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Guideline for LCA practitioners and users of building related LCA studies

Final

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About This Report

Title

Guideline for LCA Practitioners and Users of Building Related LCA Studies

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Abstract

Life cycle assessment (LCA) is increasingly accepted as a tool to analyse the environmental impacts related to building materials and buildings. When using LCA data and results, it is important to understand the scope and purpose of the studies. The ISO framework and 14040 series of standards, provide an appropriate basis for LCA studies. This paper assists LCA practitioners to implement the ISO framework in relation to building related LCAs, and enables users of LCA results to assess the quality and relevance of existing LCA studies.

Note

This report was written as part of the research Beacon Pathway Limited (Beacon) commissioned under the banner of "LCA education". The project had two main components. The first was to conduct workshops that would introduce the concept of LCA, demonstrate its application in the built environment and highlight specific issues related to LCA and the building industry. The second component involved the production of two reports, the first to describe LCA methodology to help stakeholders interpret LCA studies and the second to document the role of LCA in decision making.

To reach our goal of a high standard of sustainability with respect to materials, Beacon (and ultimately the building industry and the regulators) needs to understand the impact of materials used in homes from cradle to grave. Beacon recognises that currently New Zealand is in the process of understanding the value of LCA and is yet to develop a national approach to providing robust information on the impact of building materials.

This report should be considered within the series of reports written for Beacon on materials, in particular the following resources:

- White paper – LCA and the Building/Construction Industry
- Analysis of current profiles of building products.
- The workshop presentations given as part of this LCA education stream of work.

Reference

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Life cycle assessment (LCA) is increasingly accepted as a tool to analyse the environmental impacts related to building materials and buildings. However, when using LCA data and results, it is important to understand the scope and purpose of the studies.

The ISO framework and 14040 series of standards provide an appropriate basis for LCA studies. This paper assists LCA practitioners to implement the ISO framework in relation to building related LCAs, and enables users of LCA results to assess the quality and relevance of existing LCA studies.

The following questions help to assess the quality of an LCA study and if it is ISO compliant. However, they should be regarded as a guideline only and do not cover all details of a LCA.

- Does the goal and scope definition clearly state the primary purpose and intended audience of the study?
- Are the system boundaries defined?
- Is the whole life cycle assessed?
- Are all relevant materials included?
- What criteria have been chosen for the data quality?
- Are the used datasets consistent with the goal and scope of the study?
- Are allocation procedures documented?
- Is a reference provided for the scientific models which are used in the impact assessment?
- If weighted results are presented, are the results of each environmental impact category provided?
- Have sensitivity analyses been used to check/validate assumptions?

LCA studies of buildings and building materials have additional issues which need to be considered, including service life, use phase, energy consumption and end of life scenarios as well as allocation procedures. All assumptions need to be clearly documented and tested in sensitivity analyses. The questions which need to be covered include the following:

- Is pro rata applied in maintenance scenarios?
- How is recycling modelled?
- Are the end of life scenarios tested in a sensitivity analysis?

2 Introduction

Life cycle assessment (LCA) is considered as an appropriate tool which is suitable for assessing the whole life cycle of building materials using a system's approach. The generic methodology and possible applications in the building industry in New Zealand were described in the White Paper – Life cycle assessment and the building and construction industry (Nebel 2006). This paper goes more into detail to enable stakeholders to interpret existing LCA studies and to assess their quality and relevance as well as to assist LCA practitioners to implement the ISO framework in relation to building related LCAs.

Although the LCA methodology is relatively complex, ISO standards (ISO 14040, 14044) have been developed to improve consistency of the methodology. However, these standards only provide a framework and are not prescriptive for LCAs for certain materials or systems.

The large number of different materials involved in buildings and the long lifetime of buildings add to the complexity of undertaking an LCA for buildings. This paper therefore describes important aspects of generic LCA methodology and highlights building / building materials related issues.

Where LCA studies are used for comparisons, for example of various materials, house design or services such as heating during the use phase of a house then a consistent LCA methodology is required. This paper, therefore, is a guideline for LCA practitioners on how to implement the ISO framework and gives LCA users guidance on the interpretation of LCA studies.

Emphasis is on the goal and scope definition, inventory analysis and the environmental impact assessment. Interpretation, which is the fourth phase of an LCA is not subject to the methodology to the same extent as the first three phases and therefore this component is only considered briefly in this paper.

The application of LCA in decision making processes will be discussed in a separate paper1. Emphasis will be on explaining and guidance on interpretation of the information delivered by an LCA as an essential part of achieving broader goals such as sustainability rather than the simple comparison of products. The paper will assist organisations to make ongoing improvements related to manufacturing and other business activities.

[1] ***See report TE201B "The role of LCA in decision making in the context of sustainable development".***

3 Background

LCA dates back to the 1960s, and to the energy analyses of industrial systems undertaken at that time and subsequently applied in response to the oil crises of the early 1970s. In the United States, the Midwest Research Institute (now Franklin Associates, Inc.) developed a methodology known as Resource and Environmental Profile Analysis (REPA), conducting its first analysis in 1969 on beverage containers for The Coca-Cola Company to “compare different containers to determine which produced the fewest effects on natural resources and the environment” (Hunt et al., 1992).

The LCA method attracted a lot of interest during the 80s due to the rise in environmental awareness, and the subsequent need for standardization of its methodology was inevitable. Since the late 1980s, SETAC (Society for Environmental Toxicity and Chemistry) has been organising LCA conferences and workshops. SETAC LCA Working Groups have carried forward this work since 1994 and prepared the release of the ISO 14040 series on LCA as an adjunct to the ISO 14000 Environmental Management Standards. The development of the International Standards on LCA has been seen as evidence that LCA is maturing as a robust environmental management approach.

In early stages of the development of LCA it was also called ecobalancing, Resource and Environmental Profile Analysis (REPA), or Life Cycle Analysis. In order to reflect the assessment aspect of the tool, LCA practitioners agreed in 1991 to use the term Life Cycle Assessment.

4 Iso Definition

The methodology of LCA is defined in a series of ISO standards, which is a key difference between this and other rating tools and environmental assessment methodologies.

ISO 14040 defines LCA as:

"… a technique for assessing the environmental aspects and potential impacts associated with a product, by

- compiling an inventory of relevant inputs and outputs of a product system;
- evaluating the potential environmental impacts associated with those inputs and outputs;
- interpreting the results of the inventory analysis and impact assessment phases **in relation to the objectives of the study**.

LCA studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use and disposal. The general categories of environmental impacts that require consideration include resource use, human health, and ecological consequences."

4.1 ISO Framework for Life Cycle Assessment Studies

ISO standards AS/NZS ISO 14040 - 43 define four generic steps which have to be taken when conducting an LCA (Figure 1).

Goal and Scope Definition: The goal and scope of an LCA study are clearly defined in relation to the intended application (ISO 14040).

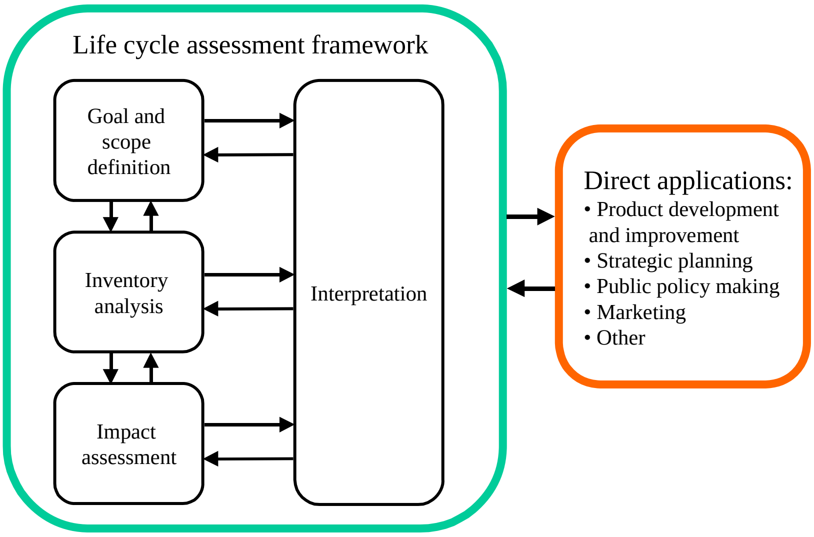
Inventory Analysis: The Life Cycle Inventory (LCI) Analysis involves the actual collection of data and the calculation procedures. The relevant inputs and outputs of the analysed product system are quantified and produced as a table (ISO 14041).

Impact Assessment: The environmental life cycle impact assessment (LCIA) translates the results of the inventory analysis into environmental impacts (e.g. climate change, ozone depletion). The aim of this phase is to evaluate the significance of potential environmental impacts (ISO 14042).

Interpretation: In this phase conclusions and recommendations for decision-makers are drawn from the inventory analysis and the impact assessment (ISO 14043).

These can be represented as shown in Figure 1. In practice, LCA involves a series of iterations as its scope is redefined on the basis of insights gained throughout the study.

Figure 1 LCA framework (ISO 14040)



4.2 Goal and scope definition

The goal and scope definition involves defining the goal of the study, its system boundaries, data requirements, functional unit, and any need for critical review. A clear definition of the goal of the study is important to avoid any subsequent misunderstandings about the wider applicability of the results. For example, a study carried out by a company to compare two alternative production processes may be adequate for internal decision-making, but its results may not be appropriate for public policy-making if the data are not representative of the national situation.

4.2.1 Goal

Several reasons and potential applications of LCA have been described in the White Paper (Nebel 2006). The aim(s) and application are important to define because they determine the goal of the study, and this in turn determines how the LCA is conducted and whether a critical review is undertaken (see Section 4.2.8).

In describing the goal of an LCA study, therefore, the following aspects should be included:

- the reasons for undertaking the study,
- the intended audience,
- and the intended application of the results.

Especially in the context of the building and construction industry this is a crucial part of an LCA due to the variety of different users who use LCA for different applications.

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Goal of an LCA on claddings

An LCA of a cladding product could be undertaken from two very different perspectives:

1) A product manufacturer wants to improve the existing product or wants to invest in the development of a new product. A screening LCA for internal purposes would be adequate for this purpose. A critical review would not be necessary.
2) An NGO wants to inform consumers about existing options for cladding systems. A detailed LCA of comparative systems would be required for this. A critical review would be required if the LCA data should comply with the ISO 14040 and 14044 guidelines.

4.2.3 Scope

Having defined the goal of the study, scoping involves defining system boundaries and other requirements for the study. The requirements may concern the desired geographical applicability of the results, time horizons over which the analysis is relevant, and the focus of the study, which could lead to omissions of particular stages of the life cycle.

In detail, the following items should be considered (ISO 14040):

- The product system to be studied, its function(s), and the functional unit
- System boundaries
- Data requirements and data quality
- Allocation procedures
- Categories, methods, and interpretation at impact assessment
- Type of critical review, if any, and
- Type and format of the report required for the study.

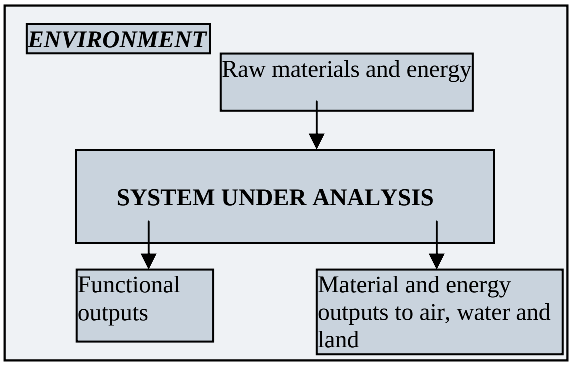
In line with the iterative character of an LCA study, it may be necessary to adjust these items as the study is conducted and additional information is collected. They are considered in further detail in the following sections.

Throughout the study it is important to state any assumptions made concerning, for example, the system boundaries, estimated data or the choice of waste management for the product system. At the same time, the limitations of the study due to these assumptions and other scoping decisions should be considered.

The product system, its function(s), and definition of the functional unit

The term "product system" is used to refer to the system under analysis. A product in the context of LCA is not always a "product" in the common sense, like a litre of paint or a bag of wood pellets. It can be a service, e.g., heating a room or the treatment of waste.

Figure 2 System under Analysis



Two aspects are particularly relevant for consideration when describing the product system for an LCA study:

1) **Function**: a product system may have several functions. But in general not all functions are relevant for a particular LCA. Thus identification of the relevant function(s) is necessary. For example, wall paint protects the wall and is decorative. But for a solid interior wall surface protection may be unnecessary, and aesthetics is the only relevant function of the paint (ISO/TR 14049).
2) **Quantification:** analysis is undertaken in relation to a specified quantity of a product, process or activity. This quantity may be arbitrary or it may be selected as relevant for a particular geographical area, a company's operations, an individual's use during a specified time period, or some other scale. A study of wallpaper may consider a) an (arbitrary) 10 square metres of wallpaper; b) the quantity of wallpaper produced in a company over one year; or, c) the quantity of wallpaper required for an average house.

Deciding on the function and quantity to be considered in the study leads to definition of the functional unit. This is the unit of analysis for the study, and it provides a basis for comparison if more than one alternative is being studied.

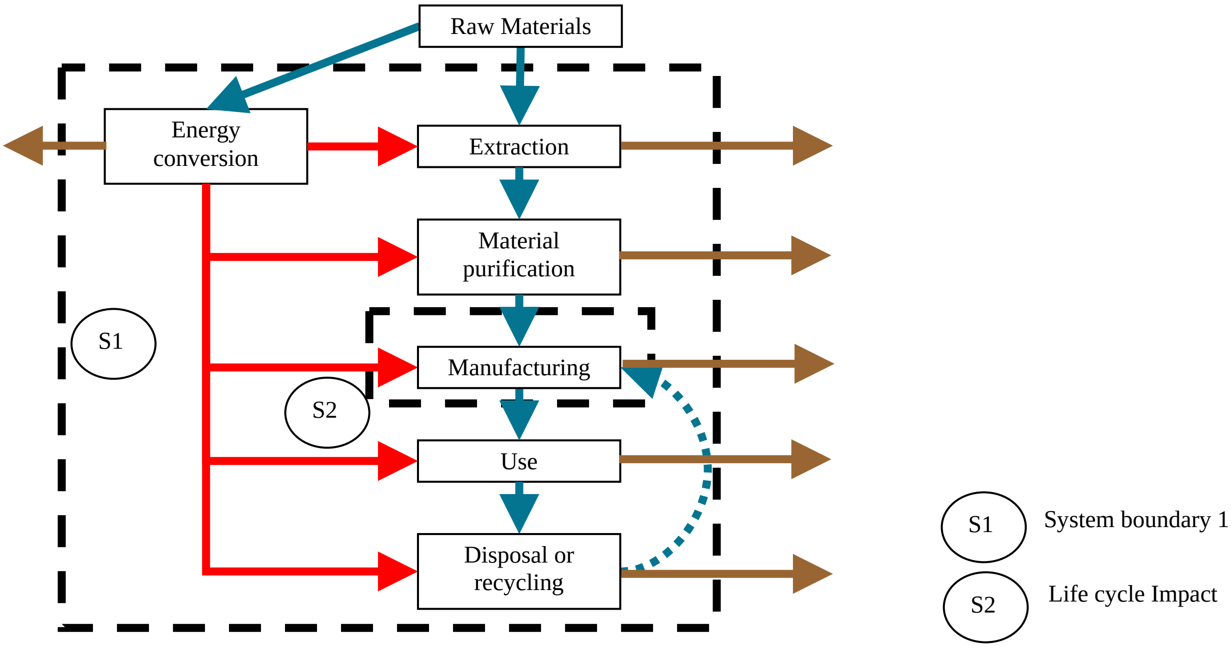
Functional unit
An appropriate functional unit for an LCA of light bulbs could be "the quantity required to provide 300 lx in 50,000h matching the daylight spectrum at 5,600 K" rather than a certain number of light bulbs.
Note: In low-energy houses sometimes even the heat provided by a light bulb is taken into account, when calculating the fuel demand for that house. However, the most obvious reason for using a light bulb is the provision of illumination. Therefore the provision of illumination would usually be the function considered in an LCA.

4.2.4 System boundaries

The system boundaries specify which economic processes are included in the study. Ideally only elementary flows enter the system under analysis; these are flows of materials and energy that have not previously been processed. In other words, the system under analysis should include upstream processing and manufacture of all materials and energy used both in the final product, process or activity and in ancillary inputs. Ancillary inputs are materials that form part of the product system but that are not part of the final product (e.g., lubricants used to oil machinery for sawing wood should be included in the system under analysis). Similarly, only elementary flows should leave the system under analysis; these are flows of materials and energy that are discarded into the environment without subsequent human transformation.

The scope of an LCA is illustrated by system boundary 1 in Figure 3. It extends from extraction and processing of raw materials through to manufacture, delivery, and use, and finally on to waste management. A number of other environmental assessment tools are restricted to the production process, illustrated by system boundary 2 in Figure 3.

Figure 3: Flows of materials and energy, and system boundaries in LCA (Cowell and Nebel, 2003)



4.2.5 Data

For LCA, as for any other model, it is true that the quality of the output is only as good as the quality of the input - "garbage in = garbage out" (cf. Guinée et al. 2002, p.491). Data quality is a critical factor for an LCA.

Before starting an LCA, data quality and data collection should be considered and stated in the goal and scope definition. The characteristics of the data should be described very carefully in the goal and scope definition, including (ISO 14040):

- Time related coverage
- Geographical coverage
- Technological coverage
- Precision, completeness and representativeness of the data
- Consistency and reproducibility of the methods used throughout the LCA
- Sources of the data and their representativeness
- Uncertainty of the information.

For all these situations, sensitivity analysis can be used to determine the impact of data deficiencies and/or omissions on the final LCA results. This is particularly important in the New Zealand situation, where robust, widely accepted and representative datasets are not common. A sensitivity analysis would highlight the critical factors and the implications of changes in the LCA results.

The availability of data in a New Zealand context and the need to develop NZ data was discussed in a previous report "TE200 - Analysis of currently available environmental profiles of building products." (Szalay, Nebel 2006).

4.2.6 Allocation

Allocation rules are required if one process leads to two or more different outputs. A hierarchy of preferred approaches to allocation has been developed and defined in the ISO 14041. It is worth noting that the preferred approach is to avoid allocation by either dividing the unit process to be allocated into subprocesses or expanding the system under analysis (see Section 4.3.1 for examples). The choice of an allocation method can influence the results of a study significantly. It is therefore important that the chosen allocation rules are documented in the Goal and Scope definition of the study.

4.2.7 Impact assessment

Two aspects of the impact assessment stage of an LCA should be described in the goal and scope definition. Firstly, the environmental categories which are assessed and secondly the methodologies that are to be applied.

Although the ISO standards do not regulate the choice of environmental impact categories there are a number of recommendations which are accepted internationally as a good guideline. Guinée et al. (2002) defines the following impact categories as baseline categories:

- Abiotic resources
- Land use (land competition)
- Climate change
- Stratospheric ozone depletion
- Ecotoxicity
- Human toxicity
- Photo-oxidant formation
- Acidification
- Eutrophication

These environmental impact categories are explained in some detail in section 4.4.2.

However, it should be noted that the methodologies for assessment of the depletion of abiotic resources, land use, ecotoxicity, and human toxicity are still under development (see also Section 4.4.1).

The scientific model which is used for the evaluation should also be mentioned. Examples are the Ecoindicator '99 (Goedkoop 1999), CML baseline 2002 (Guinee 2002), Impact 2002+ (Jolliet et al.) for all impact categories or IPCC (2001) for greenhouse gas emissions. It is important to also state the exact version which is used. IPCC have for example updated the methodology for green house gas emissions several times over the last 10 years and the value of the CO_2 equivalent for methane has been revised from 23.5 kg CO_2 equivalent (IPCC1996) to 21 kg CO_2 equivalent (IPCC 2001).

4.2.8 Critical Review

Critical review involves review of the study by a third party to ensure that the methodology and the report are scientifically and technically valid. It is optional, unless the results of the study are used to make a comparative assertion that is disclosed to the public (according to the ISO standards).

There are three different ways of conducting a critical review (ISO 14040):

- Review by an internal expert: A critical review may be carried out internally by an expert independent of the LCA study. This expert should be familiar with the ISO Standards 14040-14043 and have the necessary scientific and technical expertise.
- Review by an external expert: In this case an external expert, who has the same qualifications as stated above for the internal expert, carries out the critical review.
- Review by interested parties: This kind of a critical review consists of an external expert who acts as a chairperson, and a review panel. Members of the panel can be further independent qualified reviewers as well as interested parties affected by the conclusions drawn from the LCA. (For example, government agencies, non-governmental groups, or competitors.)

In each case the review statement should be included in the LCA study report.

4.3 Inventory analysis

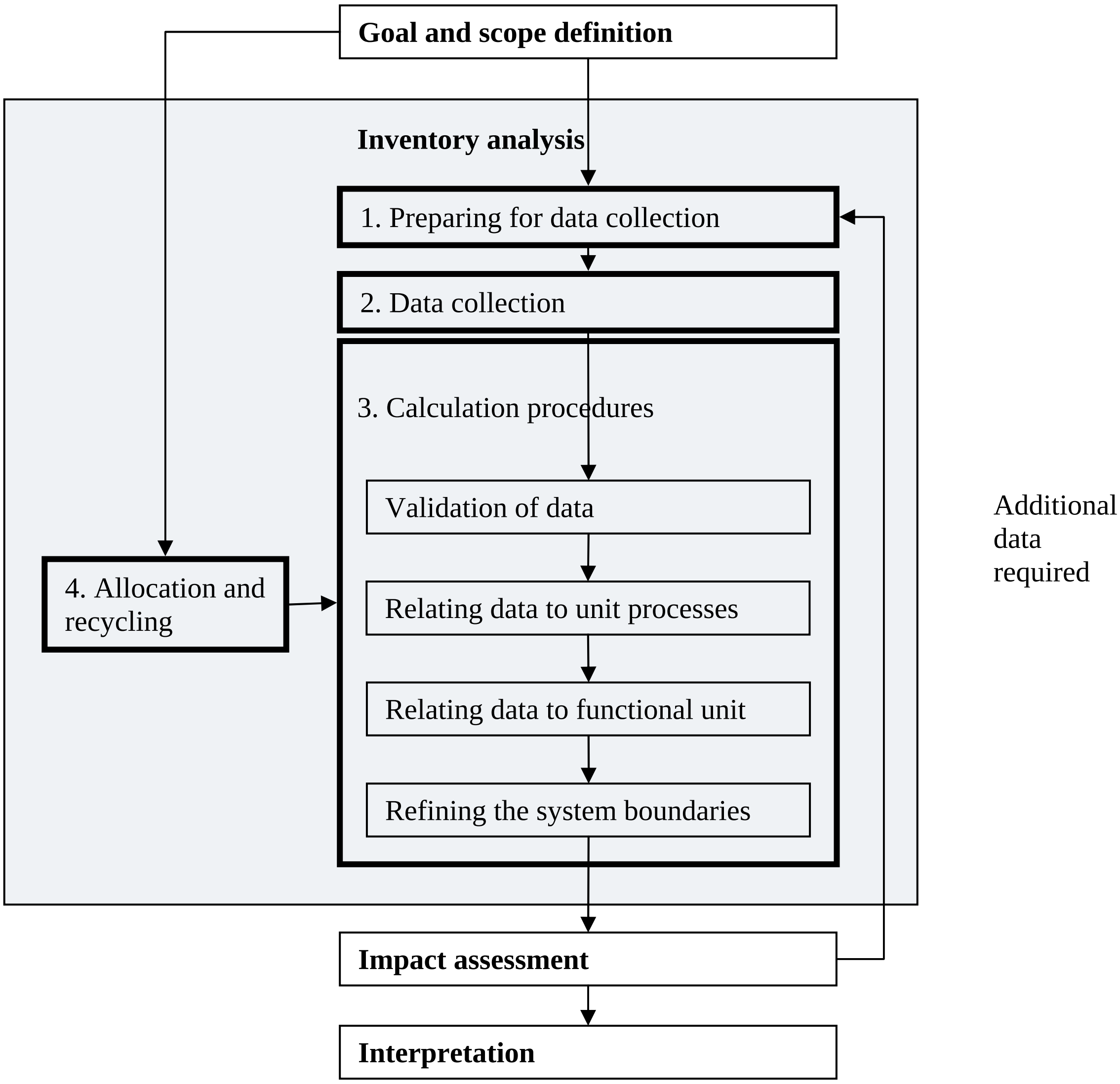
At the inventory analysis phase of an LCA, the elementary flows associated with the product system are quantified and related to the functional unit.

This section outlines the inventory analysis in general and some building-specific issues which include:

- allocation
- service life
- use phase
- energy and LCA

The procedure for undertaking an inventory analysis is shown in Figure 4. However, it should be noted that inventory analysis is really an iterative process and the LCA analyst revisits the different steps as the study progresses.

Figure 4: Procedure for inventory analysis (adapted from ISO 14041)



At the inventory phase, the environmental interventions associated with the life cycle for the functional unit are quantified. These are the material and energy inputs, and product and emission outputs to air, water, and land. The methodology involves drawing a boundary around the system under analysis and quantifying the inputs and outputs across this boundary, as shown in Figure 3. Within the system, a number of discrete unit processes are identified, and input-output analysis is undertaken for each unit process (including transportation). In effect, this analysis amounts to carrying out detailed material and energy balances over the system identified in goal and scope definition. However, it differs from conventional material and energy balances as applied to a process in two respects:

- The balances are carried out over the broader system shown by boundary 1 in Figure 3, rather than over a single process or plant.

- The inputs and outputs go into more detail than would normally be used in analysing a process (for example, they quantify trace emissions of all chemicals with toxic effects on human beings and ecosystems).

A generic life cycle for different products and their related services has already been shown in Figure 3. In an LCA, the material and energy flows should be "drawn from the environment ... or discarded into the environment without ... human transformation" [ISO 14040]. Thus the overall product system should extend upstream to primary resources, and downstream to the point where material is emitted into the environment so that it is dispersed in an uncontrolled way. Treatment of solid waste should therefore be considered as part of the product system (as in Figure 3).

Once all the data on environmental interventions have been collected, and allocation issues resolved, they are normalised to the functional unit and compiled into an inventory table prior to Impact Assessment.

4.3.1 Allocation

Collecting the data is only one part of establishing the inventory related to the functional unit. Some modelling is required because production processes are not usually simple linear chains. Processes might have multiple outputs which are then used in different product systems (Co-production). Recycling and the use of waste of one product system as a useful input into another product system are further examples where allocation is required.

- **Co-production**: In these systems, one process yields two or more useful products. Allocation refers to the problem of partitioning the inputs and outputs between these products. Examples include production of different grades of product from one log.
- **Recycling:** In recycling, an output from a system becomes an input to a system or process. The recycle may go back into the same system from which it was produced (closed-loop recycling). Alternatively, it may become an input into a different system or process (open-loop recycling). Closed-loop recycling does not present an allocation problem because the system can be modelled to take account of this type of recycling. For example, off cuts from aluminium window frame production get recycled into another window frame. However, open-loop recycling does present an allocation problem because the recycle becomes an input to another system producing a different product or products. For example, recycled concrete is used as hardfill for road building.

Co-production:
For example, the production of construction timber is always linked to the production of lower grade sawn timber and sawdust, which are then used either for a different product, or in the case of sawdust, for the production of composite boards or production of energy (either directly or as pellets). They may even end up as waste in a landfill. The following question arises: How much of the energy required for sawing gets allocated to the construction timber and how much to the sawdust and lower grade timber? If the sawdust is actually waste, it should not get any energy allocated to it. But some of the energy should be allocated to the lower grade timber. Following the ISO standards an allocation based on mass would be made in this case. The decision as to whether sawdust is waste or a by-product with a market value is critical in this process.

These examples demonstrate the importance of a very transparent documentation of all allocation processes. It also shows that consistent data is crucial when doing an LCA of building components.

4.3.2 Service life

There are several important issues which arise when modelling the inventory of a building material or building component (Kotaji et al., 2003):

- Service life
- Replacements
- Maintenance.

The service life can be either the "designed service life" or the "actual service life". Multilayer parquet is, for example, designed to last 20 years. However, according to the experience of the parquet manufacturers a floor covering of this type is typically replaced after 15 years for aesthetic reasons. In order to reflect the actual environmental impacts the "actual service life" should be used as the basis for the calculations (Nebel 2003).

Replacements are required when the actual lifetime of a building component is shorter than the timeframe defined in the functional unit. A difficulty arises in modelling this when the assumed service life of the replaced component then exceeds the assumed lifetime of the building. For example, a roof is replaced after 40 years, and the functional unit is based on 60 years. The remaining 20 years lifetime of the roof can be taken into account or not. If it is taken into account the replacement would be calculated pro rata, i.e., the roof has to be built 1.5 times during the lifetime of the house. The other option is to base the calculation on true activities and take the roof twice into account. However, the argument for the pro rata calculation is that it would reflect an average situation, i.e. a replacement of 50 % of the roof, because there are great uncertainties in the service life of a building component.

Maintenance activities are closely related to the service life and the defined functional unit of the study. The frequency can be prescribed on either "best practice" recommended by the manufacturer or on "actual practice" from the experience of practitioners.

Decisions on all issues related to service life must be discussed during the definition of goal and scope and must be clearly defined there. However, there is potential for a review of the goal and scope definition during later stages of the study. Data collection and discussions with stakeholders during the life cycle of a building might, for example, show that actual life times or maintenance schemes are different from what was originally assumed.

4.3.3 Energy and LCA

This section describes energy related issues in the inventory analysis. A way to present the results as primary energy consumption or embodied energy is outlined in Section 4.4.1.

Energy use in a system under analysis can be categorised in different ways[2]:

- Feedstock energy: heat from combustion of raw material inputs, which are not used as an energy source for a product system. Example: the calorific value of construction timber would be taken into account, because some of it, i.e. off cuts, or all of it might be converted into energy at some point in the life cycle, e.g. where timber is burned for energy when withdrawn from service.
- Process energy: energy input required to operate processes (or equipment within processes) excluding energy inputs for production and delivery of this energy. Example: the energy to run a heating appliance in a home.
- Production and delivery energy: the energy input required to extract, process, refine and deliver energy or material inputs to processes. Example: diesel required to run a truck.
- Total primary energy: the sum of the feedstock energy, process energy, and production and delivery energy.

In LCA the total primary energy is conventionally assessed because it represents the aggregated total use of energy resources. It is important to include both the process energy and the production and delivery energy in the analysis as the difference between these figures can be large due to the efficiencies of conversion for different energy carriers. For example, in New Zealand electricity is produced at an average efficiency of 54% and only 31 % in Europe, due to the high proportion of fossil fuels in the European energy mix. In other words, an input of 100 MJ of primary energy results in an output of respectively 54 and 31 MJ electricity.

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[2] ***The term 'embodied energy' is used to summarise the energy consumed by all processes from extraction of raw materials through to the end product. See section 4.4.2 for further detail.***

Use of a 100% efficient heater?
The efficiency of some electric heaters is stated as 100 %, e.g. for oil column heaters. Information provided on electric heaters says “100%” efficiency. However, this only refers to the conversion of electricity into heat. If the whole life cycle of electricity was taken into account, i.e. the conversion of primary energy into heat, the same heater is actually only 54 % efficient.

4.3.4 Use phase

The use phase of a building plays a significant role in a life cycle assessment. Buildings use energy for heating, hot water preparation, lighting, and for cooling and ventilation during the operation phase. Energy efficiency is of great importance for all types of energy use. However, if the aim is to analyse and optimise the building design and the choice of building elements, only the components directly related to the building should be considered. The hot water energy demand, for example, is not determined by the building itself, but by the number of users, their habits, and the type and efficiency of the water heating system. Lighting and mechanical ventilation are related to the building to some extent; the size and location of the openings, e.g., influence the level of daylight and natural ventilation. However, the most significant building-related components are heating and cooling. They are mostly determined by the building envelope, the solar gains, and the thermal mass, while obviously they are also influenced by the user behaviour and other factors.

According to literature, 80 to 90 % of the life cycle energy is involved in the use phase and only 10 to 20 % is related to the production and transport of building materials as well as the actual construction of the building. However, these figures are mainly based on European conditions and are dependent on the heating schedule and level of heating. These figures would, for example, not apply to a well-insulated house in Auckland where limited heating may be required or when a home is heated only in the evenings.

It is important to consider the use phase as part of the whole life cycle of the building, including the materials. For example, environmental impacts of additional insulation material can partly be compensated for by energy savings. A study by Emmenegger et al. (2006) has shown that a reduction of the end energy use in a building does not necessarily lead to a reduction of the overall environmental impacts to the same extent.

4.3.5 End of life

The last part of a building life cycle is the end of life scenario. Due to the long life time of a building this is subject to a number of uncertainties. A clear definition of the chosen scenarios and the applied allocation rules is therefore crucial for this part of the LCA. This is particularly true for quantities of secondary materials which are used today and might be recycled in the future.

There are two main options for the end of life:

- Apply today's situation concerning the percentage of recycling, e.g., based on current statistics.
- Define scenarios which are based on future situations, e.g., based on legislation which will be in place in the future

> The sensitivity and importance of choosing relevant of end-of-life scenarios is relatively high. A case study for an office building in Switzerland (Lalive d'Epinay 2000) showed that in a worst-case end-of-life scenario, the disposal phase is as relevant as the construction phase of the life cycle of the building. The building was very energy efficient, and the use phase therefore did not dominate the life cycle:
>
> - Construction: 37.4 %
> - Use phase: 26.1 %
> - Demolition phase: 36.5 %

4.4 Impact assessment

The environmental interventions calculated in the analysis are "translated" into environmental impacts during the impact assessment phase of LCA (LCIA). The objective of this phase is to present the environmental impacts of the system in a form that meets the purpose of the study and can be understood by users of the results. This includes the following steps (examples are given below):

Mandatory, according to ISO 14042:

- selection of impact categories and indicators
- classification of inventory data into impact categories
- characterisation of inventory data within each category

Optional, according to ISO 14042:

- normalisation
- grouping
- weighing.

This section describes the baseline impact categories, explains how the environmental profile is calculated in the classification and characterisation steps and explains the concept of normalisation and weighting.

4.4.1 Classification and characterisation

For a number of categories, internationally agreed characterisation models exist (e.g., the Intergovernmental Panel on Climate Change (IPCC) model for climate change). For other categories, characterisation models have been developed and are used internationally, but are still subject to change as more research is completed. Toxicity is a key example of this, since for a lot of substances the degree of toxicity is still not known. The results for toxicity-related impact categories are therefore to be treated with care. The development of characterisation models is still the subject of research (e.g., land use, depletion of biotic resources).

The process of establishing the environmental profile is described in the following paragraphs. At first each emission is linked to one or more types of environmental impact categories; these include climate change, ozone depletion, eutrophication, and human toxicity. In the next step all emissions that have, for example, an impact on climate change are converted into kg CO_2 equivalents.

CO_2 has a weighting of 1 whereas the more potent greenhouse gas methane has a value of 21 kg CO_2 equivalents, in other words 1 kg of methane contributes 21 times as much to global warming as 1 kg CO_2. This way it is possible to add up the results of all emissions which contribute to the same environmental impact category. The other impact categories are calculated accordingly, using appropriate reference emissions.

It is important to realise that the impacts are calculated at this stage on the basis of their incremental effect on the environment. This means that the actual effect is taken into account and not related to politically determined target values or emission thresholds. The aim is, therefore, general prevention of impacts, under the assumption that 'less is better'.

4.4.2 Impact categories

A short description of the baseline environmental impact categories is provided in this section, along with the recommendations of leading LCA scientists (Udo de Haes et al. 1999, Guinee et al. 2002) for the relevant impact assessment methodologies. The UNEP SETAC life cycle initiative is currently working on a recommendation which should be adopted globally by LCA practitioners (for further information refer to: http://lcinitiative.unep.fr/).

Climate change

Increasing amounts of greenhouse gases (such as carbon dioxide and methane) enhance the natural greenhouse effect and are likely to be leading to an increase in global temperature. During the 20th century, the average global temperature increased by about 0.6°C due to the enhanced greenhouse effect. Climate change is therefore often referred to as 'global warming'. Since the effects may also include storms or regional cooling, the term 'climate change' is more suitable. The natural greenhouse effect is an important factor in heating the atmosphere: short wavelength solar radiation entering the Earth's atmosphere is re-radiated from the Earth's surface in longer infrared wavelengths, and then reabsorbed by components of the atmosphere. Without the natural greenhouse effect the average global temperature would be about -18°C. Due to the greenhouse effect the average global temperature is 15°C.

The general recommendation is to use the most recent figures for CO_2 equivalents for greenhouse gas emissions published by the Intergovernmental Panel for Climate Change (IPCC). In 2001, the IPCC updated its estimates of Global Warming Potentials (GWPs) for key greenhouse gases from 1996.

Ozone depletion

The ozone layer in the stratosphere (10-50 km above Earth) absorbs 95-99 % of the sun's ultraviolet radiation. This radiation is harmful and sometimes lethal to wildlife, crops, and vegetation, and can cause fatal skin cancer, cataracts, and immune system damage in humans. The ozone layer therefore is crucial for any life on earth.

The natural seasonal Antarctic 'ozone hole' has been enlarging since the early 1980s. On a global scale, the decline of ozone in the stratosphere recently slowed. This depletion is mainly caused by CFCs which are used in aerosols, air conditioning, and refrigerators.

Halon, which is a fire retardant, is one of the key ozone-depleting gases. However, the use of this substance has been reduced significantly and will soon be phased out completely due to the successful implementation of the Montreal Protocol. It is therefore important to state in the impact assessment how much of the Ozone Depletion Potential (ODP) is due to Halon.

The ODP of a substance represents the integrated impact of an emission of a substance in comparison with CFC-11. The unit of the ODP is therefore kg CFC-11 equivalent. Currently the most recent Ozone Depletion Potentials are published by the World Metereological Organisation (WMO 1999, WMO 2002). It should be stated that the model developed by WMO is mainly applicable to polar ozone depletion rather than global ozone depletion (WMO 1991).

Acidification

The acidity of water and soil systems can be increased due to acid deposition from the atmosphere, mainly in the form of rain. The major acidifying emissions are oxides of nitrogen (NO_x) and of sulphur (SO_2) and ammonia emissions (NH_3), which lead to nitrogen and sulphate depositions.

The reference substance is sulphur dioxide (SO_2) which has an acidification potential of 1. Acidifying emissions are usually added together in LCAs. Generic acidification potentials have been developed by Heijungs et al. (1992) and have been updated by Wenzel et al. (1998).

Eutrophication

Eutrophication occurs when there is an increase in the concentration of nutrients in a body of water or soil, occuring both naturally and as a result of human activity. It may be caused by the run-off of synthetic fertilisers from agricultural land, or by the input of sewage or animal waste. It leads to a reduction in species diversity as well as changes in species composition, often accompanied by massive growth of dominant species. In addition, the increased production of dead biomass may lead to depletion of oxygen in the water or soil since its degradation consumes oxygen. This contributes to changes in species composition and death of organisms.

The reference substance for the calculation of the eutrophication potentials for each emission is phosphate (PO_4^{3-}), which has a eutrophication potential of 1. A generic approach, covering eutrophication independent of the site has been developed by Heijungs et al. 1992; site-specific datasets (terrestrial vs. aquatic ecosystems) for Europe have been developed by Huijbregts et al. 2000 and Hauschild and Potting 2002, for example.

Photochemical oxidant formation

Ozone (O_3) is a form of oxygen. In contrast to the protecting role of the ozone layer in the stratosphere, ozone in the troposphere is toxic. The rising level of ozone in the troposphere is mainly due to the increase of nitrogen oxides (NO_x), hydrocarbons and hydrogen peroxide from which O_3 is produced through photochemical reactions. The formation of O_3 is dependent on the presence of NO_x, and a relatively high level of NO_x in the atmosphere has been assumed in the calculations.

The impact assessment for photo-oxidant formation in Europe is usually based on the photochemical ozone creation potential (POCP), which was introduced in a UN protocol in 1990 (UNECE 1990). The POCP was defined in this protocol as the ratio between the change in ozone concentration due to a change in the emission of that oxidant and the change in the ozone concentration due to a change in the emission of ethylene (C_2H_4). Following on from this definition, ethylene was chosen as the reference substance in LCIA and is given a POCP of 1. Derwent and Jenkin (1990) calculated POCPs for different substances, which have been used as characterisation factors. They were updated in 1996, 1998 and 1999 (Derwent et al. 1996, 1998; Jenkin and Hayman 1999).

Primary energy

Primary energy consumption is strictly speaking not an environmental impact category, but part of the inventory analysis (see Section 4.3.3). The primary energy is usually given in MJ per functional unit and includes feedstock energy, process energy, and production and delivery energy.

Embodied energy

Figures for embodied energy have been published for a number of building materials. However, the same criteria for the definitions of the system boundaries, goal, and scope etc. as in LCA should be applied in order to provide transparent and reliable figures for embodied energy. Energy use is also not in all cases directly linked to other environmental impacts (see Szalay and Nebel 2006 for further information).

Embodied energy is the energy consumed by all processes from extraction of raw materials through to the endproduct. The definition of the system boundaries varies for different assessments and sometimes includes the delivery to the building site, energy requirements for installation, and transport of workers to the site “cradle to site”. However, data for these processes are often hard to quantify. Published figures for embodied energy are therefore often based on a “cradle to gate” concept. They can vary significantly for specific materials and applications of materials depending on the efficiency of the individual manufacturing process, the fuels used in manufacture of the materials, the distances materials are transported, and the amount of recycled product used, etc. Each of these factors varies according to product, process, manufacturer, and application. Figures for embodied energy should therefore be taken as broad guidelines only and should not be taken as 'correct'. What is important is to consider the relative relationships and try to use materials that have the lower embodied energy (Your home, 2005).

Further impact categories

The following impact categories are usually also considered, but the results are subject to a high degree of uncertainty because there are many unknowns associated with them.

Abiotic resource depletion: Abiotic resources are regarded as non-living, e.g., iron ore, wind energy, coal, oil. Most abiotic resources are non-renewable resources (except, for example, wind). Renewable resources such as wood, are part of the product system if sourced from sustainable management, i.e., their sustainable production is included in the life cycle.

Human toxicity and ecotoxicity: Substances considered to be toxic to humans and to flora and fauna are assessed in these categories. The human toxicity potential includes substances that have both chronic (i.e., longer-term, slower acting) and acute (i.e., shorter-term, faster acting) effects. Ecotoxicity (terrestrial, freshwater, marine) is concerned with impacts on all species in terrestrial, freshwater, and marine ecosystems. Different emissions are most relevant in these three categories. Ecotoxicity is therefore split up in terrestrial, freshwater aquatic, and marine aquatic ecotoxicity potential.

Impacts which are currently usually not considered in LCA are:

Indoor air climate:

Indoor air climate includes a number of issues such as temperature, humidity, lighting, and concentration of particles or gases. Indoor air quality usually describes the concentration of dust and particles, aerosols, inorganic gases, and volatile organic compounds (VOCs).

Since the main focus of LCA is the impact on the regional and global external environment, it is difficult to cover indoor air quality per se. The feasibility of including indoor air quality in LCA has been investigated by Jönsson (1998). Jönsson came to the conclusion that other tools such as Risk Assessment were more suitable to deal with these local emissions, because “only problems that can be predicted and quantified, based on representative data from the designed situation, could be included in LCA. Such problems constitute a very limited part of the total indoor climate problems” (Jönsson 1998).

Land use:

Land use is highly relevant for the building and construction sector from two different points of view:

- direct land use of the building which results in the occupation of land
- land use and transformation for the production of building materials (mineral extraction, agriculture, silviculture)

These issues are currently not reflected in most LCAs. Several methods have been developed for including land use in LCA, but determining the effects on the ecosystem is a very complex task. It is not only the occupied area itself which is relevant, but also the degree of change. For example, one square metre of sealed ground can’t be compared to one square metre of plantation forest. Research on land use in general is currently undertaken by a number of organisations. However, direct land use of buildings is a largely new field in the area of LCA.

4.4.3 Normalisation

Normalising the results provides an estimate of the relative significance of the results in each environmental impact category. This is usually done by dividing each score by the total score for each category in a given geographical area. For example, the Global Warming Potential (GWP) calculated for a system could be divided by the total GWP of gases released in New Zealand each year to give a normalised score. Other alternatives include normalisation in relation to an average person's annual contribution to each impact, or in relation to impacts caused by familiar products or activities (such as electric fires or cars).

The normalised score is then considered alongside normalised scores for other impact categories in order to gain an impression of the relative contribution made by the system to each impact category within a given geographical area.

4.4.4 Weighting

The normalised result for each impact category can be further multiplied by a weighting factor representing the relative importance of the different impact categories. For example, climate change may be considered twice as important as stratospheric ozone depletion, and so it is weighted in the ratio 2:1. The weighted results for each impact category may then be added to give one final value for the environmental impact of the system under analysis.

Weighting can be done according to the view of stakeholders, based on surveys, or against politically set target values for emissions. Research to determine a weighting dataset for New Zealand is currently underway.

Weighting raises the same methodological issues for LCA as exist in all types of multi-criteria analysis. Since there is no purely scientific basis for assessing the relative importance of impacts such as climate change and stratospheric ozone depletion, weighting factors for these different impacts must be derived. According to ISO 14042 weighting "shall not be used in comparative assertions disclosed to the public" (ISO 14042).

Example

The three steps of calculating the environmental profile, normalising the data, and aggregating them to a single score are illustrated in an example of timber-based products. The results are based on an existing LCA study for research purposes. Since there are some gaps in the data collection and no critical review has been undertaken, the product categories are not named.

Environmental profile

The environmental profiles for three alternative products are shown in Table 1. Based on these profiles it is difficult to determine which alternative is the most environmentally benign option. For global warming it would be alternative 3 which has to the lowest CO_2 emissions, but for Ozone depletion it would be alternative 2.

Table 1 Environmental profile of different products

Impact category	Alternative 1	Alternative 2	Alternative 3
Global warming (kg CO_2 equiv.)	45.474	25.241	16.248
Ozone depletion (kg CFC-11 equiv.)	5.41E-06	1.60E-06	2.93E-06
Acidification (kg SO_2 equiv.)	0.140	0.241	0.193
Eutrophication kg PO_4^{3-} equiv.)	0.022	0.023	0.011
Ozone formation (kg C_2H_2 equiv.)	0.049	0.043	0.022

The environmental profile can also be shown in much more detail. In order to identify the "hot spots" in the life cycle of a product, for example, it is useful to look at the results for just one impact category. The results for global warming in alternative 1 are shown in Table 2.

Table 2 Detailed environmental profile of one product

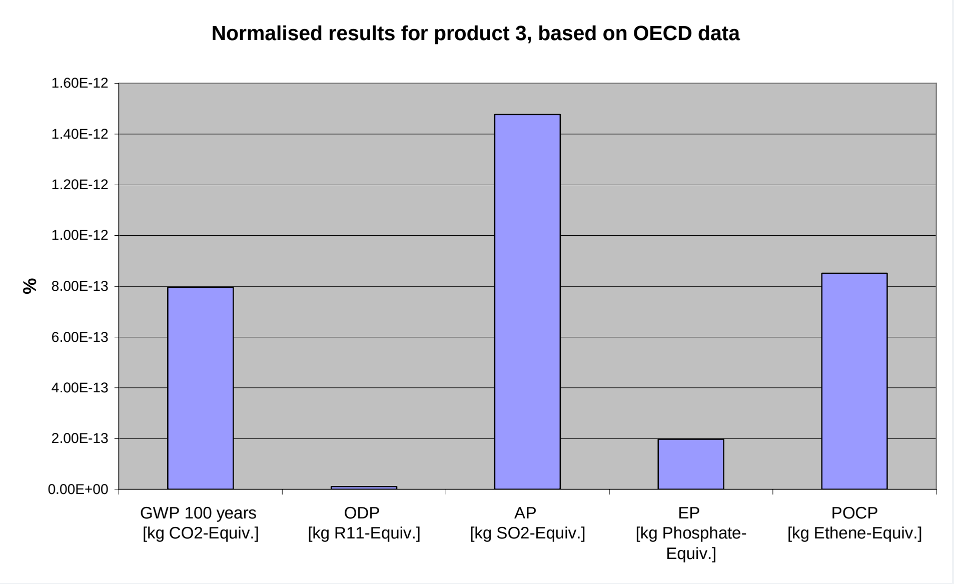
Life cycle stage	kg CO_2 equiv.
1 Forestry	0.502
2 Sawmilling	9.448
3 Production of preservative	8.879
4 Treatment	0.024
5 Transport	0.354
6 Use	0.000
7 Transport to disposal	0.600
8 Disposal	4.893

The results in Table 2 show clearly that the main contribution to the global warming potential is coming from the sawmilling stage. Transport does not contribute significantly to this impact category.

Normalised results

Based on the environmental profile shown in Table 1 it is difficult to determine whether it would be useful to improve the product in terms of its global warming potential (25 kg CO_2 equiv) or its ozone formation potential (0.02 kg C_2H_2 equivalents). The process of normalising the results facilitates their interpretation. Figure 5 shows the results of Alternative 1 in the table above, normalised to the total emissions in the OECD (CML 2001). Since a number of impact categories have a truly global impact, it is useful to use larger scale normalisation data in addition to more regional data. However, normalisation data for New Zealand are currently not readily available.

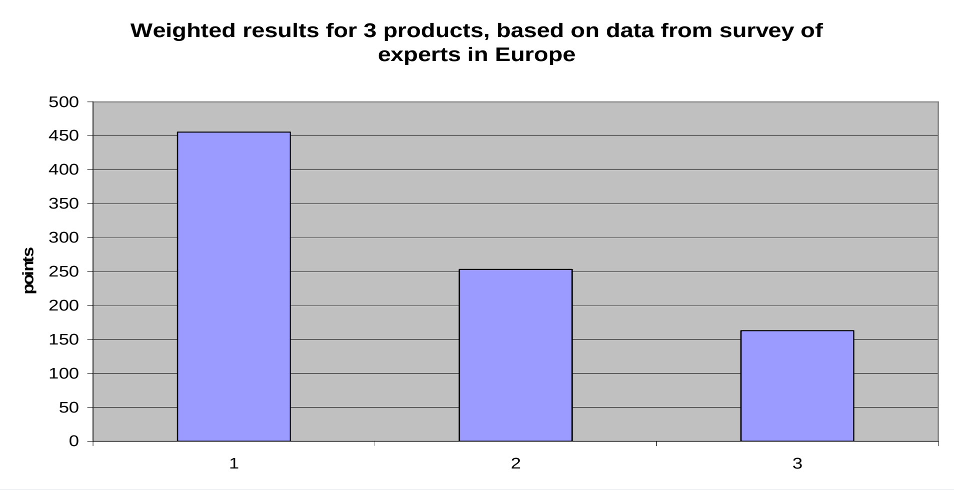
Figure 5 Normalised LCA results for a product



Weighting

Normalised results can be further aggregated to a single score for each alternative. In the example shown in **Error! Reference source not found.** a weighting matrix based on a survey of environmental experts in Europe has been used (IKP 2001).

Figure 6 Weighted results for 3 products



4.5 Interpretation

The final phase of an LCA is the interpretation phase. During this phase, the results of the analysis are discussed and opportunities for reducing the environmental impacts associated with the functional unit are identified and evaluated. ISO 14043 states that this phase should include communication of the study results "in a form that is both comprehensible and useful to the decision-maker" and defines this phase as follows:

> *"Life cycle interpretation is a systematic procedure to identify, qualify, check and evaluate information from the results of the LCI and/or LCIA of a product system, and to present them in order to meet the requirements of the application as described in the goal and scope of the study.*
>
> *Life cycle interpretation includes communication, to give credibility to the results of other LCA phases (namely the LCI and LCIA), in a form that is both comprehensible and useful to the decision-maker."*

From this definition the following aims of the interpretation phase can be derived:

- **To check the results of the inventory and impact assessment phases against the goal and scope of the study**

  If, for example, the subject of the study relates to a comparison of products A and B, and the data quality for both products is not the same (for example, if data for product A are taken from generic data in literature and data for product B are collected on site), the results may not be in line with the goal and scope of the study.

- **To check the impact of choices that have been made in the study**
  If, for example, two options for an end-of-life scenario are equally common, say, incineration and landfill, and only incineration is considered in the LCA, the choice to omit the landfill option should be revisited.
- **To reach conclusions and provide recommendations based on the findings of the preceding phases of the LCA**
  Decision-makers often find it difficult to interpret the results of the preceding phases of an LCA. Therefore part of the interpretation phase is the preparation of conclusions and recommendations, according to the goal and scope of the study, that are comprehensible and useful for the decision-maker.

5 Summary and Conclusions

LCA studies can provide reliable and detailed information about building materials, building components and whole buildings. Since the whole life cycle is considered and the provision of energy and transport processes is included, LCA studies present a holistic picture of the environmental burdens.

The ability to compare the results of different LCA studies or to combine several LCA studies of building materials to one study of a whole building is subject to a transparent and good documentation of all steps in an LCA. The application of the ISO guidelines ISO 14040-14043 contributes to the credibility and transparency of an LCA study.

The comprehensive nature of the methodology requires transparent documentation of all steps of the LCA. In the goal and scope definition it is especially important to describe the system boundaries, data quality as well as the primary goal of the study.

Building related issues, such as service life and use phase as well as recycling options and end-of-life scenarios are especially important in the inventory analysis. A detailed description of the system under analysis should also be provided.

Due to the different life time of various building materials and the whole building, a decision has to be made if pro rating is applied for the replacement of building materials. This should be clearly documented in the LCA report. Allocation procedures and the modelling of recycling scenarios as well as the assumptions for the use phase should also be outlined in the inventory analysis.

The impact assessment phase is based on scientific models which should be clearly referenced. If a weighting is applied, it is required to provide the original dataset for the LCA user as well, because every weighting methodology is subject to a range of value choices.

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