A practical guide to LCA

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), 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) 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’ (Vogtländer et al., 2011).

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A practical guide to LCA for students designers and business managers

Cradle-to-Grave and Cradle-to-Cradle

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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 recent LCA manual of the International Reference Life Cycle Data System of the EU 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, Ecological Scarcity, Ecoindicator 99, Recipe, Carbon Footprint, etc.

My hope is that this book will not only be used by students, but also by designers, architects, and business managers (and their consultants), since they all need a practical guide to assess the sustainability of their innovative ideas.

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Contents

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[1], 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 a 3 common misunderstandings about LCA:

1. To make an LCA requires a lot of time (at least 2 - 3 month) 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

[1] 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[2]. 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 (ILCD, 2010). 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 reporting.

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 [1]).
- 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 the LCI and the LCIA, but on the comparison of design alternatives.

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

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[2] '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 (ISO, 2006) and LCA manuals (ILCD, 2010)(Guinée, 2002).
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, available in databases (e.g. the Idemat 2010 database or the Ecoinvent database with over 4500 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'[3] and must go from 'cradle-to-grave'. In many cases this is not an easy starting point:

- what is the functional unit of an armchair? What kind of arbitrary assumptions do we take for its maintenance and 'End of Life'?

[3] 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 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_2, 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 (recently, such a 'plug-in' for ArchiCad became available[4] for architects, to check the costs and the eco-costs of the design).

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.

The website www.winket.nl provides extensive tables on eco-costs of building components, based on tables for materials and processes at www.ecocostsvalue.com (tab data).

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[4] Eco-costs tables are available on www.ecocostsvalue.com (for materials, energy, transport), and on www.winket.nl (for buildings). Eco-costs plug-ins are available for CES Edupack (Cambridge Engineering Selector), password on request, website: http://www.grantadesign.com/download/teachingmaterials/users.htm#matdb and for ArchicCad software at www.kubusinfo.nl , see also Appendix I.

house:	
net m²	196
volume (m³)	705

Table 1.1. The costs and the eco-costs of a building cradle-to-site. Source www.winket.nl.

subsystem	quantity (m²)	costs (€/m²)	costs (€)	eco-costs (€/m²)	eco-costs (€)
foundation	133	232.5	30.919	81.7	10.860
outer walls	190	184.2	34.994	42.1	8.004
outer walls openings	73	474.8	34.661	207.1	15.117
inner walls	64	166.2	10.634	36.0	2.301
inner walls openings	29	177.0	5.132	53.6	1.555
floors	269	111.2	29.902	28.9	7.770
roof	180	289.8	52.160	62.6	11.259
structure elements	294	13.2	3.869	4.3	1.264
heating & electrical			26.213		3.757
miscellaneous			30.429		9.816
total construction costs			258.913		71.703

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[5], 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 (ILCD, 2010).

There are other practical issues, which can not 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:

- transport of light freight
- choice of 'energy mix' for gas and electricity
- combustion of waste at the End of Life

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5 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 separate (Vogtländer, 2010).

- 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^3.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 modelled in LCA is still under discussion. In the ISO 14044 (ISO, 2006) it is hardly defined. In the manual of the EU (LICD, 2010) some alternative solutions are provided (applying either 'attributional modelling' or 'consequentional modelling'), however, the text is not easy to understand for non-specialists. This guide provides practical choices (applying 'consequentional modelling' and the 'recyclability substitution approach'), which are easy to understand and easy to apply in practice. 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?

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 Figure 2.1. The calculation is based on a system approach of the chain of production and consumption, analyzing 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

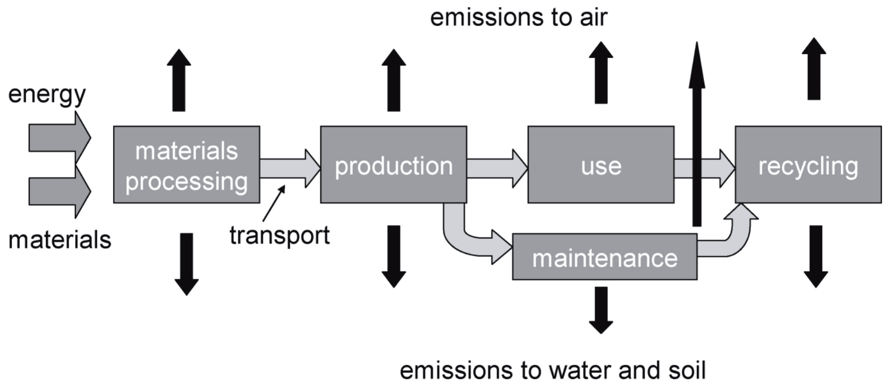


Figure 2.1. The basic calculation system of LCA

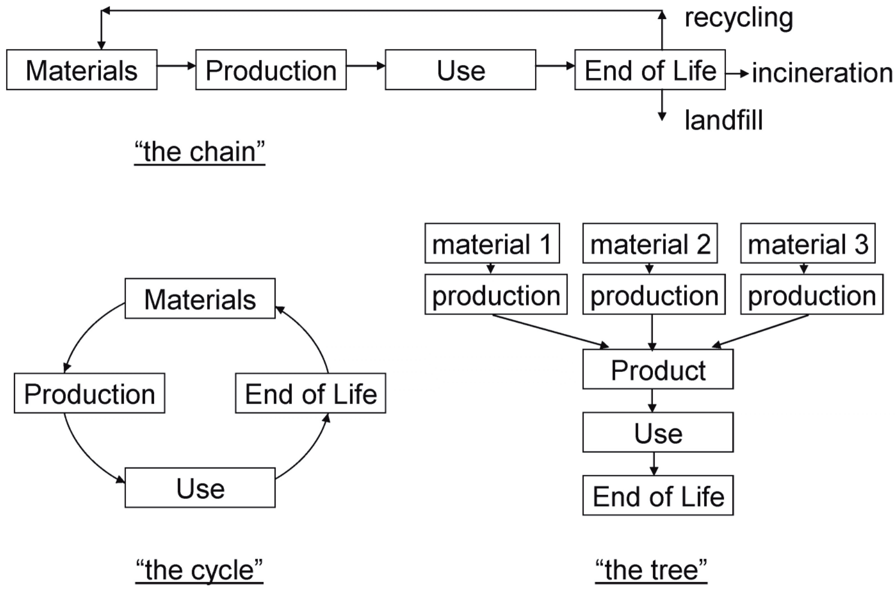
Each LCA starts with the definition of the Processes inside the 'black boxes' of Figure 2.1. Such a process definition is unique for each case. When the definition of the process system is wrong (or not suitable for the goal of the study), the output of the calculation will be wrong. The biggest mistakes 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 Figure 2.2):

a. 'the chain' (from cradle-to-grave)
b. 'the cycle' (C2C)
c. '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[6], and the fact that in real life recycle loops are 'open' rather than 'closed'[7] in 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. Figure 2.3 depicts the alternative solutions of the total system.

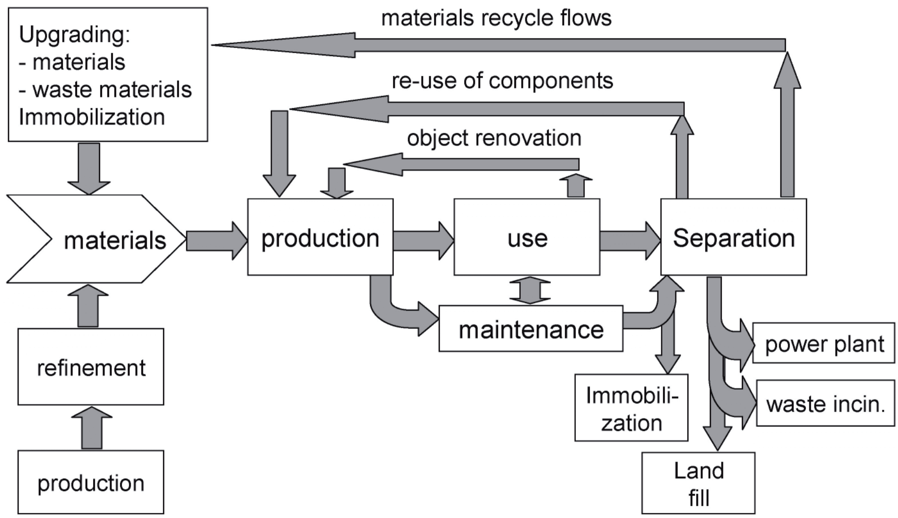


Figure 2.3. The flow of materials in the Life Cycle

Figure 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')

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

7 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).

- 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:

- 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[8]. 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[9]
- gate-to-grave, which is normally from the end-user to the End of Life (landfill, combustion, etc., including transport, disassembling or demolishing).

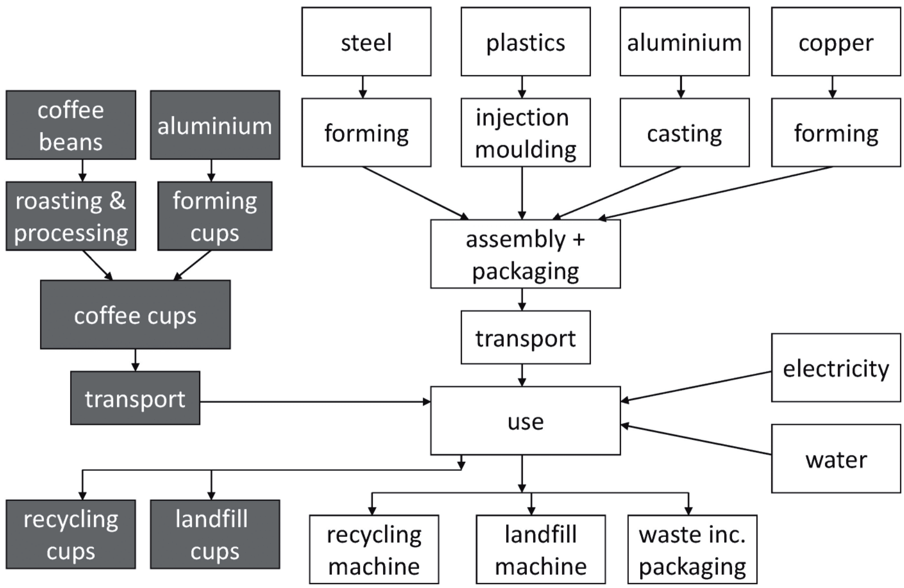

Figure 2.4. The input of a computer program (simplified), depicted as 'the tree'. Case: a modern coffee machine

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

8 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)

9 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.

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 Figure 2.4):

- 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 Figure 2.5[10]. 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. Figure 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

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[11].

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[10] Note that Figure 2.5 is also called a 'tree'. The tree is depicted upside down (in comparison to Figure 2.2 and 2.4), as it is done in computer programs like Simapro.

[11] Note that the cascading as depicted in Figure 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.

Figure 2.5. Each LCA system has its system boundary

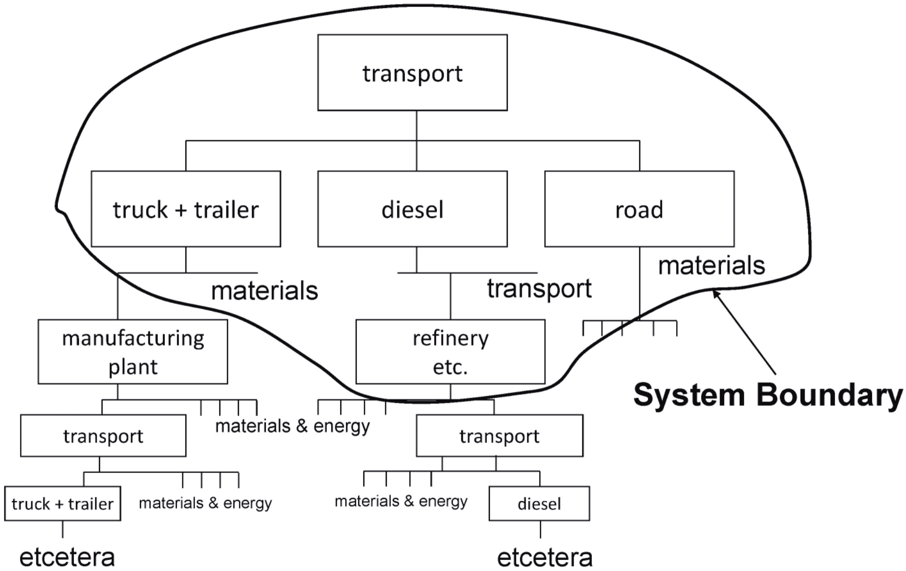

Table 2.1 is an example of a calculation on bamboo stems, transported to the Netherlands. It is obvious that lines 1, 2 and 6 can be neglected. In tables like this, however, they are included to avoid confusion by the less experienced reader who might think that something was omitted.

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
- 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 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[12]:

- sales and marketing activities
- retailer activities

[12] One might apply here the EVR data of the Excel tables at www.ecocostsvalue.com

Process step	Amount	Unit	Eco-costs (€/unit)	Eco-costs (€/FU)	Eco-costs (€/kg)	%
1. Cultivation and harvesting from plantation. Gasoline consumption	0.016	liter/FU	1.04 /liter	0.017	0.0022	0.3%
2. Transport to stem processing facility; 5-ton lorry (transport 320 FUs)	30	Km	0.243 /km per 5t truck	0.0228	0.0030	0.4%
3. Preservation & drying: Energy consumption	1	kWh/ FU	0.109 /kWh	0.109	0.0142	1.7%
4. Transport from stem preservation facility to harbour (28-ton truck)	4.59	ton.km/FU	0.033 /ton.km	0.151	0.0226	2.7%
5. Transport from Shanghai to Rotterdam. Volume based; 400 ft container in a trans-oceanic freight ship	1300	m^3.km/FU	0.0041 /m3.km	5.330	0.795	94.5%
6. Transport from harbour to warehouse (28-ton truck)	0.88	ton.km/FU	0.033 /ton.km	0.029	0.0043	0.5%
Total eco-costs (€)				5.66	0.842	100.0%

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.

Note: FU=functional unit = bamboo stem per piece, 5.33 m (diameter 7 cm at the top, 10 cm at the bottom) in Rotterdam, produced in China (Moso).

For commodity products these omissions might be acceptable, however, for luxurious products these subsystems must absolutely be included.
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"[13]). 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 71% 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.

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.

[13] RER means in this database that the LCI is for the European Region, U means that the primary building blocks ('units') are shown.

Table 2.2. The subsystem (building block) of drilling a hole in low-alloy steel

	Subsystem	CED (MJ/kg removed)	CED %	eco-costs (€/kg removed)	eco-costs %
1	Electricity, low voltage, production UCTE, at grid/UCTE U	6.91	12.57%	0.059	4.68%
2	Compressed air, average installation, >30 kW, 7 bar gauge, at supply network/RER U	3.19	5.80%	0.028	2.20%
3	Lubricating oil, at plant/RER U	0.30	0.55%	0.001	0.07%
4	Metal working machine, unspecified, at plant/RER/I U	0.00	0.01%	0.000	0.01%
5	Metal working factory/RER/I U	4.27	7.78%	0.055	4.37%
6	Metal working factory operation, average heat energy/RER U	12.40	22.56%	0.216	17.15%
7	Steel, low-alloyed, at plant/RER U	27.88	50.74%	0.897	71.39%
8	Disposal, used mineral oil, 10% water, to hazardous waste incineration/CH U	0.00	0.00%	0.002	0.12%
	Total	54.96	100.00%	1.257	100.00%

Note: CED = Cumulative Energy Demand

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) [14].

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

[14] "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)

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.

Figure 2.6. A 3 gang extension socket out of cork

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 Figure 2.6. 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 Figure 2.7.
In streamlined LCA, the Use phase and the End of Life phase must be taken into account as well, when these phases are different.
A practical consequence of the streamlined LCA of Figure 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).

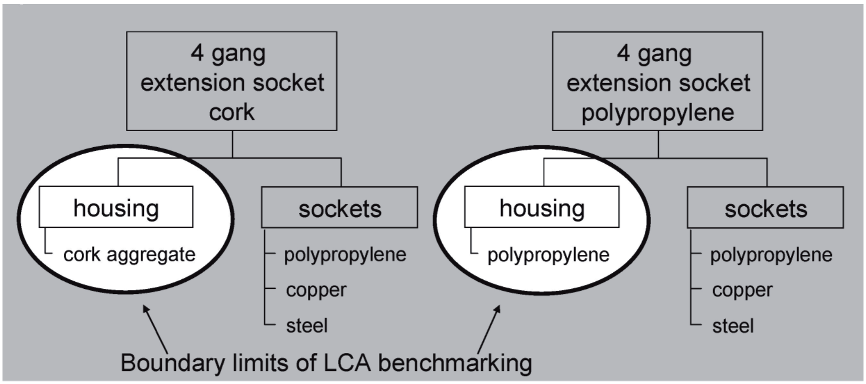

Figure 2.7. Streamlined LCA: a restricted scope of study

The second example is about an innovative design of an electric garbage collection truck, a bit smaller than a normal diesel truck, used for collection of garbage in inner cities and shopping centers. See Figure 2.8. The primary advantage to make the truck electric is the fact that is 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

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 per km = per ton.km , per m^3.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 *x* cups of coffee in its lifespan).
The LCA of this system, already given in Section 2.1 Figure 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 coffee machine of Table 2.3 is assumed to be produced in China and transported to Europe by sea container. It might be considered to add this information to the functional unit.
Example 2: the FU of the bamboo stem of Table 2.1 is "bamboo stem per piece, 5.33 m (diameter 7 cm at the top, 10 cm at the bottom) in Rotterdam, produced in China (Moso)".

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 with a 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 = {system function} per {unit of calculation} {plus optional: main scenario}

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.

	1 weight (kg)	2 material eco-costs (€/kg)	3 processing eco-costs (€/kg)	4 end of Life eco-costs (€/kg)	5=1(2+3+4) total eco-costs (€)
machine					
steel	0.471	0.64	0.062	0.007	0.33
plastics	0.893	1.03	0.25	0.13	1.26
aluminium	0.56	2.71	0.042	0.007	1.55
copper	0.08	3.21	0.023	0.007	0.26
assembly + packaging	0.2	0.175	0	-0.128	0.0094
transport (China-Europe)	eco-costs= 0.0044(€/m^3.km)				1.06 *)
machine total					4.47
period 3 years, 1095 days:					
per cup, 10 cups per day					0.0004
per cup, 1 cup per day					0.0041
cups (excl coffee extract)					
aluminium cup not recycled	0.0012	2.71	0.042	0.118	0.0034
50% aluminium recycled	0.0012	2.71	0.042	-1.175	0.0019
plastic cup	0.0015	1.03	0.25	0.13	0.0021
electricity per cup					
40 kJ per cup of coffee	eco-costs = 0.0302 (€/MJ)				0.0012 **)

*) 1.06= 0.0044*0.2(m)*0.2(m)*0.3(m)*20.000(km)

**) 0.0012=0.0302*40/1000

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 the next section, Section 2.5.

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 Figure 2.9.

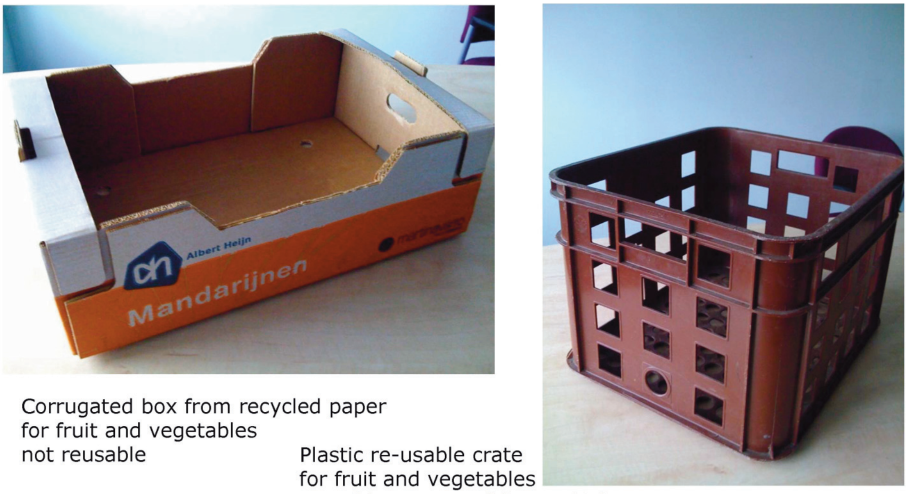

Figure 2.9. Two types of transport packaging: a corrugated board box and a plastic re-usable crate

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

	Corrugated BOX	Plastic CRATE
Size (L,W,H) (m)	0.6 × 0.4 × 0.24	0.6 × 0.4 × 0.24
Volume (litres)	53.4	43.92
Weight (kg)	1.086	1.95
Eco-costs (€/kg)	0.175	1.03
Eco-costs (€/unit)	0.19	2.01
Nr of trips	1	30
Eco-costs (€/trip)	0.190	0.067
Eco-costs (€/litre)	0.0036	0.0015

FU= containment of vegetables for transport per litre volume

Table 2.5. Summary of an LCA of transport by truck and trailer

	Corrugated BOX	Plastic CRATE
Litres per pallet	2670	2196
Litres per truck	69.420	57.096
Eco-costs of:		
- truck+trailer (€/km)	0.423	0.423
- driver (€/km)	0.015	0.015
- road €/km)	0.135	0.135
Subtotal (€/km)	0.573	0.573
distance full loaded truck (km)	500 + 500 * 0.3 = 650	500 + 500 = 1000
Eco-costs (€/trip)	372	573
Eco-costs per trip (€/litre)	0.0054	0.0100

FU= transport of vegetables per litre 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

	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 (€/litre)	0.00060	0.00131

FU= containment for transport of vegetables per litre 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 Figure 2.10. See for a full analysis of this case (Vogtländer, 2010).

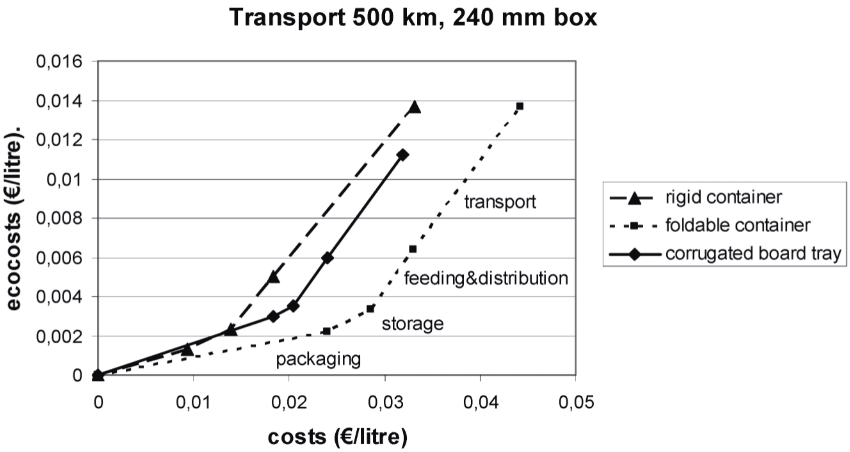

Figure 2.10. The eco-costs of transport of vegetables from Holland to Frankfurt in different types of transport packaging

The corrugated box scores slightly better in the total system (eco-costs of the total chain is 0.011 €/litre[15]) 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.

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

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

[15] 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 Frankfort. Hence the distance of 500 + 500 × 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.

process of thinking about the system in step A. In reporting, the formal top-down sequence should be applied.

2.5 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 Figure 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^3) and their quality in terms of tensile strength (N/m^2 = 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 Chapter 7). More examples - applications of the CES software - are given in (Ashby, 2009) and (Vogtlander, 2011).

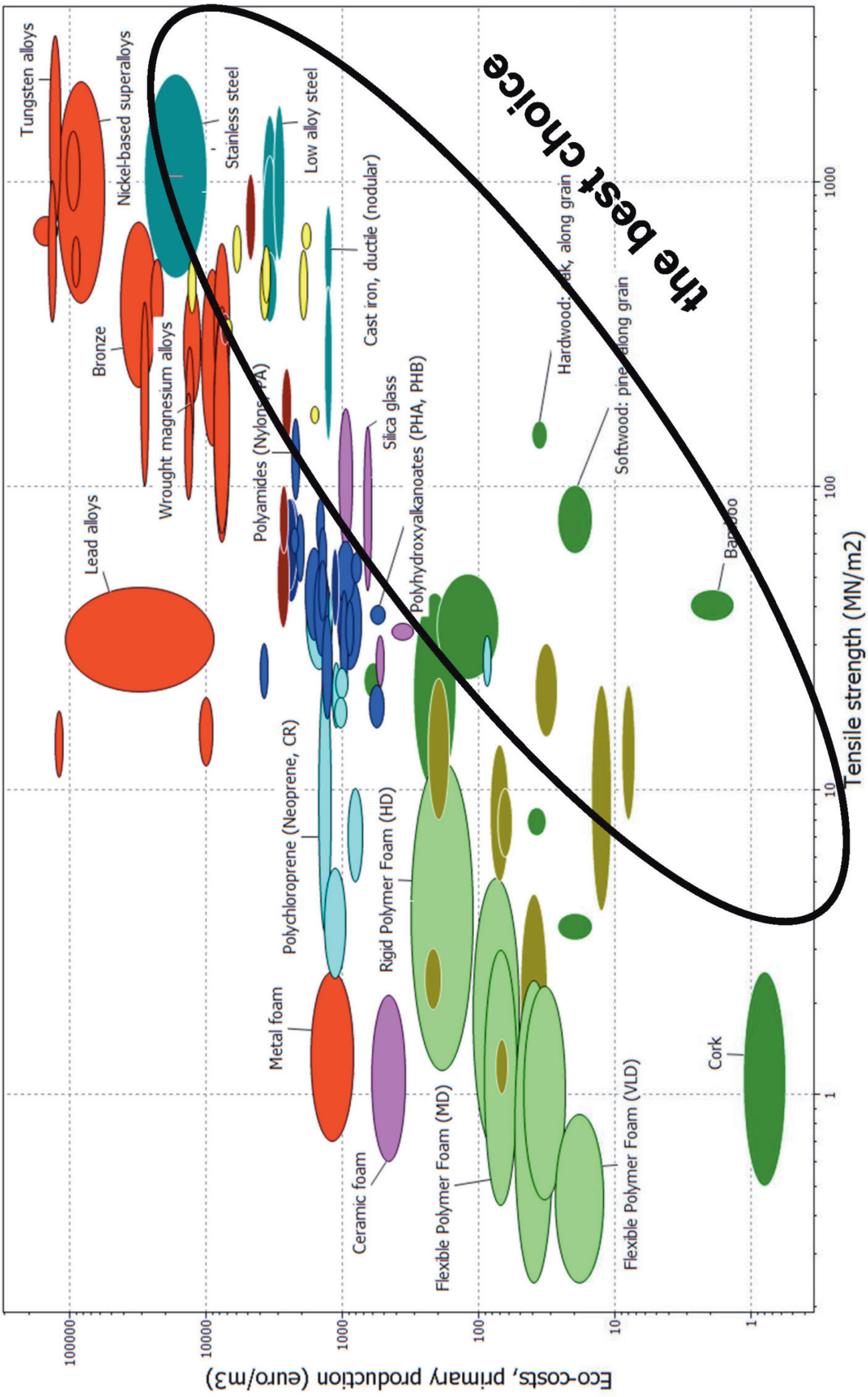

Figure 2.11. LCA benchmarking: the eco-costs/kg of materials and their quality in terms of tensile strength. Software: CES

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 realise 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), see Appendix IV. 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.