. 9.1). Occupying land for plantations results in a loss of valuable nature that could be tropical forest.

Some information is shown on the yield from plantations in Table 9.1.

<sup>44</sup> Nevertheless, it is possible to estimate the energy part of the Ecological Footprint of a product in Simapro, applying the Ecoinvent database, with the assumption of an average carbon sequestration rate of 0.3674 kg CO<sub>2</sub> per m<sup>2</sup>.yr (2.6722 m<sup>2</sup>.yr / kg CO<sub>2</sub>)

| wood type              | volume growth<br>(m <sup>3</sup> /ha.year) | yield sawn logs<br>(m <sup>3</sup> /ha.year) | yield sawn timber<br>(m <sup>3</sup> /ha.year) |
|------------------------|--------------------------------------------|----------------------------------------------|------------------------------------------------|
| baby teak              | 12.5                                       | 10                                           | 4.4                                            |
| regular teak           | 6                                          | 4.8                                          | 2.1                                            |
| european oak           | 5                                          | 4                                            | 1.8                                            |
| eucalyptus             | 25                                         | 20                                           | 8.8                                            |
| bamboo (latin america) | -                                          | -                                            | 8.8                                            |
| bamboo (china)         | -                                          | -                                            | 4.7                                            |

Table 9.1  
Yield from  
plantations of  
some wood  
types

## 9.2 Fresh water

In terms of sustainability, two issues about water are important:

- the pollution of water
- the scarcity of water as such

The pollution of water is part of LCA, related to eco-toxicity. However, **scarcity** of water is another issue in LCA, since it is highly determined by local circumstances: water in countries like Germany is not scarce, whereas water in the Middle East is extremely scarce. Based on 'Baseline Water Stress' (the Acqueduct Project of the WRI) the eco-costs 2023 system has incorporated the eco-costs of water scarcity (part of the eco-costs of resource depletion, see Appendix I).

The main problem of the scarcity of water is the availability of (safe) drinking water for the poor people in the developing countries, see Fig. 9.2.



Figure 9.2  
Scarcity of  
drinking water in  
the world  
(source:  
Wikimedia  
commons)

The scarcity of drinking water is a combination of the local climate conditions and the local level of prosperity (the costs of desalination of water is about 1.06 euro per m<sup>3</sup>, plus transport). Table 9.2 clearly indicates the relation between poverty and lack of safe drinking water.

It is obvious that the designer must take into account the usage of water of products and production systems for the yellow and red countries in Fig. 9.2. LCI databases, like the Ecoinvent database, provide data on the usage of fresh water for the production of materials and products. It is a matter of common sense to select the right products and production systems, in line with the local circumstances.

Table 9.2

The access to safe drinking water is a problem of poverty

| Percentage of population with access to safe drinking water (2000)                  |    |             |    |              |    |             |    |           |    |
|-------------------------------------------------------------------------------------|----|-------------|----|--------------|----|-------------|----|-----------|----|
| Country                                                                             | %  | Country     | %  | Country      | %  | Country     | %  | Country   | %  |
| Albania                                                                             | 97 | Algeria     | 89 | Azerbaijan   | 78 | Brazil      | 87 | Chile     | 93 |
| China                                                                               | 75 | Cuba        | 91 | Egypt        | 97 | India       | 84 | Indonesia | 78 |
| Iran                                                                                | 92 | Iraq        | 85 | Kenya        | 57 | Mexico      | 88 | Morocco   | 80 |
| Peru                                                                                | 80 | Philippines | 86 | South Africa | 86 | South Korea | 92 | Sudan     | 67 |
| Syria                                                                               | 80 | Turkey      | 82 | Uganda       | 52 | Venezuela   | 83 | Zimbabwe  | 83 |
| All industrialized countries (as listed by UNICEF) with data available are at 100%. |    |             |    |              |    |             |    |           |    |

## 9.3 Other issues

There are other issues as well which might need separate attention:

- risks of calamities (e.g. transport of toxic materials, deep sea oil production)
- hindrance (e.g. hindrance of smell, noise pollution)

These issues are important in terms of sustainability, but are not (yet) part of LCA. It is the responsibility of the designer and the business manager to take these issues into account, when they design and select products and production systems. One should not only adhere to governmental laws, but one should exceed the best practices.

The so-called **social-eco-costs (s-eco-costs)** have been developed for the appalling labour conditions in the poor countries in our world. It covers *child labour, extreme poverty, excessive working hours, occupational safety & health, and the fair wage deficit*, see Appendix I.

The s-eco-costs have been applied to S-LCA of the supply chain of garments, and the system is regarded a suitable to analyse social aspects of mining operations. A database is available for Simapro.

# Appendices

## Appendix I

### The model of the Eco-costs 2023 (source: Wikipedia)

#### General

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

For example: for each 1000 kg CO<sub>2</sub> emission, one should invest €123,- in offshore windmill parks (plus in the other CO<sub>2</sub> reduction systems at that price or less). When this is done consequently, the total CO<sub>2</sub> emissions in the world will be reduced by 70% compared to the emissions in 1995. As a result, global warming will stabilize. In short: "the eco-costs of 1000kg CO<sub>2</sub> are € 123,-".

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

The eco-costs of a product are the sum of all eco-costs of emissions and use of resources during the life cycle "from cradle to cradle". The widely accepted method to make such a calculation is called life cycle assessment (LCA), which is basically a mass and energy balance, defined in the ISO 14040, and the ISO 14044 (for the building industry the EN 15804).

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

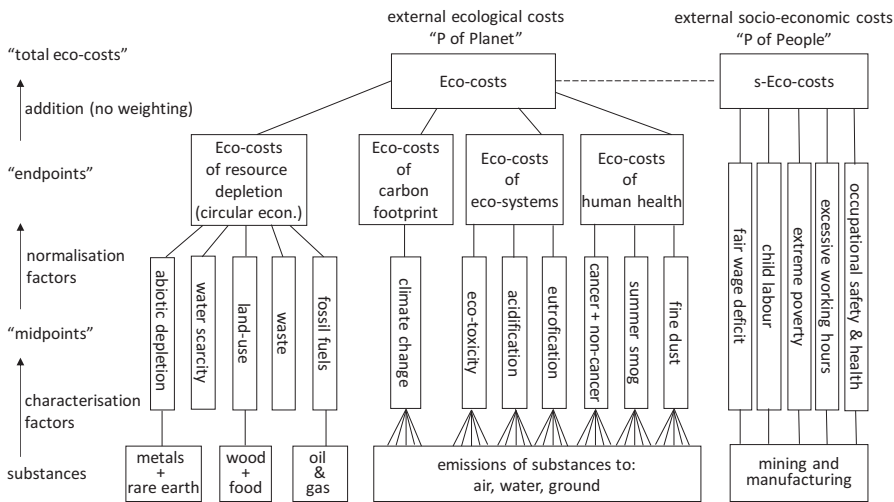
The system of eco-costs is part of the bigger model of the ecocosts/value ratio, EVR, see Appendix IV.

Background

The eco-costs system has been introduced in 1999 on conferences, and published in 2000-2004 in the *International Journal of LCA*, and in the *Journal of Cleaner Production*. In 2007 the system has been updated, and published in 2010. The next updates were in 2012, 2017, 2022 and 2023. It is planned to update the system every 5 years to incorporate the latest developments in science.

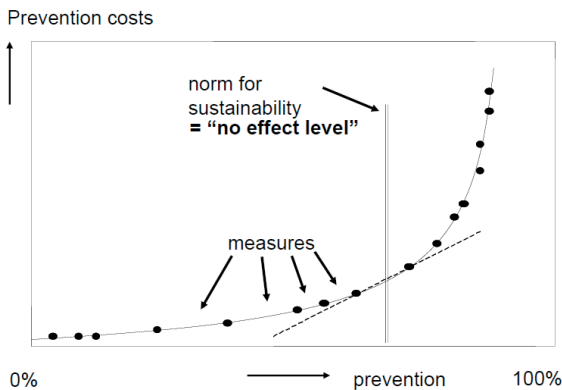
The concept of eco-costs has been made operational with general databases of the Delft University of Technology, and is described at [www.ecocostsvalue.com](http://www.ecocostsvalue.com). The method of the eco-costs is based on the sum of the marginal prevention costs (end of pipe as well as system integrated) for toxic emissions related to human health as well as ecosystems, emissions that cause global warming, and resource depletion (metals, rare earth, fossil fuels, water, and land-use). For a visual display of the system see Fig. A1.

Figure A1  
The eco-costs  
2023  
calculation  
structure



Marginal prevention costs of toxic emissions are derived from the so-called prevention curve as depicted in Fig. A2. The basic idea behind such a curve is that a country (or a group of countries, such as the European Union), must take prevention measures to reduce toxic emissions (more than one measure is required to reach the target).

Figure A2  
The prevention  
curve and the  
marginal  
prevention  
costs



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

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

The calculation of the eco-costs is based on classification and characterisation tables as well (combining the tables of the Environmental Footprint as derived from e.g. IPCC and the USEtox model (usetox.org), however has a different approach to the normalization and weighting steps. Normalization is done by calculating the marginal prevention costs for a region (i.e. the European Union), as described above. The weighting step is not required in the eco-costs system, since the total result is the sum of the eco-costs of all midpoints. The advantage of such a calculation is that the marginal prevention costs are related to the cost of the most expensive Best Available Technology which is needed to meet the target, and the corresponding level of Tradable Emission Allowances which is required in future. From a business point of view, the eco-costs are the costs of the risk of non-compliance with future governmental regulations. Example from the past: NO<sub>x</sub> emissions of Volkswagen diesel..

The eco-costs have been calculated for the situation in the European Union. It is expected that the situation in some states in the USA, like California and Pennsylvania, give similar results. It might be argued that the eco-costs are also an indication of the marginal prevention costs for other parts of the globe, under the condition of a level playing field for production companies..



## Eco-costs 2023

The method of the eco-costs 2023 (version 2.1) comprises tables of over 58.000 emissions (for foreground calculations), and has been made operational by special databases for SimaPro and OpenLCA. For students, engineers and architects, the Idematapp 2023 for IOS and Android, and Idemat2023 excel look-up tables for so called Scope 3 (= background) data, and calculation tools are provided at [www.ecocostsvalue.com](http://www.ecocostsvalue.com).

For emissions of toxic substances, the following set of multipliers (marginal prevention costs) is used in the eco-costs 2023 system:

- prevention of acidification 9.275 €/kg SO<sub>x</sub> equivalent
- prevention of eutrophication 5.0 €/kg phosphate equivalent
- prevention of ecotoxicity 360.4 €/kg Cu equivalent
- prevention of carcinogens 3754 €/kg Benzo(a)pyrene equivalent
- prevention of non-carcinogens 25500 €/kg Mercury. equivalent
- prevention of summer smog (respiratory diseases) 5.67 €/kg NMVOC equivalent
- prevention of fine dust 37.1 €/kg fine dust PM<sub>2.5</sub>
- prevention of global warming (GWP 100) 0.123 €/kg CO<sub>2</sub> equivalent

The characterisation ('midpoint') tables which are applied in the eco-costs 2023 system are from the Environmental Footprint (in line with EN15804):

- IPPC 2013, 100 years, for greenhouse gasses
- USETOX 2, for human toxicity (carcinogens), and ecotoxicity
- ILCD, for acidification, eutrophication, and photochemical oxidant formation
- RiskPoll, for fine dust

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

- eco-costs of metals scarcity (metals, including rare earth), and eco-costs of fossil fuels
- eco-costs of land-use change (based on loss of biodiversity - of vascular plants and mammals - used for eco-costs of tropical hardwood)
- eco-costs of water, based on the Baseline Water Stress (WRI) of countries
- eco-costs of landfill

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

|                                |                                                                                 |
|--------------------------------|---------------------------------------------------------------------------------|
| eco-costs of human health      | = the sum of cancer, non-cancer, summer smog, fine dust                         |
| eco-costs of ecosystems        | = the sum of acidification, eutrophication, ecotoxicity                         |
| eco-costs of resource scarcity | = the sum of materials scarcity, land-use, baseline water stress, and land-fill |
| eco-costs of global warming    | = the sum of CO <sub>2</sub> and other greenhouse gases (the GWP 100 table)     |
| total eco-costs                | = the sum of human health, ecosystems, resource depletion and greenhouse        |

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

The eco-costs of global warming (also called eco-costs of carbon footprint) can be used as an indicator for the carbon footprint. The eco-costs of resource depletion can be regarded as an indicator for 'circularity' in the theory of the circular economy. However, it is advised to include human toxicity and eco-toxicity, and include the eco-costs of global warming in the calculations on the circular economy as well. The eco-costs of global warming are required to reveal the difference between fossil-based products and bio-based products, since biogenic CO<sub>2</sub> is not counted in LCA (biogenic CO<sub>2</sub> is part of the natural recycle loop in the biosphere). Therefore, total eco-costs can be regarded as a robust indicator for cradle-to-cradle calculations in LCA for products and services in the theory of the circular economy. Since the economic viability of a business model is also an important aspect of the circular economy, the added value of a product-service system should be part of the analysis. This requires the two dimensional approach of Eco-efficient Value Creation as described at Appendix IV.

The Delft University of Technology has developed an single indicator for S-LCA as well, the so-called s-eco-costs, to incorporate the sometimes appalling working conditions in production chains (e.g. production of garments, mining of metals). Aspects are the low minimum wages in developing countries (the "fair wage deficit"), the aspects of "child labour" and "extreme poverty", the aspect of "excessive working hours", and the aspect of "OSH (Occupational Safety and Health)". The s-eco-costs system has been published in the Journal of Cleaner Production.

### **Prevention costs versus damage costs**

Prevention measures will decrease the costs of the damage, related to environmental pollution. The damage costs are in most cases the same (or a bit higher) compared to the prevention costs. So the total effect of prevention measures on our society is that it results in a better environment at no extra costs..

### **Discussion**

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

- single issue
- damage based
- prevention based

The best known 'single issue' indicator is the carbon footprint: the total emissions of kg CO<sub>2</sub>, or kg CO<sub>2</sub> *equivalent* (taking methane and some other greenhouse gasses into

account as well). The advantage of a single issue indicator is, that its calculation is simple and transparent, without any complex assumptions. It is easy as well to communicate to the public. The disadvantage is that it ignores the problems caused by other pollutants and it is not suitable for cradle-to-cradle calculations (because materials depletion is not taken into account).

The most common single indicators are damage based. This stems from the period of the 1990s, when LCA was developed to make people aware of the damage of production and consumption. The advantage of damage based single indicators is, that they make people aware of the fact that they should consume less, and make companies aware that they should produce cleaner. The disadvantage is that these damage based systems are very complex, not transparent for others than who make the computer calculations, need many assumptions, and suffer from the subjective weighting procedure as last step at the end. Communication of the result is not easy, since the result is expressed in 'points' (attempts to express the results in money were never very successful, because of methodological flaws and uncertainties). The most recent endpoint indicators avoid the last step to a single indicator: UseTOX 2 and ReCiPe 2016, resulting in 2 respectively 3 endpoints (human health, ecosystems and resources separately).

Prevention based indicators, like the system of the eco-costs, are relatively new. The advantage, in comparison to the damage based systems, is that the calculations are relatively easy and transparent, and that the results can be explained in terms of money and in measures to be taken. The system is focused on the decision taking processes of architects, business people, designers and engineers. The advantage is that it provides 1 single endpoint in euro's. The disadvantage is that the system is not focused on the fact that people should consume less.

The eco-costs are calculated for the situation of the European Union, but are applicable worldwide under the assumption of a level playing field for business, and under the precautionary principle. There are two other prevention based systems, developed after the introduction of the eco-costs, which are based on the local circumstances of a specific country:

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

## References

For references see:

- [8]
- [www.ecocostsvalue.com](http://www.ecocostsvalue.com)
- the references given in <http://en.wikipedia.org/wiki/Eco-costs>

## Four operational databases

In line with the policy of the Sustainability Impact Metrics Foundation to bring LCA calculations within reach of everybody, open access excel databases (tables) are made available on the internet, free of charge.

Experts on LCA who want to use the eco-costs as a single indicator, can download the full database for Simapro (the Eco-costs Method as well as the Idematapp LCIs), when they have a Simapro licence. Also available in OpenLCA

Engineers, designers and architects can have Excel databases, free of charge, for IOS and Android.

The following databases are available:

- excel tables on the website [www.ecocostsvalue.com](http://www.ecocostsvalue.com), tab data (for designers, engineer, architects, business managers, and students, to be used for the Fast Track LCA calculations of this guide):
  - a table with data on emissions and materials depletion (more than 58.000 emissions)
  - Scope 3 tables on products and processes: Idemat LCIs<sup>45</sup> (more than 1.500 materials, processes, electricity, heat transport, agro products),
- an import Simapro database for the method and an import database for Idemat LCIs (software for LCA specialists, only available for Ecoinvent licence holders)
- import tables for OpenLCA
- the IdematApp for Sustainable Materials Selection, available in the App Store of Apple and in the Google Play store. See for more information [www.idematapp.com](http://www.idematapp.com).

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<sup>45</sup> Features of the Idemat LCIs are:

- extra LCIs of alloys (frequently used by designers and engineers)
- a correction of the “market mix” data of metals (Ecoinvent data are outdated)
- extra LCIs of wood types (softwood types as well as hardwood types)
- a specific selection of LCIs for electricity, heat and transport
- extra LCIs of End of Life (combustion, waste incineration, recycling)
- eliminate double counting (of CO<sub>2</sub> and fossil fuels) of electricity in eco-costs
- a table on electricity in 230 countries and provinces in USA, Canada, India, China

## Appendix II

### Calculation structure in computer software for LCA and Single Indicator Systems

This Appendix gives a short explanation on the way LCA calculations are structured in computer software. Basically there are two steps in an LCA calculation:

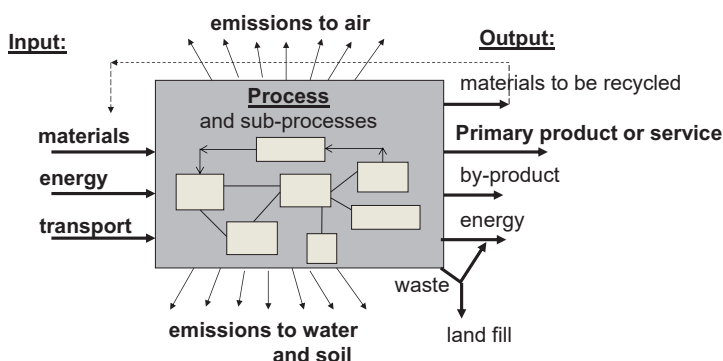
- Step 1. the Life Cycle Inventory (LCI)
- Step 2. the Life Cycle Impact Assessment (LCIA)

The Life Cycle Inventory is a long list of all emissions during the life cycle and all the natural resources which are required. The subsequent step in LCA is the Life Cycle Inventory Assessment, where these long lists are compressed to a few indicators or to a single indicator.

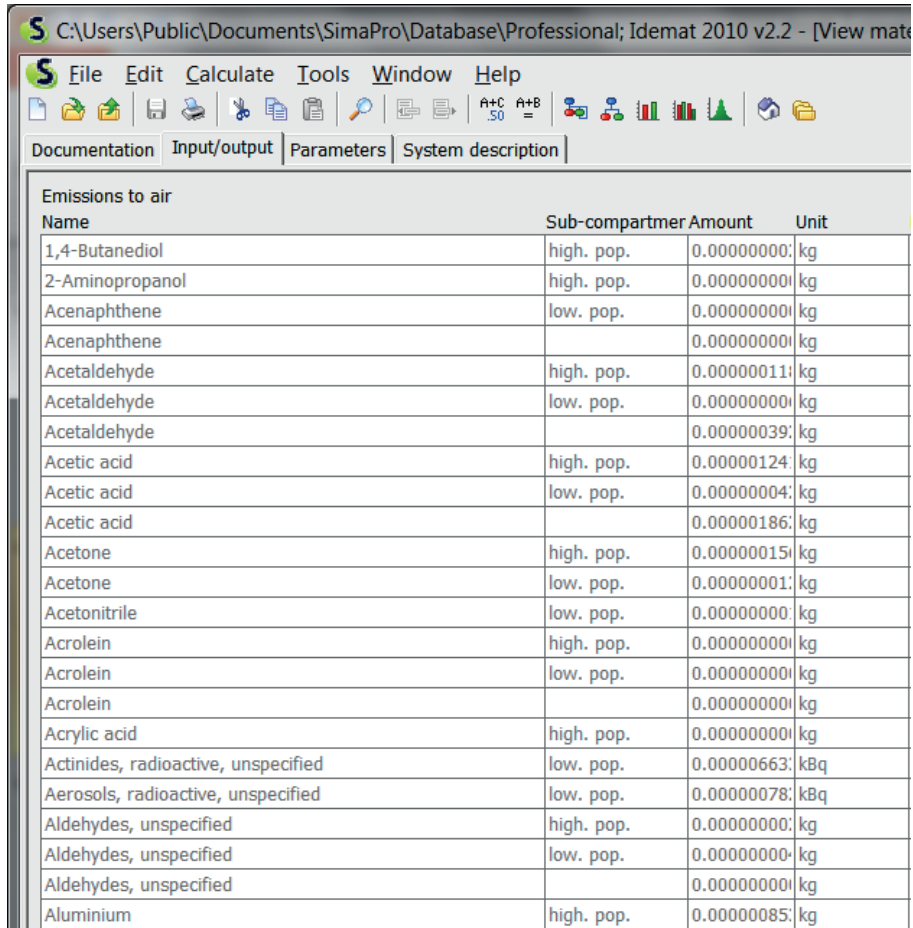
#### Step 1. the Life Cycle Inventory (LCI)

The LCI is calculated in a modular way, where each system (or sub-system) is described in terms of its input and output. See Fig. A3.

Figure A3  
The modular  
structure of LCA



The process and its sub-processes in the module can be anything (cradle-to-gate, gate-to-gate, gate-to-grave). As an example we take the cradle-to-gate process of the product "Sheep for slaughtering at the farm gate". Fig. A4 is a screenshot of 24 emissions to air of the row of more than 550 emissions to air (database Ecoinvent, software Simapro).



| Emissions to air Name               | Sub-compartment | Amount     | Unit |
|-------------------------------------|-----------------|------------|------|
| 1,4-Butanediol                      | high. pop.      | 0.00000000 | kg   |
| 2-Aminopropanol                     | high. pop.      | 0.00000000 | kg   |
| Acenaphthene                        | low. pop.       | 0.00000000 | kg   |
| Acenaphthene                        |                 | 0.00000000 | kg   |
| Acetaldehyde                        | high. pop.      | 0.00000011 | kg   |
| Acetaldehyde                        | low. pop.       | 0.00000000 | kg   |
| Acetaldehyde                        |                 | 0.00000039 | kg   |
| Acetic acid                         | high. pop.      | 0.00000124 | kg   |
| Acetic acid                         | low. pop.       | 0.00000004 | kg   |
| Acetic acid                         |                 | 0.00000186 | kg   |
| Acetone                             | high. pop.      | 0.00000015 | kg   |
| Acetone                             | low. pop.       | 0.00000001 | kg   |
| Acetonitrile                        | low. pop.       | 0.00000000 | kg   |
| Acrolein                            | high. pop.      | 0.00000000 | kg   |
| Acrolein                            | low. pop.       | 0.00000000 | kg   |
| Acrolein                            |                 | 0.00000000 | kg   |
| Acrylic acid                        | high. pop.      | 0.00000000 | kg   |
| Actinides, radioactive, unspecified | low. pop.       | 0.00000663 | kBq  |
| Aerosols, radioactive, unspecified  | low. pop.       | 0.00000078 | kBq  |
| Aldehydes, unspecified              | high. pop.      | 0.00000000 | kg   |
| Aldehydes, unspecified              | low. pop.       | 0.00000000 | kg   |
| Aldehydes, unspecified              |                 | 0.00000000 | kg   |
| Aluminium                           | high. pop.      | 0.00000085 | kg   |

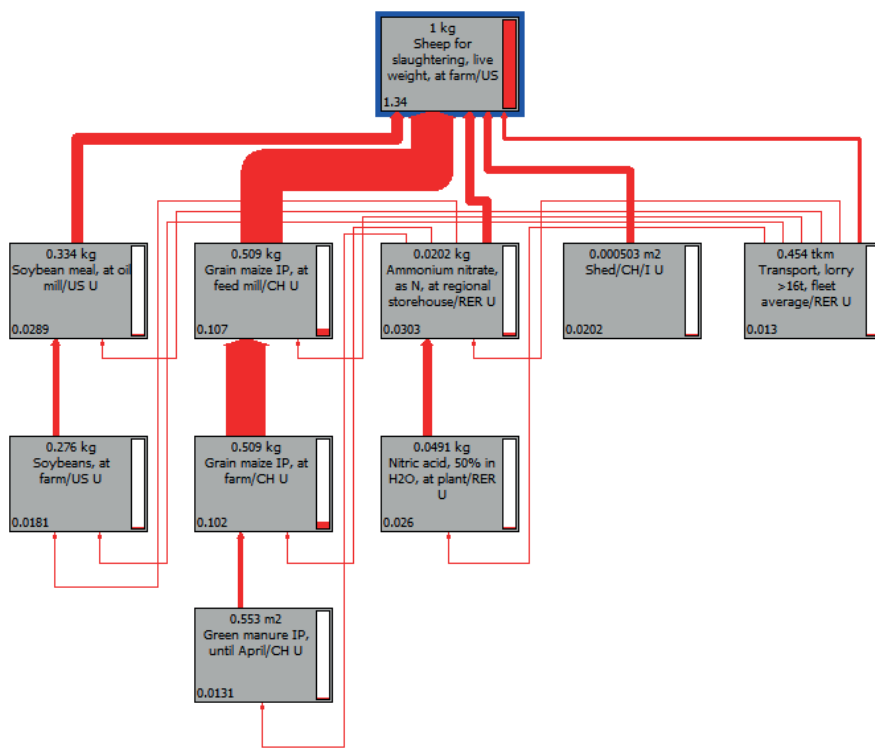
Figure A4

Twenty four emissions to air of a row of 550 of "sheep for slaughtering, life weight, at farm" (source: Ecoinvent V2 software: Simapro)

Many people wonder where such a long list of emissions comes from. It is a compilation (addition) of the emissions of 2018 (!) sub-processes, of which the 9 most important sub-processes of the calculation tree are depicted in Fig. A5.

Figure A5

The 9 most important sub-processes of "sheep for slaughtering, live weight, at farm" (source: Ecoinvent V2 software: Simapro)



Most of the other sub-processes are subs of these 9 sub-processes. Only 5 emissions to air result directly from the farming operation itself<sup>46</sup>. All the other emissions to air are emissions of inputs to the farm system (Soybean meal, Grain maize, Fertiliser, a Shed and Transport).

This calculation structure reveals the power of modern LCI calculations: LCIs can relatively easy be determined using a structure of building blocks.

It is obvious that the usefull 8000 processes (building blocks) of Ecoinvent do not cover everything. By means of the computer software of Simapro (and Gabi), people can build their own LCIs, based on the existing building blocks.

Examples are shown in Fig. A6 and A7.

In such a way, the Idemat database (1400 extra LCIs) of the Delft University of Technology has been created, building on Ecoinvent LCIs, to create LCI for alloys,

<sup>46</sup> In this case 83.5% of the eco-costs comes from direct emissions from the farm (main midpoints: greenhouse effect and acidification), the remainder comes from the sub-processes ('input'). There are other cases, however, where the main eco-costs come from the sub-processes (e.g. in the case of high consumption of electricity).

several types of wood, and food (combining the Danish database on food with Ecoinvent), see footnote 45 (Appendix I).

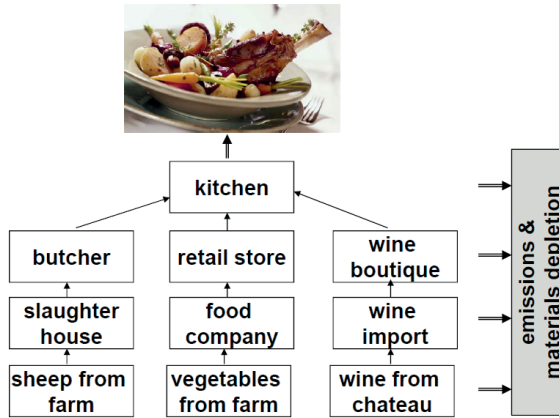


Figure A6

The LCA calculation tree of a meal

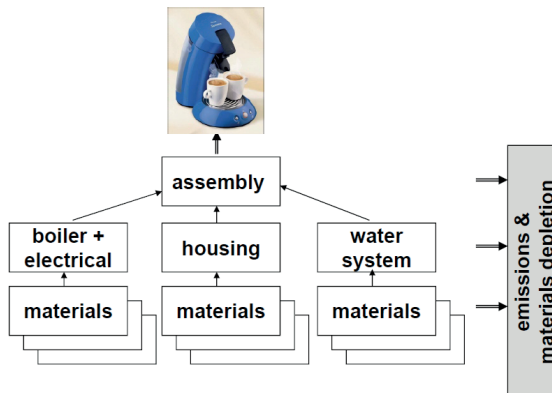


Figure A7

The LCA calculation tree of a Senseo coffee machine

## Step 2. the Life Cycle Impact Assessment (LCIA)

When the LCI of a product or process has been compiled, the LCI must be transformed to a limited number of indicator scores, expressing the severity of the environmental burden. This is called Life Cycle Impact Assessment, LCIA

In Simapro (and Gabi), this is done by transformation tables and specific multipliers. These tables (the so called characterisation tables) and the multipliers are calculated outside Simapro, and are different for the method of transformation which is selected. The transformation methods as such have to comply with ISO 14044.

The transformation method has two steps (the first step is mandatory in ISO 14044):

- Calculating the so called 'midpoints' by classification (assignment of emissions to impact categories) plus characterisation (calculation of the midpoint category indicators, i.e. greenhouse effect, acidification, etc.)

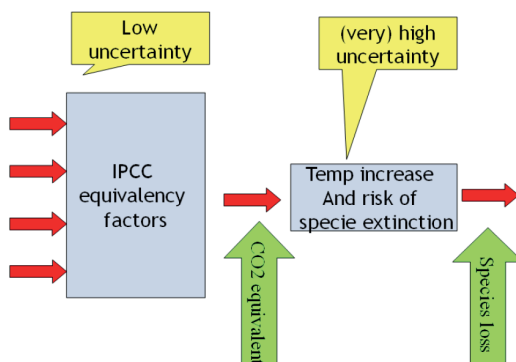
In damage based systems: Calculating the so called 'endpoints' (i.e. human health, eco-



toxicity and resource depletion) and weighting them to arrive at a ‘single score’ for the damage based indicator system (e.g. Environmental Footprint, Recipe)<sup>47</sup> In prevention based systems: calculating the prevention costs for each midpoint and adding them up to arrive at the ‘single score’ (e.g. eco-costs)

It is important to realize that the advantage of creating a damage based ‘single indicator’ in the second step has the disadvantage of introducing a lot of uncertainties. See Fig. A8, A9, and A10.

Figure A8  
The choice  
between  
midpoint and  
endpoint in  
LCIA (source:  
lcia-recipe.net,  
assessed 2016)



This is explained clearly on the website of Recipe<sup>48</sup> [www.lcia-recipe.net](http://www.lcia-recipe.net).

*Quote:* “ReCiPe uses an environmental mechanism as the basis for the modelling. An environmental mechanism can be seen as a series of effects that together can create a certain level of damage to for instance, human health or ecosystems. For instance, for climate change we know that a number of substances, increases the radiative forcing, this means heat is prevented from being radiated from the earth to space. As a result, more energy is trapped on earth, and temperature increases. As a result of this we can expect changes in habitats for living organisms, and as a result of this species may go extinct.

From this example it is clear that the longer one makes this environmental mechanism the higher the uncertainties get. The radiative forcing is a physical parameter, which can be relatively easily measured in a laboratory. The resulting temperature increase is less easy to determine, as there are many parallel positive and negative feedbacks. Our understanding of the expected change in habitat is also not complete, etc.” *unquote.*

<sup>47</sup> According to ISO 14044, weighting of the three endpoints is formally not allowed in “LCA studies to be used in comparative assertions intended to be disclosed to the public.” (Section 4.4.5, Appendix III.) Note that the eco-costs system does not have such a weighting step.

Weighting is defined as “the process of converting indicator results of different impact categories by using numerical factors based on value-choices. It may include aggregation of the weighted indicator results. Weighting steps are based on value-choices and are not scientifically based. Different individuals, organizations and societies may have different preferences” (ISO 14044, see Appendix III)

<sup>48</sup> It is advised to apply Recipe (2016), see Fig. A10, since materials scarcity (materials depletion) is incorporated in the system in a well defined way.

# From emissions to human health, a complex calculation

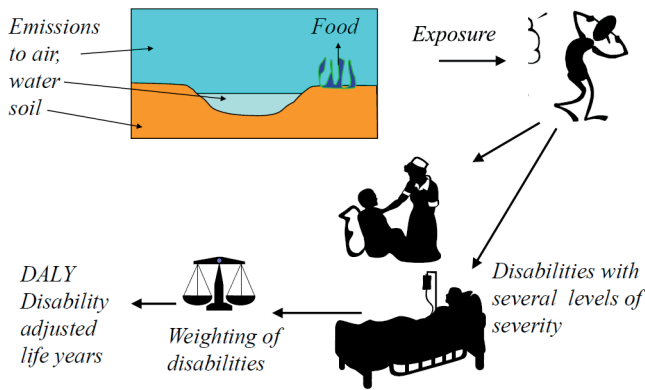


Figure A9

The calculation route of Recipe for human health (source: Pré Consultants [www.pre.nl](http://www.pre.nl))

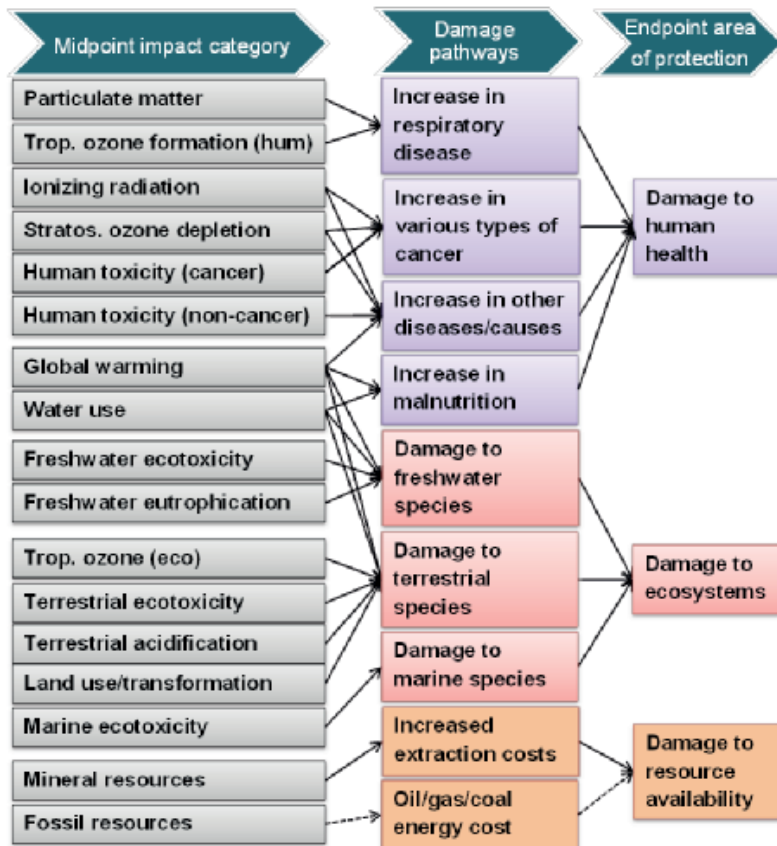


Figure A10

The midpoints and endpoints of Recipe (source: [icia-recipe.net](http://icia-recipe.net), assessed 2017)

Apart from Recipe and the Environmental Footprint, there are other single indicators, which do not suffer from the inaccurate calculations with a weighting step at the end. These are monetized indicators like the Eco-costs (see Appendix I for a short

description), and two important ‘single issue’ indicators: the Carbon Footprint (kg CO<sub>2</sub> equivalent) and the Cumulative Energy Demand (embodied energy). The advantage of these last two single issue indicators is that they are easy to understand and communicate, but the disadvantage is that they do not perform well in calculations on recycling and C2C systems. The reason is that materials depletion is not incorporated in both systems. Furthermore there is a risk in neglecting toxicity (leading to the problem of ‘Volkswagen engineering’, where they only minimised CO<sub>2</sub> emissions, and forgot to look at NO<sub>x</sub>).

Given the pro and cons of the several systems for a single indicator, the system of the eco-costs is the system which is preferred by most students at the Delft University of Technology.

### The Fast track LCA

The difference between the classic, formal, way of LCA and the Fast track way is not the calculation as such, but the sequence of calculation.

Since the single indicator is often chosen at the beginning of the study in the Goal and Scope phase (which is a requirement in ISO 14044), it does not make sense to generate the full LCI lists first, and then analyze it. It is easier to multiply the inputs and outputs directly by eco-burden factors (which are available in the Ecocosts 2023 LCA excel tables<sup>49</sup>, not only for eco-costs, but also for Recipe, Carbon Footprint, CED, and the Environmental Footprint). We call this the Fast Track LCA Method (also called the “Philips method”, since Philips Electronics was the first company which did LCAs in this way).

The enormous advantage of this approach is that the designer is directly aware of the environmental consequences of the choice on materials, since it follows directly from the tables (without the need of a computer calculation). See Fig. 3.1 and 3.2.

## Appendix III

### ISO 14040 and ISO 14044

This Appendix is not meant as an abstract, but provides a summary of the most important issues on which this LCA Guide is based. People who have to make a formal LCA study must purchase by the original ISO 14044 text<sup>50</sup>.

The most important issues of ISO **14044** are covered by the following quotes:

- Introduction: “The scope, including system boundary and level of detail, of an LCA depends on the subject and the intended use of the study. The depth and the

<sup>49</sup> See <http://www.ecocostsvalue.com/EVR/model/theory/subject/5-data.html>.

<sup>50</sup> Apart from some general remarks on LCA in Section 4 and a more precise description of the critical review in Section 7, the ISO 14040 does not have any information which is not in the ISO 14044, (ISO 14044 is the most comprehensive one), so there is no direct need to purchase both ISOs.

breadth of LCA can differ considerably depending on the goal of a particular LCA.”

- System boundary, 4.2.3.3.1: “The deletion of life cycle stages, processes, inputs or outputs is only permitted if it does not significantly change the overall conclusions of the study. Any decisions to omit life cycle stages, processes, inputs or outputs shall be clearly stated, and the reasons and implications for their omission shall be explained.”
- System boundary, 4.2.3.3.3: “The cut-off criteria for initial inclusion of inputs and outputs and the assumptions on which the cut-off criteria are established shall be clearly described. The effect on the outcome of the study of the cut-off criteria selected shall also be assessed and described in the final report.”
- LCIA methodology, 4.2.3.4: “It shall be determined which impact categories, category indicators and characterisation models are included within the LCA study. The selection of impact categories, category indicators and characterisation models used in the LCIA methodology shall be consistent with the goal of the study and considered as described in 4.4.2.2.”
- Types and sources of data, 4.2.3.5: “Data selected for an LCA depend on the goal and scope of the study. Such data may be collected from the production sites associated with the unit processes within the system boundary, or they may be obtained or calculated from other sources. In practice, all data may include a mixture of measured, calculated or estimated data.”
- Calculating data, 4.3.3.1: “Inputs and outputs related to a combustible material (e.g. oil, gas or coal) can be transformed into an energy input or output by multiplying them by the relevant heat of combustion. In this case, it shall be reported whether the higher heating value or the lower heating value is used.”
- Allocation procedure, 4.3.4.2: “The study shall identify the processes shared with other product systems and deal with them according to the stepwise procedure presented below.
  - a) **Step 1:** Wherever possible, allocation should be avoided by
    - 1) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or
    - 2) expanding the product system to include the additional functions related to the co-products, taking into account the requirements of 4.2.3.3.
  - b) **Step 2:** Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.”
  - c) **Step 3:** Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For

example, input and output data might be allocated between co-products in proportion to the economic value of the products.”

- Selection of models, 4.4.2.2.1: “The selection of impact categories, category indicators and characterisation models shall be both justified and consistent with the goal and scope of the LCA.

The selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration.”

- Selection of models, 4.4.2.2.3: the impact categories, category indicators and characterisation models should avoid double counting unless required by the goal and scope definition, for example when the study includes both human health and carcinogenicity
- Weighting, 4.4.3.4.: “Weighting is the process of converting indicator results of different impact categories by using numerical factors based on value-choices. It may include aggregation of the weighted indicator results. Weighting steps are based on value-choices and are not scientifically based. Different individuals, organizations and societies may have different preferences; therefore it is possible that different parties will reach different weighting results based on the same indicator results or normalized indicator results. In an LCA it may be desirable to use several different weighting factors and weighting methods, and to conduct sensitivity analysis to assess the consequences on the LCIA results of different value-choices and weighting methods.”
- LCIA in comparative assertions, 4.4.5: “An LCIA that is intended to be used in comparative assertions intended to be disclosed to the public shall employ a sufficiently comprehensive set of category indicators. The comparison shall be conducted category indicator by category indicator. **Weighting, as described in 4.4.3.4, shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public.**”
- Critical review 6.3: “The review statement and review panel report, as well as the comments of the expert and any responses to recommendations made by the reviewer or by the panel, shall be included in the LCA report.”

The critical review is best described in ISO 14040 Chapter 7:

- General, 7.1: “In general, critical reviews of an LCA may utilize any of the review options outlined in 7.3. A critical review can neither verify nor validate the goals that are chosen for an LCA by the study commissioner, nor the ways in which the LCA results are used.
- Need for critical review, 7.2: “The use of LCA results to support comparative assertions raises special concerns and requires critical review, since this application is likely to affect interested parties that are external to the LCA. However, the fact that a critical review has been conducted should in no way imply an endorsement of any comparative assertion that is based on an LCA study.”

- Critical review expert, 7.3.2: “The internal or external expert should be familiar with the requirements of LCA and should have the appropriate scientific and technical expertise.”
- Critical review panel 7.3.3: “An external independent expert should be selected by the original study commissioner to act as chairperson of a review panel of at least three members. Based on the goal, scope and budget available for the review, the chairperson should select other independent qualified reviewers. This panel may also include other interested parties affected by the conclusions drawn from the LCA, such as government agencies, non-governmental groups, competitors and affected industries.

## Appendix IV

### **Benchmarking products with different quality and/or functionality: the EVR (source: Wikipedia)**

#### **General**

The EVR model is a Life Cycle Assessment based method to analyse consumption patterns, business strategies and design options in terms of eco-efficient value creation. Next to this it is used to compare products and service systems (e.g. benchmarking).

The eco-costs/value ratio (EVR) is an indicator to reveal sustainable and unsustainable consumption patterns of people. The eco-costs is an indicator for the environmental pollution of the products people buy, the value is the price they pay for it in our free market economy. Example: When somebody spends 1000 euro per month on housing (in Europe: EVR approx. 0,3) it is less harmful for the environment than when 1000 euro is spend on diesel (in Europe: EVR approx. 1,0).

The EVR is also relevant for business strategies, because companies are facing the slow but inevitable internalization of environmental costs. At the moment the costs of products don't take into account the environmental damage caused by these products. This "pollution is for free" mentality is less and less accepted by communities.

The EVR makes companies aware of the relative importance of the environmental pollution of their products, and the relative risk they run that future production costs will increase because of this internalization of environmental costs. By using the EVR, companies can make decisions for their product portfolio: abandon products with low value and high environmental costs and stimulate products with high value and low environmental costs. See below under 'The model' and 'Eco-efficient Value Creation'.

#### **Background**

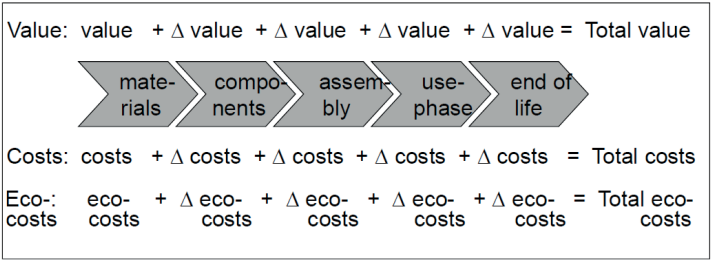
The EVR model has been introduced in 1998 and published in 2000-2004 in the International Journal of LCA, and in the Journal of Cleaner Production. In 2007, 2012, 2017, 2022, and 2023, the eco-costs system was updated. General

databases of eco-costs are provided (open source) at [www.ecocostsvalue.com](http://www.ecocostsvalue.com) of Delft University of Technology (the Netherlands). In 2010 a book named "LCA-based assessment of sustainability: the Eco-costs/Value Ratio (EVR)" was published containing the most important articles about the EVR.

**The model**

EVR = Eco-costs/value. The basic idea of the EVR model is to link the ‘value chain’ to the ecological product chain. In the value chain, the added value (in terms of money) and the added costs are determined for each step of the product ‘from cradle to grave’. Similarly, the ecological impact of each step in the product chain is expressed in terms of money, the so-called ‘eco-costs’ (See Appendix I). See Fig. A11.

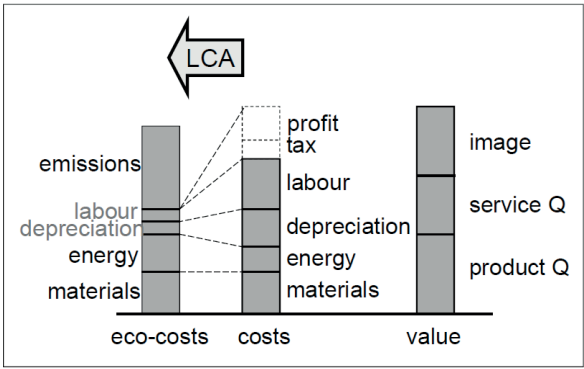
Figure A11  
The basic idea of combining the economic and ecological chain: ‘the EVR chain’



**Note that there exists also a Porter chain from the right to the left in Fig A11, starting with waste and adding value by recycling. In this way the Porter chain becomes circular.**

The EVR combines eco-cost and value to see whether a product will be successful. The product should have low environmental impact in its lifecycle (low eco-costs) and an attractive value for consumers. The value here is the market value (perceived customer value, also called fair price). Fig. A12 depicts the three dimensions of a product: the value, the costs and the eco-costs.

Figure A12  
The three dimensions of a product: the costs, the value and the eco-costs



It is a trend in society that heavy pollution of industry is not accepted anymore by the inhabitants of a country. This results in stricter regulations by countries (e.g. tradable emission rights, enforcement of best available technologies, eco-taxes, etc.). Eco-costs

will then become part of the internal production costs. This internalizing of eco-costs might be a threat to a company, but it might also be an opportunity: “When my product has less eco-burden than that of my competitor, my product can withstand stricter regulations of the government. So this characteristic of low eco-costs of my product is a competitive edge.” To analyse the short term and the long term market prospects of a product or a product service combination (Product Service System, PSS), each product or PSS can be positioned in the portfolio matrix of Fig. A13.

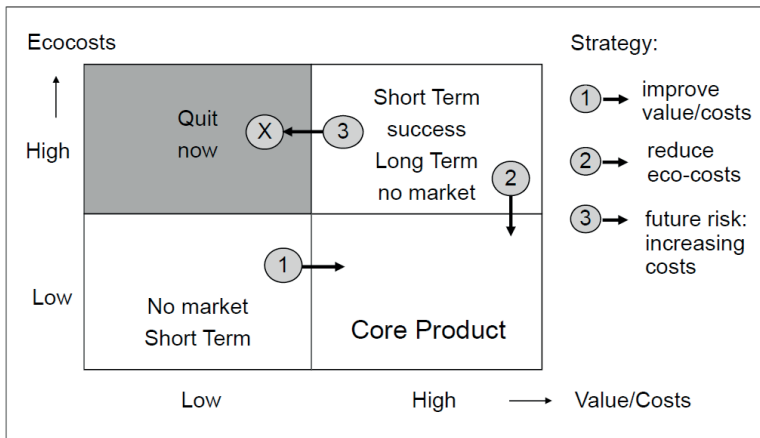


Figure A13  
Product portfolio  
matrix for  
product  
strategies of  
companies

The basic idea of the product portfolio matrix is the notion that a product, service or PSS is characterised by:

- its short term market potential: high value/costs ratio
- its long term market requirement: low eco-costs.

In terms of product strategy, the matrix results in 3 strategic directions:

- enhance the value/costs ratio of a green design to create a bigger market
- lower the eco-costs of current successful products to make it fit for future markets
- abandon products with a low value/costs ratio (not much profit, small market) and high eco-costs

For many ‘green designs’, the usual problem is that they have a low current value/costs ratio. In most of the cases the production costs are higher than the production costs of the classic solution; in some cases even the (perceived) quality is poor. There are two ways to do something about it:

- enhance the (perceived) quality of the product
- attach to the product a service (create a PSS) in a way that the value of the bundle of the product and the service is more than the value of its components.

For a product which has a good present value/costs ratio, but high eco-costs, the product and the production process have to be redesigned to lower the eco-costs. This road towards sustainability is often far more promising in the short term than the strategy of enhancing the value/costs ratio of a green design. The reason is that the



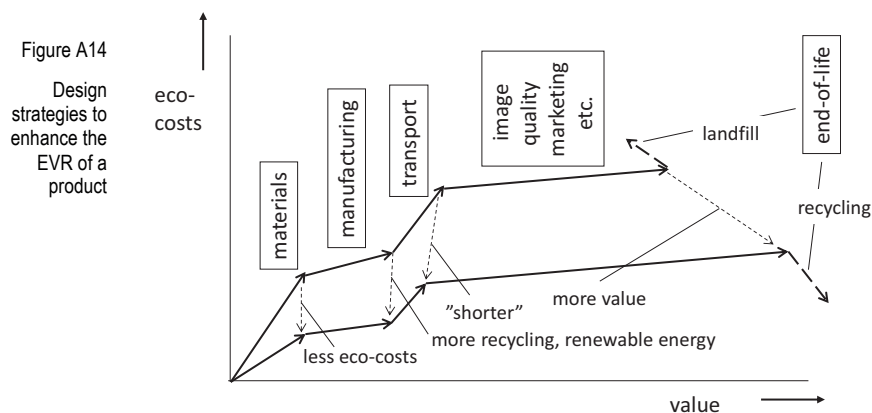
economies of scale for production and distribution are available and that the new product is marketed to an existing client base which is used to the brand name, the quality standards, the service system, etc.

Note: The most common fear of business managers is that their new green products end up with a deteriorated value/costs ratio, and hence will have a cumbersome position in the market. The stability of the governmental policy plays an important role here. When governmental regulations which level the playing field are postponed or even abandoned, proactive companies with sound product strategies are harmed. This can cause severe damage to the transition process and may lead to reluctance of players to move proactively in the future.

The most successful design options are depicted in Fig. A14.

In general, the EVR is getting better with less material and more labour. The best design strategy is [9, Section 2.2]:

- to increase value where value is high (more quality, service, life span, and image)
- to decrease the eco-costs where the eco-costs are high (a shift to bio-based materials, recycling and renewable energy)



The importance of the end-of-life solution is clearly depicted in Fig. A14. Landfill reduces the value of the total system, and leads to higher eco-costs. Recycling (as well as re-use and remanufacturing) results in an added value combined with lower eco-costs ('end-of-life credits' in LCA). Fig. A14 clearly shows that the transformation towards a circular economy fulfils the 'double obligation' of 'eco-efficient value creation' as further explained in this Appendix. However, it also shows that designing a sustainable circular system needs to address more than circularity only: other aspects as clean production, minimum transport and optimal marketing play an important role as well.

### EVR & de-linking

In economics, delinking (also known as decoupling) is often used in the context of economic production and environmental quality. In this context, it refers to the ability of an economy to grow without corresponding increases in environmental pressure. In many economies increasing production (GDP) would involve increased pressure on the environment. An economy that is able to sustain GDP growth, without also experiencing a worsening of environmental conditions, is said to be delinked.

There is a consumer's side of the delinking of economy and ecology. Under the assumption that most of the households spend in their life what they earn in their life, the total EVR of the spending of households is the key towards sustainability. Only when this total EVR of the spending gets lower, the eco-costs related to the total spending can be reduced even at a higher level of spending. There are two ways of achieving this:

- At the production side: the improvement of eco-efficiency ('lowering EVR') of products and services by the industry
- At the consumer's side: the change of lifestyle of customers in the direction of 'low EVR' products.

At the production side, our society is heading in the right direction: gradually, industrial production is achieving higher levels of the value/costs ratio and is at the same time becoming cleaner. At the consumer's side, however, our society is suffering from the fact that the consumers preferences are heading in the wrong direction: towards products and services with an unfavourable EVR (like driving in SUVs, more kilometres, intercontinental flights for holidays). These unfavourable preferences can be concluded from Fig. A15.

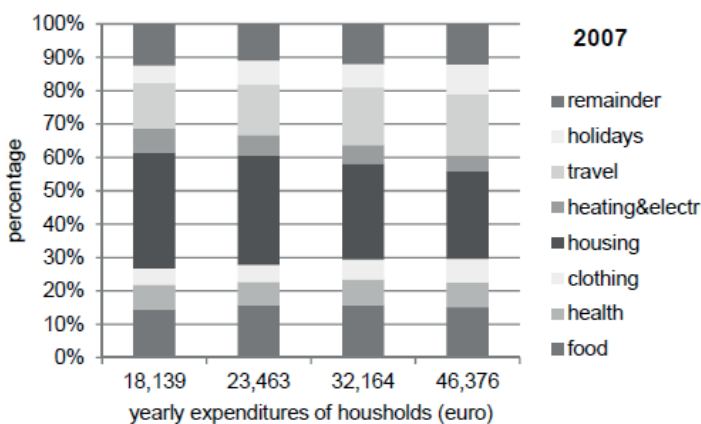
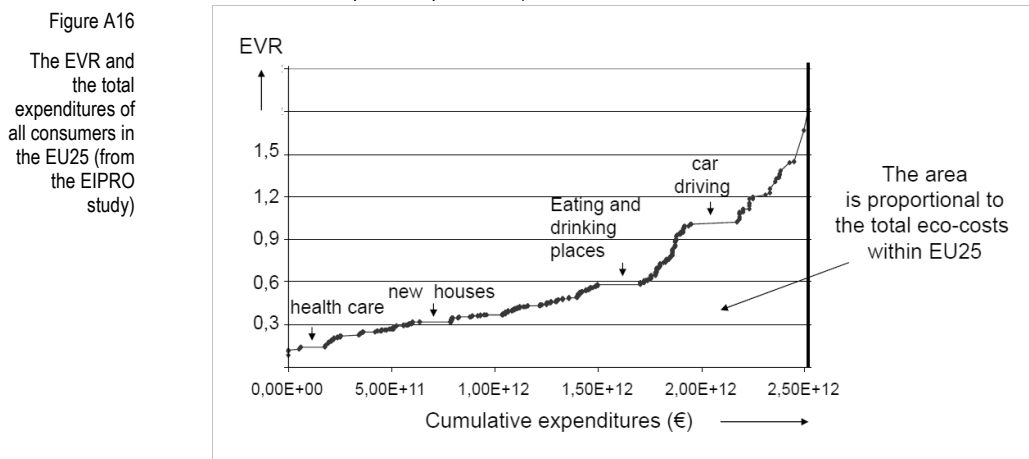


Figure A15  
The consumer's side: preference of expenditures in Dutch households

Fig. A15 shows that people in The Netherlands (and probably in the other EC countries as well) spend relatively more money on cars and holidays when the have

more money available. Other studies show that people tend to have intercontinental holidays at the moment they can afford it. This shift in consumer spending will become a big problem in the near future, since the EVR of e.g. housing and health care is much lower than the EVR of transport and (inter)continental holidays by plane.

Fig. A16 shows the EVR (= ecocosts/price) on the Y-axis as a function of the cumulative expenditures of all products and services of all citizens in the EU 25 on the X-axis. The data is from the EIPRO study of the European Commission (EIPRO = environmental impact of products).



The area underneath the curve is proportional to the total eco-costs of the EU25. Basically there are two strategies to reduce the area under the curve:

- ask industry to reduce the eco-costs of their products (this will shift the curve downward)
- try to reduce expenditures of consumers in high end of the curve, and let them spend this money at the low end of the curve (this will shift the middle part of the curve to the right).

The question is now how designers and engineers can contribute to this required shift towards sustainability and what this means to product portfolio strategies of companies. The solution is eco-efficient value creation.

### Eco-efficient Value Creation

The way towards sustainability requires a double aim in product innovation, see Fig. A17:

- lower eco-costs, and at the same time
- higher value (a higher market price).

We call this: eco-efficient value creation. The reason we need value creation for eco-efficient products is threefold:

- the higher price in the market is required to cover the higher production cost of green products (note that a higher price is only accepted by the consumer when the perceived value is higher, otherwise the consumer will not buy the product)
- the higher price prevents the ‘rebound effect’ of savings
- lowering the EVR appears the key to a sustainable development at the level of countries (Fig. A17).

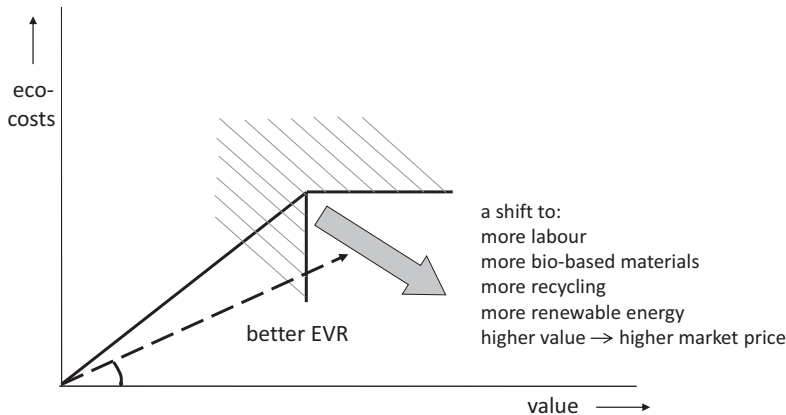


Figure A17  
The double objective for design & engineering: less eco-costs, more value

Below, an example of eco-efficient value creation is given. The example is the introduction of the hybrid Lexus in the USA:

- the customer value has increased, by emphasising its combined power and comfort (from the advertisement in the US: “... While it may have a V6 engine under the hood, the extra boost from the electric-drive motor gives the vehicle the acceleration power of a V8 ... and the noise levels in Lexus hybrid vehicles have been reduced even more”)
- the eco-costs of driving are lower, since its excellent overall fuel economy.

Note that the acceleration of a car is an interesting issue in terms of value. High acceleration is associated with expensive sports cars (Porsche, Ferrari). But people who buy these fast cars hardly use it. For these people acceleration is more part of the image of the product than it is part of the product qualities they use on a daily basis.

### Environmental Benchmarking in LCA

Life Cycle Assessment (LCA) is the generally accepted method to compare two (or more) alternative products or services. A prerequisite for such a comparison is that the functionality (‘functional unit’) and the quality of the alternatives are the same (you cannot compare apples and oranges in the classical LCA). In cases of product design and architecture, however, this prerequisite seems to be a fundamental flaw in the application of LCA: the designer or architect is aiming at a better quality (in the broad sense of the word: including intangible aspects like beauty and image), so the new design never has the same quality. In some cases the functionality of the design is not the same, since the design solution is limited by a maximum budget, in some cases the

functionality is the same, but the higher quality results in a higher price. In all these cases a single indicator in LCA (like the eco-costs) is not suitable for environmental benchmarking. In these cases however, it does make sense to compare the design alternatives on the basis of the eco-costs/value ratio (EVR), where the value is the perceived customer value (the fair price). See EVR & de-linking.

Example 1. Different types of armchairs differ in terms of comfort, aesthetics, etc. rather than in terms of functionality. A classical LCA (with a single indicator like eco-costs, carbon footprint, etc.) does not make sense here. Selection on the basis of EVR, however, is the key to a sustainable consumption pattern. The chair with the lowest EVR is the best solution in terms of sustainability.

Example 2. In LCA, the comparison of a new building and a renovated building is in the majority of cases not possible, since, in practice, both solutions differ in almost all quality aspects (tangible as well as intangible). However, the solution with lowest EVR is the best in terms of sustainable consumption.

Note that the renovated building is the best solution in most of the cases, because it has the lowest EVR in the production phase. However, in some cases the renovated building is not the best solution, because of unfavourable energy consumption (high EVR) in the use phase.

## Appendix V

### How to apply Idemat (and Ecoinvent) data for recycling and re-use

Section 5 deals with the issue of End-of-Life and recycling of products. The subject of recycling, however, generates a lot of questions on how to apply the specific rows in the excel tables of Idemat and Ecoinvent (see [www.ecocostsvalue.com](http://www.ecocostsvalue.com) tab data). The question is: “when do you apply which LCA row in practice?” For some cases, the answers on specific questions are given below<sup>51</sup>.

#### Case 1. Open-loop upcycling of metals and polymers

When a metal is bought from the open market, the Idemat “trade mix” lines must be applied. Such an LCI is the combination of primary (virgin) material and secondary (recycled) material. Idemat uses the market mix ratio given by Eurostat (EoL-RIR). Ecoinvent V2 calls this “at regional storage”, Ecoinvent V3 calls it “market for”; however, Ecoinvent global recycling percentages are less recent than those from Eurostat, so Idemat data are recommended.

Often, the end-of-life scenario is not known. For Western Europe it can be assumed that nearly 100% of metals is open loop upcycled, except from metals in electronic

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<sup>51</sup> This issue is also dealt with in Appendix IX of [9]

equipment. There is **no credit in open loop recycling for these metals to be recycled**, since open loop recycling is counted in the input of the system by the market mix ratio, as explained in Section 5.5. The eco-costs of the waste handling, including transport, should be taken into account. The LCI data are provided under the heading “Materials, metals, waste metals (scrap)” in the Idemat tables. In the Ecoinvent tables, data for waste handling can be found under “waste treatment”. All waste treatment data include (scenarios for) transport of waste. Since these data are dominated by transport, and since the transport is taken for a Swiss scenario (short transport distances), it is recommended not to use these ‘default’ Ecoinvent tables. It is better to define the specific transport scenario for end-of-life transport of waste. Note that the impact on the total life cycle is usually rather small.

Recycling of polymers is an important issue in the circular economy. However, open loop upcycling systems are still under development. Only a few polymers, like PET from the process of Ionika, can be bought on the market as open loop upcycled material. For other polymers pyrolysis is chosen as the most promising route for upcycling in Idemat. **primary-secondary**). In Western Europe, it can safely be assumed for end-of-life that polymers go to a municipal waste incinerator (apply then the Idemat data ‘waste treatment, municipal waste incineration with electricity’). Polymers outside Western Europe go to land-fill (only a few big cities have a municipal waste incinerator with electricity production).

### Case 2. Closed-loop upcycling of metals and mechanical recycling of polymers

The situation of closed-loop upcycling in LCA is a bit more complex.

For metals, the best approach is to calculate the quantity in the closed upcycling loop, and apply that for the input flow, using the Idemat LCA data for the ‘secondary’ material. For the remaining quantity (which is bought from the market), the ‘trade mix’ data from Idemat is to be applied.

Another approach for metals is to take the ‘trade mix’ for 100% of the input flow, and apply the ‘recycling credit’ for the quantity of the closed-loop system. In Idemat, this credit is counted only for the primary part of the ‘trade mix’ input (double counting is avoided in Idemat).

For polymers the situation is rather simple, since there is no ‘trade mix’. The main recycle flows in plastics apply “mechanical recycling”, mostly related to plastic bottles: rPE, rPET, rPP, rPS and rPVC. It is a form of downcycling, but closed loop recycling of uncoloured bottles can keep the quality degradation to a minimum <sup>52</sup>).

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<sup>52</sup> Colored plastics are downcycled as well (e.g. ending up in street furniture). In the Idemat tables it is called “moulded recycled mixed polymer” (in the group “recycled plastics”)

### Case 3. Downcycling

Materials to be recycled in an open-loop system end up in a 'end-of-waste' stockpile (the so-called **cut-off point**, not with any credit, nor debit). Materials from such a stockpile, which can be input for an upcycling as well as a downcycling process, start with  $\text{eco-cost} = 0$  in the process for the new product. **In such an approach, the waste materials neither have a credit nor a debit in LCA, regardless of the value (price) of the waste. See also [9, Appendix IX]**

Secondary products from waste or downcycled materials (e.g. carton boxes from waste paper) must be calculated as explained at page 55-56, and in Fig. 5.12: the final end-of-life (i.e. incineration or landfill) must be shared between the primary and secondary products. The source material for the secondary product has  $\text{eco-costs} = 0$ .

In the case of mechanical recycling (re-melting) of clean and pure plastics (like PET bottles), the downcycled product is often blended with the virgin product. The eco-costs of such a blend is obviously calculated from the virgin/downcycling ratio.

In the quest for products made out of waste, design proposals evolve which have the disadvantage that the end-of-life of these secondary products cannot be the same as the end-of-life of the primary product. For instance:

- clean plastic waste (without colour) is given a colour in the secondary product
- plastic waste is mixed with glass fibre in the secondary product

It is obvious that the classical recycling credit approach cannot be applied here

### Case 4. Re-use

The eco-costs of something which can be re-used is derived from the eco-costs of the new product by economic allocation (Section 6.2), fully in line with the approach of Section 5.6.

The formula is:

$$\text{eco-costs of the old product for re-use} = \text{eco-costs of the new product (from cradle-to-grave)} \times P_o / P_n$$

where  $P_n$  = price of the new product and  $P_o$  = price of the old product

Note that the ownership during the lifespan of a product is not a formal issue in LCA (the analysis is independent of change of ownership). However, when a distinction is needed between the first and the subsequent user(s) economic allocation is the way to make such a distinction.

## Appendix VI

### Foreground and Background Systems

The Foreground System in LCI is the system under study: it has its system boundary with input flows (materials, energy, transport) and its output flows: the product, its waste, but also its emissions to air, water and soil, see Fig.5.1, Section 5.1. The eco-costs of these emissions are given in the excel table “Ecocosts 2023 data on emissions and resources depletion.xlsx”. By means of this table, the eco-costs of every system can be calculated when the LCI data are known (just as it is the case in Simapro or Gabi). It is the choice of the LCA practitioner to define the system boundary of the Foreground system. By this choice, it is decided what is foreground and what is background in the total calculation.

The Background Systems are the systems outside the system boundary of the foreground (i.e. the systems which deliver the energy, fuels, chemicals, components, etc.). For these input flows, the LCAs are calculated from LCI databases which are based on generic data. The results are provided in the Idemat and the Idematapp tables. When you have no information on the origin of an input flow, it does make sense to take these generic data. However, when you know the supplier and its supply chain, it is obviously better to ask for the specific LCI of that specific product. In fact, the LCI of the supplier becomes then part of the foreground system. In the past it was not realistic to ask the supplier to make a rigorous LCA, since that is a lot of work. However, more and more suppliers have an LCA of their products, because it is the basis of an EPD (Environmental Product Declaration), and the EPD databases are growing rapidly (the reason is that EPDs are becoming a “licence to sell” in certain markets, like the building industry). The more data on supply chains become available, the more specific and accurate an LCA can be made.

The reason that the Fast Track LCA method is becoming quite popular under industrial designers and architects is because of the fact that their products are assemblies, with hardly or no relevant toxic emissions in the final assembly step. In such a situation the relevant emissions are in the background processes (the supply chain), so that the total eco-costs can be calculated from the Idemat tables only. The fact that generic data can be replaced by specific data of manufacturers with EPDs, makes that LCA becomes quite doable (for the conversion from EPD data to eco-costs, see Appendix VII).

An example on the issue of foreground versus background data is given for the horticultural sector: the production of tomatoes in a Dutch greenhouse with a CHP (combined heat and power system) with a gas engine.



Horticulture systems are quite complex, so the choice on what to calculate in the foreground system and what to regard as a background system is quite relevant.

Apart from the greenhouse itself (glass, aluminium, steel, concrete, et cetera) the main input flows for the process are: heat, light, CO<sub>2</sub> as fertilizer, water, plants (from seeds), fertilizer, pesticides, et cetera. The list of emissions depends on the system boundaries, see Fig A18a, A18b, A18c.

The background systems for Fig A18a are all available in the Idemat and Ecoinvent tables, but it is much better to incorporate the CHP system in the foreground system, see Fig A18b, in order to apply specific data. The input is then natural gas, and the production of heat, light and CO<sub>2</sub> fertilizer become internalized in the foreground system. CO<sub>2</sub> is now an emission.

Note that part of the CO<sub>2</sub> is emitted directly from the greenhouse, and part of it is emitted via the tomatoes (after consumption). The same applies for the emissions of pesticides.

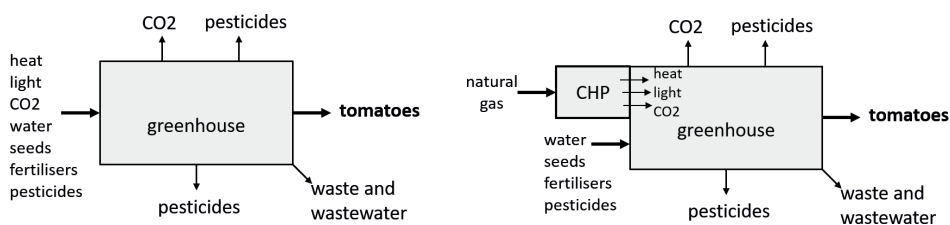


Figure 18a Tomato production, foreground greenhouse only

Figure 18b Tomato production, foreground greenhouse + CHP

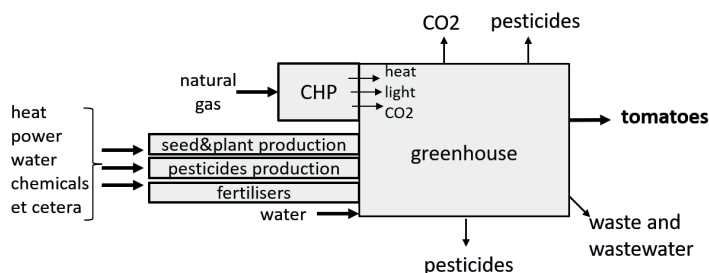


Figure 18c Tomato production, foreground greenhouse + CHP + seed & plants + pesticides + fertilisers

Fig 18c depicts a foreground system which is normally regarded as 'the total foreground', however, one should realise that there are still much processes in the background, such as electrical power, chemicals and water for the processes, and transport. In fact, every LCA has processes in the background, see also Fig. 2.5.

## Appendix VII

### Converting EPD data in eco-costs (cradle-to-gate)

Important sources of eco-costs of products in the building industry are EPDs (Environmental Product Declarations). Germany and France have databases with hundreds of products (<http://ibu-epd.com/>, [www.inies.fr](http://www.inies.fr)). Although the full LCIs are often not available, the major information which is required to make an estimate of eco-costs is given in the text of the documents. The fact that the Calculation Rules for the building industry have recently been standardised in EN 15804, makes that EPDs can be used now for environmental comparison..

The structure of an EPD calculation is depicted in Fig. A18.

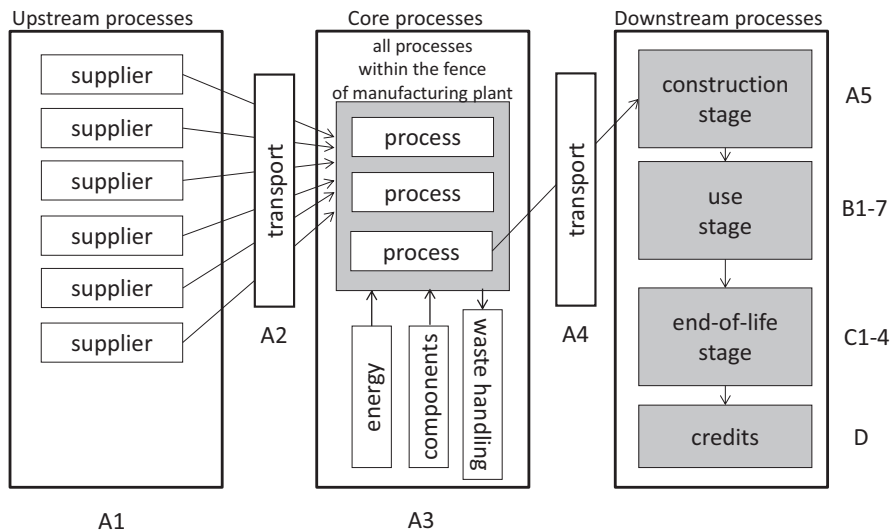


Figure A19

The calculation structure of an EPD according to EN 15804

By far the most EPDs are cradle-to-gate. For these EPDs only the first 3 blocks are included:

- A1 all upstream processes (also called background processes, see Appendix VI)
- A2 transport to the production site
- A3 all foreground processes at the production site plus outsourced activities

Since most of the manufacturers hate to give detailed information on their core processes, by far the most EPDs provide only information on the sum of A1+A2+A3.

There are two ways to calculate the eco-costs of EPDs: a method A and a method B. Method A is the most accurate one, based on available data in the text about the

materials in the product. Method A is basically the 'normal' Fast Track method, with a slight complication to calculate the energy requirements in block A3 (if significant). There are, however, many EPDs where detailed data on the materials in the product is missing. Then method B is required, based on the midpoints which are given in each EPD. Do not mix method A and B, to avoid double counting.

#### Eco-costs calculation method A

The calculation method A starts from the assumption that the eco-costs can be calculated by adding up the eco-costs from all background processes (as explained in Appendix VI). The best way to calculate the cradle-to-gate eco-costs of such a product is to start with the 'bill of materials' (the materials composition) of a product, add the estimated production waste for each material (especially important for wooden products like window frames), and multiply it with the ecocosts/kg of the Idematapp data tables. A simple summation results then in the total eco-costs of block A1, which is by far the most important contribution to the total eco-costs cradle-to-gate.

Add for block A2 the inland transport scenario (keep in mind that the Idematapp data are calculated for products from the Rotterdam harbour, but that might be replaced by any other big European harbour).

The emission of toxic substances of block A3 is negligible for most production sites in Western Europe<sup>53</sup>. The only unknown eco-costs are the eco-costs of heat and electricity. When the EPDs give details on the energy use in block A3 (the so called PENRE = Primary Energy Non-Renewable, plus the PERE = Primary Energy REnewable), the eco-costs of it can be calculated by multiplying the PENRE+PERE with the eco-costs of Idematapp 2023 Industrial Heat of gas (0.0115 euro/MJ).

Unfortunately most EPDs give only data for block A1+A2+A3 *in total*. Then there is a simple way to estimate the eco-costs of heat and electricity of block A3 in three steps: Step 1. Calculate the carbon footprint (kg CO<sub>2</sub>e) of your input so far, and subtract that from the carbon footprint of A1+A2+A3 of the EPD. The result is the carbon footprint of block A3.

Step 2. Divide the carbon footprint (kg CO<sub>2</sub>e) by 0.083 to get the equivalent amount of MJ 'Industrial Heat, General' (or, divide by 8.3 to get the amount in 100 MJ)..

Step 3. Add the MJ industrial heat to your calculation. The result is that the total eco-costs of heat and energy of block A3 is added to your LCA.

---

<sup>53</sup> In many Western European countries, the emissions of the production site can be found by checking the maximum allowed emissions in the permits of the local nuisance law. In the Netherlands the emissions of production sites can be found in the National Pollutant Release and Transfer Register at [www.emissieregistratie.nl](http://www.emissieregistratie.nl).

The eco-costs of these emissions can be found by multiplication of the emission data per kg in the table Ecocosts2023\_V1-0\_midpoint\_tables.xlsx excel file at [www.ecocostsvalue.com](http://www.ecocostsvalue.com)

### Eco-costs calculation method B

The calculation method B starts from the assumption that the eco-costs can be calculated by adding up the eco-costs from all emissions and resources, regarding everything as one foreground system (as explained in Appendix VI).

For products which are made from renewable or non-scarce materials only (e.g. wood from plantations, sand, stone), the 'eco-costs of metals depletion' is negligible. The total eco-costs can then be calculated on the basis of the impact categories as given in the EPD, and the conversion factors of Table A1. Note: the other emissions are negligible.

| Impact Category in EN 15804                                      | Quantity and Unit                           | Eco-costs |
|------------------------------------------------------------------|---------------------------------------------|-----------|
| for abiotic depletion potential for fossil resources, take PENRM | 1 MJ, net calorific value                   | 0.016 €   |
| Acidification for soil and water                                 | 1 kg SO <sub>2</sub> equiv                  | 9.28 €    |
| Ozone Depletion                                                  | 1 kg CFC 11 equiv                           | 0.000 €   |
| Global Warming                                                   | 1 kg CO <sub>2</sub> equiv                  | 0.123 €   |
| Eutrophication                                                   | 1 kg (PO <sub>4</sub> ) <sub>3</sub> -equiv | 5.00 €    |
| Photochemical ozone creation                                     | 1 kg Ethene equiv                           | 9.85 €    |

Table A1  
The relationship between impact categories in EN 15804 and eco-costs

This calculation method can also be used when the quantities of metals, are earth, and fossil based polymers are relatively low. The 'eco-costs of resource depletion' (containing depletion of metals and fossil fuels) from Table A2<sup>54</sup> must be added then to the calculation on the basis of the impact categories of Table A1.

Table A2, at the next page, shows a list of the most common materials (see the Idematapp table of footnote 54 for other materials, such as precious metals, rare earth, paints, textiles, specific wood species, and special plastics). Note that the eco-costs of resource depletion in these tables are from-cradle-to-gate, including the required production facilities.

**Sometimes the type of plastic is not specified (this is often the case for EPDs of paint). Then the PENRM data in the EPD can be used (PENRM = Primary Energy Non Renewable use as raw Materials). This indicator is in MJ, net calorific value. The conversion factor to 'Eco-costs of resource depletion' (euro/kg) is 0.0186 (euro/MJ).**

---

<sup>54</sup> For materials which are not in this table, and for specific types of wood, see at [www.ecocostsvalue.com](http://www.ecocostsvalue.com), tab Data, Tools, Books

| materials in EN 15804                  | Eco-costs of resource scarcity (euro/kg) | materials in EN 15804                          | Eco-Eco-costs of resource scarcity (euro/kg) |
|----------------------------------------|------------------------------------------|------------------------------------------------|----------------------------------------------|
| Aluminium trade mix                    | 0.94                                     | BR and IIR (butadiene rubber and butyl rubber) | 0.70                                         |
| Copper wire, plate, pipe, trade mix    | 1.89                                     | EPDM (ethylene propylene diene monomer rubber) | 0.91                                         |
| Lead trade mix                         | 0.39                                     | EVA (ethylene vinyl acetate rubber)            | 0.63                                         |
| Magnesium trade mix                    | 0.14                                     | SBR (Styrene butadiene rubber)                 | 0.69                                         |
| Nickel trade mix                       | 8.27                                     | Silicone rubber                                | 0.32                                         |
| Silicon                                | 1.10                                     | ABS (Acrylonitrile butadiene styrene)          | 0.85                                         |
| Zinc trade mix                         | 1.09                                     | PA 66 (Nylon 66, Polyamide 6-6)                | 0.67                                         |
| Steel beams, pipes, sheet, market mix  | 0.04                                     | PB (Polybutylene)                              | 0.85                                         |
| Cast irons                             | 0.04                                     | PC (Polycarbonate)                             | 0.79                                         |
| Inox X5CrNi18 (304) EU, USA            | 0.36                                     | PE (Polyethylene)                              | 0.85                                         |
| Inox X5CrNiMo18 (316) EU, USA          | 0.64                                     | PEEK (Polyetheretherketone),                   | 0.98                                         |
| Brass CuZn40Pb                         | 1.50                                     | PET (bottle grade)                             | 0.62                                         |
| Recycled Inox (market average)         | 0.02                                     | PMMA (Polymethyl methacrylate)                 | 0.60                                         |
| Bitumen                                | 0.85                                     | POM (Polyoxymethylene, polyacetaal)            | 0.4                                          |
| Red clay brick, sand-lime brick, tiles | 0.00                                     | PP (Polypropylene)                             | 0.85                                         |
| Concrete                               | 0.00                                     | PS (polystyrene)                               | 0.92                                         |
| Sand and gravel                        | 0.00                                     | PTFE (Teflon, Polytetrafluoroethylene)         | 0.64                                         |
| Glass, uncoated for windows etc.       | 0.00                                     | PVC (Polyvinylchloridex)                       | 0.38                                         |

Table A2 The eco-costs of resource depletion to be applied to EN 15804 calculations (eco-costs 2023 data)

Three general remarks:

1. The EPDs of wood are often a bit confusing, since they are not always made according to the current consensus in LCA how to deal with carbon sequestration (storage from carbon in wood). In some EPDs the stored carbon is subtracted from the LCA result (approximately 1.85 kg CO<sub>2</sub> per kg dry wood), which leads to an overall negative carbon footprint score, and which is not general practice in LCA. Often this amount of carbon sequestration is not specified separately, so that it is better to calculate the eco-costs of wood on the basis of the use of energy in block A1+A2+A3 (the PENRE). Take Idemat 2023 Energy gas (heat) = 0.0115 (euro/MJ) as conversion factor.
2. Note that the eco-costs of an EPD is in most of the time lower than the eco-cost of Idemat and Ecoinvent LCIs. There are three main reasons for that:
  - a. EPDs are calculated excluding the infrastructure which is needed (e.g. the facilities for production). It may cause up to 15% difference between Method A and B.
  - b. Manufacturers who make EPDs, perform in most of the cases better than the average manufacturing practice (the reason a manufacturer

invests in time and money to make an EPD is often that the manufacturer believes that the product is better than the average product in the market). Idemat and Ecoinvent data are averages of older processing techniques, instead of the best Practices.

- c. Manufacturers who make EPDs try to keep the eco-score as low as possible, e.g. by taking short transport distances in their scenarios.
3. Calculation method A gives a more accurate (slightly higher) result, since the eco-costs contain more, rather important, impact categories than specified in the old EN 15804, like fine dust, ecotoxicity, and human toxicity. The new EN 15804 (+A2 2019) has a wider range of impact categories



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Note: this reference list is kept as short as possible. Long reference lists can be found in: [2] [8] [10], and further in the *Int. J. of LCA* and the *J. of Cleaner Production*.

It is recommended to use this LCA guide in combination with:

- [11] Vogtlander, J.G.; A quick reference guide to LCA data and eco-based materials selection; Delft Academic Press, Delft



# Abbreviations

|         |                                                                                                                                           |
|---------|-------------------------------------------------------------------------------------------------------------------------------------------|
| C2C     | Cradle-to-Cradle                                                                                                                          |
| CML     | Center voor Milieukunde Leiden (Leiden University. Institute of Environmental Sciences), also the name for characterisation tables in LCA |
| CED     | Cumulative Energy Demand                                                                                                                  |
| CNC     | Computer Numerical Control                                                                                                                |
| EIPRO   | Environmental Impact of Products (study)                                                                                                  |
| EVR     | Eco-costs/Value Ratio                                                                                                                     |
| ENTSO-E | European Network of Transmission System Operators for Electricity                                                                         |
| EPD     | Environmental Product declaration                                                                                                         |
| EU      | European Union                                                                                                                            |
| FSC     | Forest Stewardship Council                                                                                                                |
| FU      | Functional Unit in LCA                                                                                                                    |
| GDP     | Gross Domestic Product                                                                                                                    |
| GLO     | Global (in Ecoinvent)                                                                                                                     |
| GWP     | Greenhouse Warming Potential                                                                                                              |
| LCA     | Life Cycle Assessment                                                                                                                     |
| LCI     | Life Cycle Inventory                                                                                                                      |
| LCIA    | Life Cycle Impact Assessment                                                                                                              |
| LCC     | Life Cycle Costing                                                                                                                        |
| ILCD    | International Reference Life Cycle Data System                                                                                            |
| IPCC    | Intergovernmental Panel on Climate Change                                                                                                 |
| ISO     | International Organization for Standardization                                                                                            |
| PAH     | Polycyclic Aromatic Hydrocarbon                                                                                                           |
| PM      | Particulate Matter (dust)                                                                                                                 |
| RER     | European (in Ecoinvent)                                                                                                                   |
| TEU     | Twenty feet Equivalent Unit (container for sea transport)                                                                                 |
| UCTE    | Union for the Coordination of the Transmission of Electricity                                                                             |
| US      | United States (in Ecoinvent)                                                                                                              |
| WLC     | Whole Life Costing                                                                                                                        |

Note: for abbreviations of countries in Ecoinvent LCI names, see the excel file on [www.ecocostsvalue.com](http://www.ecocostsvalue.com) tab data: Idemat2017+EI\_V3-3.xlsx , tab 'full list Ecoinvent' column AI and AJ

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## A 'Fast Track' guide to LCA

Life Cycle Assessment (LCA), a well defined method to calculate the environmental burden of a product or service, has been made so complex that it seems to be a job for specialists only.

This 'Practical Guide' to LCA gives a hands on approach for students, designers, architects, and business managers with limited time. Starting with the common sense, and building on it with practical solutions for, sometimes, complex issues (like recycling).

To assess the sustainability of your innovative ideas, practical guidance is given during the decision making process. It does not take a lot of time and a lot of money. The 'Fast Track' LCA of this guide can be made in hours, and is just as accurate as the classical LCA.

This guide shows also the way to enable cradle-to-cradle calculations:

- a. It provides practical solutions to calculate the impact of recycling
- b. It shows how to start with LCA in the early ('fussy') design stages ('Life Cycle Design')

Contents: 1. Introduction • 2. The system you want to study • 3. The step by step approach and LCA as an iterative process • 4. Transport and the use phase • 5. By-products, waste, recycling • 6. Services in LCA • 7. Cradle-to-Cradle • 8. Carbon sequestration in wood • 9. Land-use, water and other issues • 10 Appendices • References •

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