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Life Cycle Assessment

Best Practices of ISO 14040 Series

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Preface

Increasing demand for preservation of the environment, conservation of resources, and a sustainable society led to the publication of two types of ISO (International Organization for Standardization) 14000 standards by ISO: management oriented and product oriented. The ISO 14000 product oriented standards include Environmental Labels and Declarations, Life Cycle Assessment and Ecodesign. These standards are intended to be used to assess and report on environmental performance of products and services, and to provide guidance on improving their environmental performance. As a result these standards may serve as norms for environmental consideration of products and services in international trade. This implies that the standards have the potential to become technical facilitators as well as barriers to trade.

The ISO 14000 product oriented standards are not easy to comprehend and require expert knowledge to use them proficiently. In addition, most APEC developing economies do not have expertise on these standards. Thus, there is a strong need to produce best practices books that enhance the level of understanding and use of the standards. This is the second of three books on the product-oriented ISO 14000 series standards to be produced as part of the APEC CTI/TILF project.

A new paradigm termed "sustainable consumption and production" has been accepted as the ultimate goal to achieve in today’s society. It is a well known fact that mass consumption as well as mass production of industrial products causes major adverse impacts on the environment, such as climate change and ozone layer depletion. Conventional end-of-pipe environmental regulation focuses only on the emissions from the manufacturing processes of a product. Often times, however, adverse impacts on the environment occur from the other life cycle stages such as use, disposal, distribution, and raw material acquisition. Without reducing environmental impacts from the entire life cycle of a product, one cannot mitigate the environmental problems that accrue from the production and consumption of the product.

Recently, many corporations recognized the importance of the environmental impacts of their products and began to incorporate environmental aspects into their product design and development processes. This requires identification of key environmental issues related to the product throughout its entire life cycle. The key issues include problematic activities, processes, and materials associated with the product from raw materials acquisition, manufacturing and distribution to use and disposal, or entire life cycle. Since a product cannot exist without materials, components, transportation, disposal, and energy, for instance, identification of key environmental issues of the product in its entire life cycle is a complicated task. Thus, there is a need for a systematic analytical tool for the environmental assessment of a product throughout its entire life cycle.

Life Cycle Assessment (LCA) is best known for quantitative analysis of the environmental aspects of a product over its entire life cycle. An LCA is a systematic tool that allows for analysis of environmental loads of a product in its entire life cycle and assessment of their potential impacts on the environment. Products in this context include both products and services. Emissions to the air, water, and land such as CO_2, BOD, solid wastes, and resource consumptions constitute environmental loads. Environmental impacts in the LCA context refer to adverse impacts on the areas of concern such as ecosystem, human health, and natural resources. There are four phases in an LCA, goal and scope definition, life cycle inventory analysis, life cycle impact assessment and life cycle interpretation.

The ISO 14040 series standards, Life Cycle Assessment, address quantitative assessment methods for the assessment of the environmental aspects of a product or service in its entire life cycle stages. ISO 14040 is an overarching standard encompassing all four phases of LCA. There are three more standards supplementing ISO 14040. ISO 14041 deals with goal and scope definition and life cycle inventory methods. ISO 14042 deals with life cycle impact assessment methods and ISO 14043 life cycle interpretation methods.

The terms and definitions taken from ISO 14040: 1997 Environmental management - Life cycle assessment - Principles and framework, Figure 1.1, and ISO 14041: 1998 Environmental management - Life cycle assessment - Goal and scope definition and inventory analysis, Figure 3.1 is reproduced with the permission of ISO. These standards can be obtained from any ISO member and from the web site of the ISO Central Secretariat at the following address: www.iso.org. Copyright remains with ISO.

I would like to extend my sincere thanks to Dr. Atsushi Inaba for his contribution to this book as a coauthor and Ms. Jenny Hillard for her thorough check of English and improving readability of this book. Special thanks are extended to many organizations and individuals including, but not limited to, ISO/TC207/SC5 and its experts, APEC/SCSC secretariat, and MOCIE of Republic of Korea.

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1 Introduction

A new paradigm termed sustainable consumption and production has been accepted as the ultimate goal to achieve in today's society. As we all know, mass consumption as well as mass production of industrial products cause major adverse impacts on the environment such as climate change and ozone layer depletion. Mass consumption of industrial products was made possible because of technological advances in manufacturing methods.

Traditionally, products were designed and developed without considering their adverse impacts on the environment. Factors considered in product design included function, quality, cost, ergonomics and safety, among others. No consideration was given specifically to the environmental aspects of a product throughout its entire life cycle. Conventional end-of-pipe regulation focused only on the emissions from the manufacturing processes of a product. Often times, however, adverse impacts on the environment occurred from the other life cycle stages such as use, disposal, distribution, and raw material acquisition. Without addressing environmental impacts from the entire life cycle of a product, for the product design, one cannot resolve the environmental problems accruing from the production and consumption of the product.

Recently, many corporations recognized the importance of the environmental impacts of their products and began to incorporate environmental aspects into their product design and development processes. This requires identification of key environmental issues related to the product throughout its entire life cycle. The key issues include problematic activities, processes, and materials associated with the product from raw materials acquisition, manufacturing, distribution, use, and disposal, in other words, the entire life cycle. Since a product cannot be designed, manufactured and marketed without materials, components, transportation, disposal, and energy, identification of key environmental issues associated with the product throughout its entire life cycle is a complicated process. Thus, there is a need for a systematic analytical tool for the environmental assessment of a products' entire life cycle. This tool is Life Cycle Assessment (LCA).

Caution must be exercised, however, in using LCA for product design. An LCA is a tool for the evaluation of a product only from the viewpoint of the environment. There are other aspects such as economic, social, and technical ones to be considered in any product design and development. In this respect, life cycle costing, material flow analysis, and other technical evaluation techniques should be an integral part of the product design and development. Trade-offs among environmental, economic, social, and technical aspects must be made.

Analytical tools for the assessment of the environmental aspects of a product

Commonly used tools for the analysis of environmental aspects of a product include LCA, simplified LCA, checklist, MET (Material, Energy, and Toxic emissions) matrix, and environmental benchmarking, among others. These are classified as quantitative and/or qualitative, depending on the nature of information generated by the tools. In general, quantitative information provides numeric values based on rather objective methods; thus, reliability of the information can be high. The other side of the coin, however, is that the analysis of quantitative information requires highly skilled experts and often involves complicated processes. Qualitative information yields results based on pre set parameters for the analysis and qualitative evaluation of those parameters; thus the reliability of the information is low. But the analysis can be simple and quick. Below we discuss widely used analytical tools briefly. They are LCA, and simplified LCA.

LCA

Life cycle assessment is best known for quantitative analysis of environmental aspects of a product over all its life cycle stages. An LCA is a systematic tool that enables the analysis of environmental loads of a product throughout its entire life cycle and the potential impacts of these loads on the environment.

- "Products" in this context include both products and services.
- Emissions to the air, water, and land (such as CO_2, BOD, solid wastes) and resource consumption, constitute "environmental loads".
- "Environmental impacts" in the LCA context, refer to adverse impacts on areas that should be safeguarded, such as ecosystem, human health, and natural resources.

There are four phases in an LCA; goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and life cycle interpretation

(ISO 14040, 1997). ISO 14040 shows the relationship among these four phases as shown in Figure 1.1. This is needed in order to analyze environmental aspects of a product in a systematic way. A brief description of each phase follows.

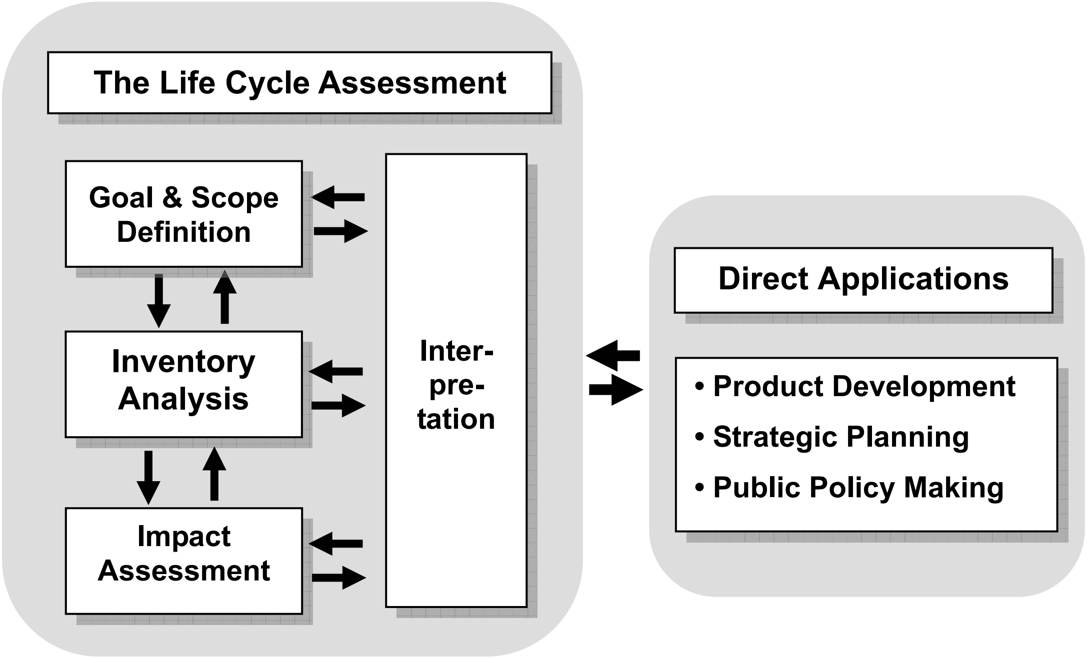


Figure 1.1 Phases of an LCA (ISO 14040, 1997)

Why perform LCA, who are the target audiences, and what is the product under LCA study? These are the questions to be addressed by the goal definition. The scope definition is much more complicated than the goal definition. It includes defining product system boundary, functional unit, data parameters, target for data quality, impact assessment methods, among others.

Once the product system boundary has been set, the input of materials and energy to each unit process and the output (such as products, co-products and emissions) from each unit process are collected and then normalized to unit mass of each unit process. Eventually the life cycle inventory result of the product under the LCA study is obtained by summing up all fractional contributions of the input and output from each of the unit process in the product system for the product. Thus LCI generates quantitative environmental load information of a product in its entire life cycle.

Environmental impacts resulting from the environmental loads of a product system are assessed in the life cycle impact assessment. To quantify the impact, impact categories are chosen followed by a process of quantifying environmental impact in a given impact category using the equivalency approach. This process is termed "characterization". Further processing of the impact information can be made by normalization and weighting. LCIA thus provides environmental impact information for the product.

The last phase in an LCA study is life cycle interpretation, where environmentally significant issues are identified and the LCA results are assessed with respect to completeness, sensitivity and consistency. In addition, conclusions, recommendations and reporting are also part of this phase.

The identified key environmental issues become the starting point for product improvement. The concept of a product that fulfills a specific function can be generated based on the key environmental issues. This is an integration of environmental aspects into product design and development, or "ecodesign". Based on concepts from the key environmental issues, detailed design and layout of the product can be completed, and eco-products results.

Once eco-products are produced, the improved environmental aspects of the eco-product must be communicated to the market, with the hope that the newly developed eco-product will increase market share or reduce product cost. These are the most likely incentives for the manufacturer to design and develop eco-products. For this reason, environmental product declarations that communicate environmental aspects of the product to purchasers are an essential component of the eco-product development. This is clearly one of the major objectives for performing environmental assessment of a product; in particular, using the tool termed "LCA".

Other applications of LCA include strategic planning, public policy making, marketing, and others (ISO 14040, 1997).

Simplified LCA

LCA of products has been criticized as taking too much time and cost. This criticism comes mainly from industry users. The purpose of the simplified LCA is to address these criticisms of LCA. The simplified LCA contains two elements that could be construed as contradictory. They are;

- the assessment of the environmental impact of a product throughout its entire life cycle with accuracy and

- the minimization of the cost and time required for the assessment (Christiansen et al., 1997).

Key to the success of the simplified LCA therefore, lies in the goal and scope definition phase by reducing the complexity of the product system boundary relevant to the goal of the LCA study.

Simplification can be classified into two different approaches: one is the approach that reduces the effort required for data collection (quantitative) and the other is the qualitative approach. Use of similar data, omitting certain life cycle stages, and exclusion of particular inventory parameters are examples of the quantitative approach. The qualitative approach includes, among others, focusing only on particular types of environmental impacts or issues. For more details, refer to a reference by Todd et al., 1999.

Based on a brief overview of the analytical tools for environmental assessment of a product, it is clear that LCA is the most comprehensive and accurate tool for the identification of key issues associated with the product design and development. In the international arena, ISO (International organization for standardization) published international standards on LCA. The ISO 14040 series is a set of standards that stipulate how to implement the LCA of a product. In these standards, LCA is defined as an "environmental assessment tool of a product" and consists of four separate phases as shown in Figure 1.1. The following chapters provide detailed discussions of each of the four phases of an LCA. The discussion, however, focuses on practical aspects of an LCA implementation, not on theoretical aspects. Thus, only information absolutely necessary for performing LCA plus illustrative examples is listed in each chapter. In addition, a complete LCA case study is shown in this book to illustrate the flow of practical LCA implementation. A simple product, a hair drier, has been chosen as the product for the case study.

2 Goal and Scope definition

As a minimum, the following items must be included in defining goal and scope of a product under LCA study.

Goal:
You should clearly state your answers to the following questions.

Why are you undertaking the LCA study? (In other words, what are the objectives of performing the LCA study?) What are the application areas of the LCA results? Who are the potential audience?

Scope:
You should provide clear descriptions of the following items including the product system, the function of the product system, the product system boundaries, and data category.

2.1 Product system and function

Product: identify the product you have chosen for LCA study, including the model number.

Product system: describe the product plus its upstream and downstream processes. This includes components and materials manufacturing, distribution, use and disposal of the product. In addition, all transportation and energy used, not only for the product but also for all elements in the product system, should be included in the product system.

Function: define the use intended and the function provided by the product

Functional unit (fu): This is a measure that allows quantification of the function you defined. It should represent performance of the functional outputs of the product system. It provides a reference to which inputs and outputs are related.

Reference flow: The amount of product that is necessary to fulfill the function.

The following example will help you with the understanding of the function, functional unit and reference flow.

Example of function, functional unit and reference flow

Product: beverage container, either a steel can or a glass bottle, each containing 300 ml of beverage

Steel can weight: 10 g
Glass bottle weight: 75 g

You can define function, functional unit and reference flow of this product as:

Function: storing beverage for transportation
Functional unit: 300 ml volume
Reference flow: Steel can - 10 g, Glass bottle - 75 g

2.2 System boundaries

Here you define which unit processes shall be included in the product system. Ideally, all processes associated with the product should be included. However, this is neither possible nor practical because of data and cost constraints, and different intended applications. Thus, less significant processes may be excluded from the product system. In this case, the decision rule for mass contribution applies.

The decision rule for mass contribution is a process that excludes processes that make a minor contribution to the overall environmental load of a product system. Most frequently used decision rules for mass contribution criteria include i) if a unit process's mass or energy fraction of the product is less than x%, then exclude the unit process. ii) if the unit process, however, is considered environmentally significant (e.g. toxic chemicals), then the process should be included in the product system. One example of decision rules for mass contribution criteria is: Include up to y% cumulative weight (exclude the remaining 100-y%). Here "cumulative weight" means you add up the weight of each component of the product. You can do this by first arranging all components in descending order based on mass or energy.

First, you need information on the product with respect to its components and the materials of the components. You can obtain this information either from bill of material (BOM) or by disassembling the product. Then, draw a process tree of the product system.

A process tree is a collection of unit processes in a product system showing their interrelationship. Each unit process is represented by a box, and the interrelationship is shown with directional arrows.

2.3 Data Category

LCA is a collection of input and output data to and from unit processes in a product system. In general, data categories under inputs include raw and ancillary materials and energy going into a process. Data categories under outputs include product, co-product, by-product, and emissions to air, water, and land from the process. Depending on the nature of a process, actual input and output data categories will include only part of the general data categories.

Data category is a collection of parameters that actually measure the magnitude of the data. For example, a data category named emissions to water includes parameters such as BOD, phenol, and SS. The parameter is often called an inventory parameter because data collection in the context of LCA is called life cycle inventory analysis.

Once you define the product system by drawing a process tree, you should have a pretty good idea regarding the inputs and outputs of the unit processes within the product system. Thus, it is necessary to select data categories and corresponding parameters for the collection of inventory data.

Example of the goal and scope definition: hair drier case

1) Goal and scope definition

Goal

The LCA study of a hair drier was undertaken to secure data for improving the environmental aspects of a product and for comparing environmental impacts of the hair drier product system based on two different disposal scenarios. The LCA data will be used to identify environmentally weak points where product improvement can be made by product designers, developers, and managers within the company, and to compare two different disposal scenarios.

- *Why do you undertake LCA study? (What are the objectives of performing LCA study?)*
  To secure data and identify environmentally weak points for improving the environmental aspects of a product.
  To compare the disposal method based on probable scenarios.
- *Who are the potential audience?*
  Product designers, developers, and managers within the company
- *What are the applications of the LCA results?*
  To be communicated to product designers, developers and managers within the company.

Scope

Product:
Hair drier model (A)

Product system:
Hair drier model (A) plus its upstream and downstream processes consist of a product system. This includes components and materials manufacturing, distribution, use and disposal of the product. In addition, all transportation and energy used, not only for the product but also for all elements in the product system, is included in the product system.

Function:
Drying hair

Functional unit (fu):
Drying hair in 5 minutes

Reference flow:
The function of the hair drier can only be performed by one hair drier. Thus, one hair drier is the reference flow.

System boundaries:
The decision rule for mass contribution is made to exclude less important processes from the product system using the following criteria.
i) Include all unit processes up to 80% cumulative weight of the total product weight. This resulted in system boundary including only four components, "Body", "Power cord (PVC)", "Packaging" and "Motor (steel)" in this study as shown in Table E2.1.

ii) If the unit process, however, is considered environmentally significant (e.g. toxic chemicals), then the process should be included in the product system. If we identify environmentally significant items later in the Life Cycle Inventory Analysis and Impact assessment, we should include those in the study.

Table E2.1 Product composition

Components	*Material*	*Weight (g)*	*Weight (%)*
Body	*PP*	*130.00*	*27.37%*
Power cord (PVC)	*PVC*	*116.00*	*24.42%*
Packaging	*Cardboard*	*75.00*	*15.79%*
Motor (steel)	*Steel*	*60.00*	*12.63%*
Motor (Cu)	*Cu*	*31.00*	*6.53%*
Power cord (Cu)	*Cu*	*25.00*	*5.26%*
Heater	*(Galvanized) steel*	*21.00*	*4.42%*
Fan	*ABS*	*10.00*	*2.11%*
Switch (steel)	*Steel*	*5.00*	*1.05%*
Switch (ABS)	*ABS*	*2.00*	*0.42%*
	Total	*475.00*	*100%*

In practice, we generally define the impact categories before performing LCI, we then collect the inventory data relevant to the impact categories. In other words, unless we define the decision rule for mass contribution from the viewpoint of cutting only processes with less impact on the targeted environmental categories we selected, we cannot fix the system boundary. However, we *cannot define the rule with certainty because one of the most important objectives of an LCA study is to identify the significant environmental aspects of the entire life cycle of a product. Thus, we should not fix environmental categories too early in an LCA study.*

Practically speaking, we review environmental categories as well as the system boundary of the product briefly at the starting point of an LCA study, and then fix the decision rule for mass contribution to define the exact system boundary. Therefore, it is an iterative process between goal and scope definition, life cycle inventory and impact assessment.

3 Life cycle inventory analysis

Life cycle inventory analysis (LCI) involves data collection and calculation to quantify inputs and outputs of materials and energy associated with a product system under study. In this case, all inputs and outputs of a unit process and of a product system are related to the main output of the unit process and the final product of the product system, respectively. Here, “related to” means “dividing by” either the unit process main output or the final product of the product system.

A product system consists of the manufacturing process of a product under study, plus the up and down stream processes of the product. A process tree or process flow diagram represents the interrelationship among unit processes in the product system.

Figure 3.1 shows general procedures for the implementation of LCI (ISO 14041, 1998). Major components shown in Figure 3.1 are delineated below.

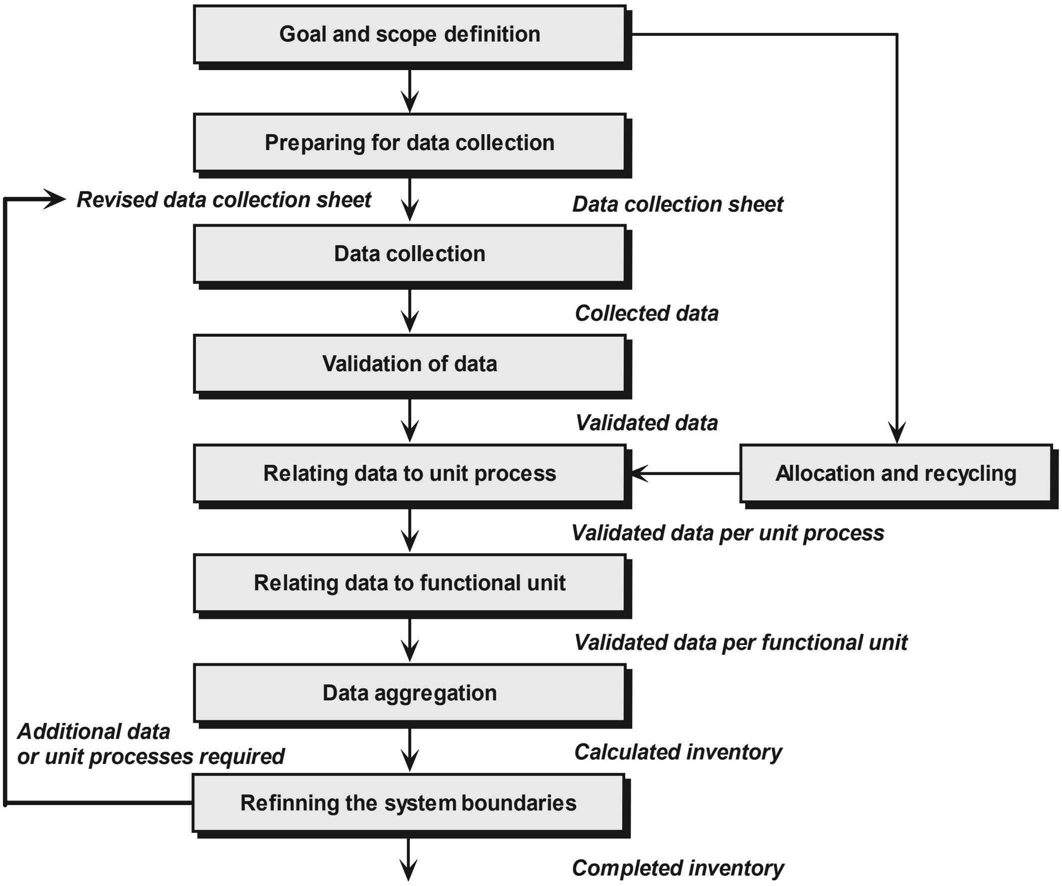


Figure 3.1 Operational procedures for LCI (ISO 14041, 1998)

3.1 Preparation for data collection

Input and output data of unit processes in the process tree are collected. Depending on the data quality requirements, various types of data can be collected such as on-site data, literature data or even database data.

You may also set targets for the data quality of the inventory parameters. Note that this is a target, not final data quality. Below is a generic framework to set up data quality requirements in an LCA study.

You should also define the following three items as part of setting the system boundary. Examples for these three items are provided.

Time related coverage: e.g. within the last 5 years
Geographical coverage: e.g. manufactured, used and disposed of in Eastern China
Technological coverage: e.g. average of current technologies

A data questionnaire is the most frequently used form of data collection medium for on-site data. The questionnaire is prepared by taking into account characteristics of the unit process under consideration. There is, however, a generic format for data questionnaires. It includes items such as product for data collection, data collector and date, period for data collection, detailed explanation of the process, inputs (raw materials, ancillary materials, energy, transportation) and outputs (emissions to air, water, and land) parameters and their quantity, and data quality, etc. Figure 3.2 shows the generic data questionnaire format.

Process :	Prepared by :
	Date :
Product Company :	Phone Number :
Product Period Beginning :	
Product Period Ending :	

1) Description of the process (in detail)

2) Inputs

Raw Materials, Ancillary Materials, Energy, Transportation

Parameter	Unit	Quantity	Data Quality	Country of Origin

3) Outputs

Emission to Air, Water, and Land

Parameter	Unit	Quantity	Data Quality	Comments

Figure 3.2 Generic data questionnaire format

3.2 Data collection and verification

Data is collected not by the LCA practitioner but by the employees who work at the site; thus, it is imperative to get their help and also ensure that they understand exactly what is involved in data collection. This means training in the basics of LCA and data parameters to be collected.

In general, the target period for data collection is one year. Data collection should begin from the most important unit processes and move towards less important processes. In addition, data for a product chosen for the LCA study should be collected from the production site.

Data sources for inputs to raw materials, ancillary materials and components include purchasing records, bill of materials, process diagram, and production records. Data sources for input energies such as electricity, fuel and steam include electricity, fuel and steam meter records, and date in electric motor power and times of operation of the motor. In the case of emissions to air, water and land, relevant data sources include measurement records or legal discharge limits. For those data related to products and co- or by-products, relevant sources include the number of product units or product mass, unit product weight, and price of the product.

Generally data for the raw material acquisition stage, including processing to usable raw materials, exists in public databases. Typical databases include data for materials (such as iron and polypropylene), energy (such as diesel and electricity), and processes (such as transportation and welding), etc. However, care must be taken when using these databases because system boundaries and assumptions made in developing the database may not be suitable for a specific LCA study.

Manufacturing data, in particular, of the product chosen for LCA study must be on-site data (either site specific or product specific). The data questionnaire shown in Figure 3.2 can be used for this purpose. For other manufacturing processes, such as components manufacturing, on-site data should be collected using the data questionnaire wherever possible. The same is true for transportation data. If site specific data is not available for transportation, then calculated or estimated transportation data can be produced. This can be done using transportation distance, transportation means, and type of fuels used.

Use data comes from customers; thus, consumer surveys, literature or manufacturer’s assumptions of the product usage become the basis for data on usage patterns during the use stage of the product life cycle. Typical data parameters include average use time, average use frequency or intensity, energy and resource (e.g. water) consumption, and emissions to air, water, and land. Disposal data collection requires information such as disposal pathways (e.g., recycling, reuse, incineration, land filling). For each pathway, relevant data should be collected, mostly through data questionnaires and literature or databases.

Before processing the data that has been collected, it should be checked for validity against each unit process or life cycle stages. Verification methods may include mass and energy balance in a given process or comparison with the emission factors for fuels, for example.

The data in LCI are often divided into “foreground data” and ‘background data”. The former is the data we collect, while the latter is database data. This type of data classification is common among LCA practitioners in Europe.

3.3 Calculation of environmental load per unit process

Data collected and verified for all unit processes in each product are now processed to facilitate calculation of life cycle inventory analysis. The input and output data for each unit process are divided by weight or energy content of the product (main output). This division results in input and output parameters expressed as per unit mass or energy of the main output of the unit process. If there are co- or by-products coming out of the unit processes under consideration, inputs and outputs corresponding to the product (main output) must be differentiated from those corresponding to units of co- and by-products. This process of allocating corresponding inputs and outputs to units of product is called allocation, which will be explained in section 7 of this chapter. Table 3.1 shows an example of the process for calculation of environmental load per unit process.

Table 3.1 Example of calculation of environmental load per unit process
Main output: product A
Output weight: 100 kg

Parameter	Data		Data divided by output weight	
	value	unit	value	unit
BOD	500	g	5	g/kg A
NO_x	750	g	7.5	g/kg A
Electricity	8,000	MJ	80	MJ/kg A
LNG	9,500	MJ	95	MJ/kg A

Values under the data heading divided by the output weight column in Table 3.1 are inventory or environmental load data of a unit process expressed as unit mass of main product, in this case product A. These values are termed unit environmental load of the unit process.

3.4 Calculation of environmental load per functional unit

By now, you should know that a process tree is a collection of unit processes.

The logical process for inventory or environmental load calculation involves a step by step procedure. First is the calculation of inventory data of a unit process as shown in Figure 3.3 (e.g., unit process A), then calculation of inventory data for a part of the entire product system (e.g., process P1 system), and then finally of the entire product system. Figure 3.3 is a fictitious process tree to illustrate the calculation procedure for the environmental load of a product system.

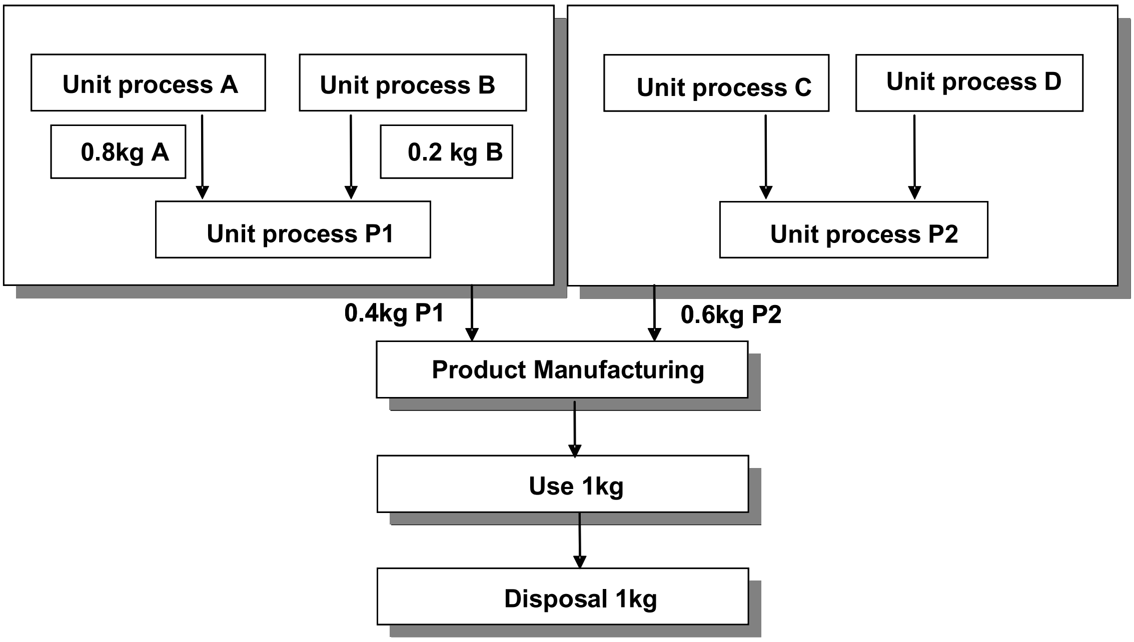


Figure 3.3 Fictitious process tree to provide an illustrative example

If you are calculating the environmental load data of a part of the entire product system (e.g., process P1 system) you must know the fractional contribution of each unit process to the main product of the product system. Multiplying fractional contribution by unit environmental load of a unit process and then summing up over the entire unit processes, enables one to obtain unit environmental load of the product system. These values are termed environmental load per functional unit of the product system.

In Figure 3.3, the main output or product of the P1 system is P1. Fractional contributions of unit process A and B to the manufacturing of P1 are 0.8 and 0.2, respectively. Unit environmental load of unit process A is shown in Table 3.1. Assuming that unit environmental load of unit process B consists of BOD, SO_2, NO_X, and electricity with values of 10 g/kg B, 15 g/kg B, 5 g/kg B, and 50 MJ/kg B, respectively, the environmental load per functional unit of sub product system

P1 is then calculated as shown in Table 3.2.

In this calculation procedure, inventory parameters from different unit processes are aggregated. For instance, BOD from process A and process B are aggregated. This is called data aggregation. The aggregation simplifies data presentation; however, transparency of the data weakens due to aggregation. In other words, one cannot trace the source of the data once they are aggregated.

Table 3.2 Example of environmental load per functional unit of product system P1

Parameter	Value	Unit
BOD	5(0.8)+10(0.2)=6	g/kg P1
SO_2	0(0.8)+15(0.2)=3	g/kg P1
NO_X	7.5(0.8)+5(0.2)=7	g/kg P1
Electricity	80(0.8)+50(0.2)=74	MJ/kg P1
LNG	95(0.8)+0(0.2)=76	MJ/kg P1

The same calculation logic applies to the calculation of the environmental load per functional unit of the entire product system shown in Figure 3.3. Denoting environmental load of each part of the entire product system in the entire product system's process tree as EL_i, where i is the i^{th} unit part of the entire product system, then environmental load of the entire product system is calculated as: (EL P1)(0.4) + (EL P2)(0.6) + (EL product)(1) + (EL use)(1) + (EL disposal)(1).

3.5 Life cycle inventory database (LCI DB)

Inventory data of common materials (e.g., steel plate, copper wire, Poly ethylene), energy (e.g., electricity, diesel), land processes (11 ton truck transportation) are often available in the form of LCI DB. The system boundary of the LCI DB usually spans from raw material acquisition to manufacturing of the materials, energy and processes. The latter includes all activities, up to factory gate, of the manufacturing plant. For instance, all unit processes and activities associated with the steel plate just before exiting the gate of the manufacturing plant are included in the system boundary. Often this type of system boundary is termed "cradle to gate" (CtG). Here, "cradle" represents raw materials extraction and "gate" represents the conclusion of the manufacturing plant process at the exit gate.

Use of LCI DB greatly simplifies the collection of life cycle inventory data. In the example of LCI at the end of this chapter are LCI DBs for the hair drier LCA study. Note that these LCI DBs are short versions of the actual LCI DBs. Each simplified DB contains less than 5 parameters. The purpose of providing simplified DB is to use it for simplified manual calculation of LCI in this book.

3.6 Preparation of a life cycle inventory table of a product system

Environmental load calculated per functional unit of a product system depicted in a process tree becomes the basis of the life cycle inventory table by arranging the results in inventory parameters. Figure 3.4 is a fictitious life cycle inventory table for illustrative purpose.

Parameters	Life cycle stages				
	Raw	Manufacturing	Use	Disposal	Total
Resources					
Iron ores	250				250
Crude oil	120	140	175	25	460
Emissions to air					
CO_2	250	270	300	30	850
SO_X	20	10	50	30	110
Emissions to water					
BOD	5	2	4	1	12
Phenol	0.3	0.2	0.1	0	0.6
Emissions to land					
Solid wastes	15	6	2	20	43

Figure 3.4 Fictitious life cycle inventory table of a product system (Unit: g/functional unit)

3.7 Allocation

Allocation is one of the most difficult components of an LCA study. Allocation is a process of partitioning the input and output flows to the product system under study. Often it is also explained as an act of distributing in proportionate share the environmental load created by unit processes to the product system under study (ISO 14041, 1998). The LCA practice related to allocation is to avoid the need for allocation as shown in Figure 3.5.

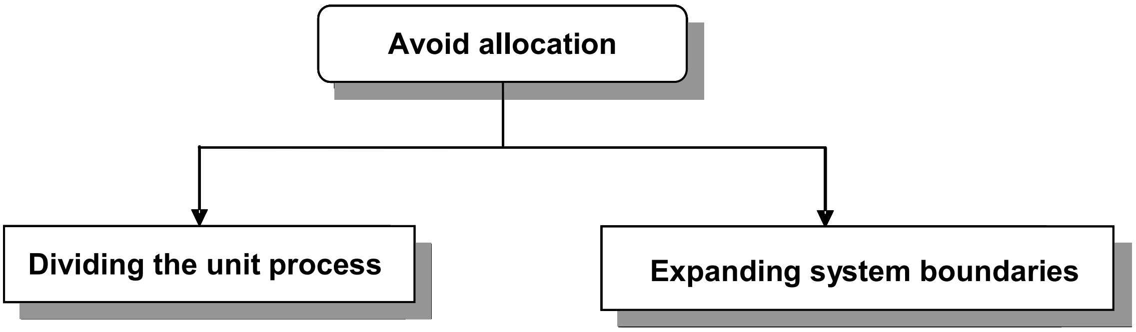


Figure 3.5 Avoiding allocation (ISO/TR 14049, 2000)

ISO 14041 recommends two approaches to avoid allocation, by subdividing the unit process under study or by expanding the system (e.g., avoided impact approach) (ISO 14041, 1998). However, there are cases where these ideal approaches cannot be applied; thus, allocation must be applied.

In this chapter, allocation is applied to two cases: a multi output process and a multi input process. Multi input processes have more than one input into a process such as the incineration process where more than one form of solid waste enters the process. In this case, allocation deals with the distribution of output from the process (e.g., waste flue gas) to an input material into the process under study. Multi output processes have more than one output in the form of co-products or by-products. Co-products and by-products must possess economic value to be allocated inputs and outputs. Allocation deals with the distribution of inputs (e.g., raw materials, ancillary materials, and energy) and outputs (e.g., environmental emissions) to a product under study.

Allocation requires criteria. Allocation criteria applicable to multi input and output processes include (in the order of preference as recommended by ISO 14041).

- Physical relationships between input and output across the unit process: e.g., a heavy metal that is contained in an input entering into a process will be present in the output of the process (for example, Cadmium in wastes entering an incinerator will be emitted as Cadmium in emissions to air in the form of flue gas).

- Economic values between product and co- and/or by-products, and physical quantities such as mass, volume, and energy of products and co- and/or by-products.

Figure 3.6 shows a copper production process to illustrate a method for the derivation of an allocation factor for different allocation criteria. Environmental loads from raw material acquisition, energy, and emissions to air, water, and land are to be allocated among product (copper), and two co- or by- products (Ag, Zn).

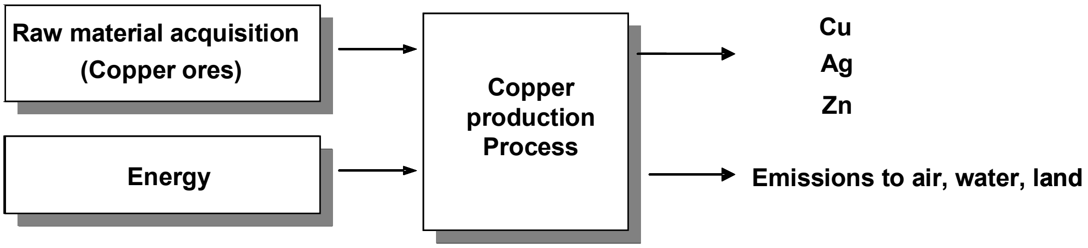


Figure 3.6 Copper production processes as allocation example

Table 3.3 provides an example calculation of allocation of a multi output process using both economic value and physical quantity as allocation criteria. One can see different allocation factor values depending on the use of different allocation criteria. In the case of economic value, the allocation factor for copper is 0.7. However, the allocation factor is 0.5 in the case of physical quantity (mass). This demonstrates how the use of allocation criteria can affect LCA results, sometimes significantly. Thus, recommendations given by ISO 14041 should be followed as closely as possible. That is, first, avoid allocation, if at all possible. If not, choose allocation criteria in the order of physical relationships, economic values, and then physical quantities. As a quality check of the life cycle inventory data, a sensitivity analysis of the allocation method is often carried out in an LCA study. This topic will be discussed in life cycle interpretation chapter.

Table 3.3 Example allocation of the Multi-output process (Copper Production Process)

Product	Economic value basis		Mass basis	
	Total value (10^6 \$/yr)	Allocation ratio (%)	Total mass (10^3 ton/yr)	Allocation ratio (%)
Cu	350	70	200	50
Ag	100	20	40	10
Zn	50	10	160	40
Total	500	100	400	100

3.8 LCI for recycling

Open loop recycling is an act of material recycling where waste from one product system enters into another product system as raw materials. By the same token, waste from another life cycle entering into the original product system as raw materials are also open loop recycling. Allocation, in this case, deals with the partitioning of the environmental load between two adjacent product systems due to waste recycling.

One may ask why there is a need for allocation in the case of open loop recycling. The argument made is that the use of recycled materials from one product system (disposed of as waste but collected and processed for recycling) as raw materials in another product system results in reduction of the environmental load of both product systems. The product system generating waste reduces some of its environmental load because of the reduced amount of waste requiring final disposal. The product system receiving the recycled materials reduces its environmental load because of the reduced use of raw materials. The reduction in environmental loads is made possible because there are two adjacent product systems. Thus, allocation is needed, and it is necessary to determine how much environmental load from the disposal process, raw material acquisition process, and recycling process should be allocated to each product system involved in the open loop recycling activity.

Allocation in the open loop recycling case is much more complicated than that of multi input or output cases. There are no firmly established methods. Currently, closed loop approximation, avoided impact, cut-off, extraction load, disposal load, 50/50, and material pool methods are in use. Of these methods, the most frequently used, such as cut-off, 50/50 and avoided impact methods are discussed here.

Figure 3.7 shows open loop recycling applied to three different product systems. Numbers in Figure 3.7 are arbitrarily chosen for illustrative purpose only. Assumptions are made to simplify the illustrative examples shown in Figure 3.7. First, material flow in each product system is assumed to be 1 kg. Second, environmental load of each life cycle stage is arbitrarily set at; raw material acquisition, manufacturing and use, disposal, and recycling as 300, 0, 200, and 100 Environmental load (EL)/kg material flow, respectively. Note that the manufacturing and use stages are not subjected to allocation so their environmental load was set to zero.

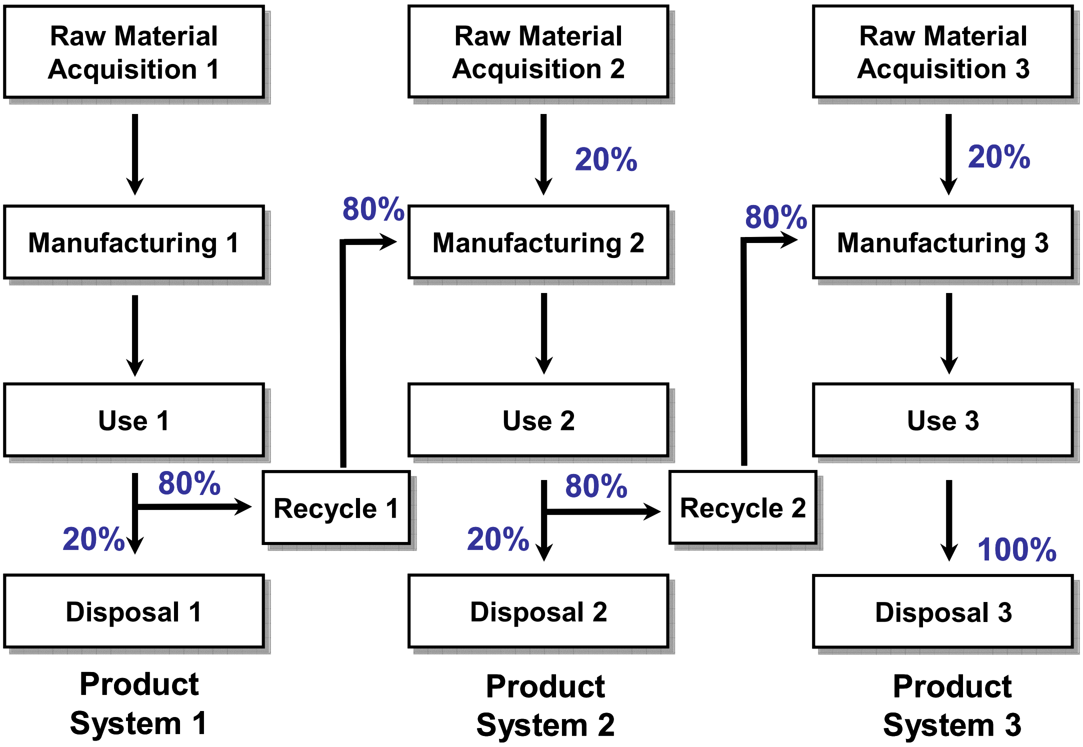


Figure 3.7 Open loop recycling applied to three product systems

1) The cut-off method

The basic assumption of the cut-off method is that all inputs and outputs to and from a product system throughout the entire life cycle are the responsibility of that product system. This means that benefits associated with recycling are not considered in this method. However, environmental load associated with the recycling process is taken into account by including the process in the product system. A decision must be made as to whether the recycling process should belong to the first product system or the subsequent product system.

The environmental load of raw material acquisition is proportional to the amount of virgin raw material used. In other words, the amount of recycled material used as raw material is subtracted from the total amount of raw material used. Environmental load of the disposal is proportional to the net amount of waste disposed of after subtracting the amount of waste recycled from the total amount of waste generated. Finally, environmental load of the recycling process is proportional to the amount of waste recycled.

Allocation of the environmental load by the cut-off method is shown in Figure 3.8.

Product system	Life cycle stage	EL allocation (Credit due to the recycled amount)
1	Raw material acquisition	Net virgin material use = 300/kg × 1.0kg = 300
	Disposal	Amount disposed of = 200/kg × 0.2kg = 40
	Recycling	Amount recycled = 100/kg × 0.8kg = 80
2	Raw material acquisition	Net virgin material use = 300/kg × 0.2kg = 60
	Disposal	Amount disposed of = 200/kg × 0.2kg = 40
	Recycling	Amount recycled = 100/kg × 0.8kg = 80
3	Raw material acquisition	Net virgin material use = 300/kg × 0.2kg = 60
	Disposal	Amount disposed of = 200/kg × 1.0kg = 200
	Recycling	Amount recycled = 100/kg × 0.0kg = 0

Figure 3.8 Allocation by the cut-off method

Results of allocation of the environmental load by the cut-off method are shown in Table 3.4.

Table 3.4 Allocation results by the cut-off method

Life cycle stages	Product system		
	1	2	3
Raw material acquisition	300	60	60
Disposal	40	40	200
Recycling	80	80	0
Sum	420	180	260

2) The 50/50 method

The basic assumption of the 50/50 method is that environmental loads of the recycling of material from one product system to another are shared equally between two adjacent product systems. In addition, environmental loads of the raw material acquisition and disposal are shared equally between the first and the last product systems. The reason being is that recycling occurs because of mutual interest between two adjacent product systems, and virgin raw material is used in the first product system while it is lost to nature in the last product system.

The environmental load of raw material acquisition is the sum of the environmental load of the virgin raw material used and half of the environmental load of the recycled material used. The environmental load of disposal is equal to the environmental load of the material disposed of and half of the environmental load of the recycled material. Finally, the environmental load of the material recycling for each product system is equal to the amount of recycled material times 0.5.

Allocation of environmental load by the 50/50 method is shown in Figure 3.9.

Product system	Life cycle stage	EL allocation (Credit due to the recycled amount)
1	Raw material acquisition	Net virgin material use(1) – raw material recovered by recycling(1)×0.5 = 300/kg×1.0kg – 300/kg×0.8kg×0.5 = 180
	Disposal	Amount disposed of(1) + Amount of disposal reduced by recycling(1)×0.5 = 200/kg×0.2kg + 200/kg×0.8kg×0.5= 120
	Recycling	Amount recycled(1)×0.5 = 100/kg×0.8kg×0.5 = 40
2	Raw material acquisition	Net virgin material use(2) + raw material recovered by recycling(1)×0.5 – raw material recovered by recycling(2)×0.5 = 300/kg×0.2kg + 300/kg×0.8kg×0.5– 300/kg×0.8kg×0.5 = 60
	Disposal	Amount disposed of (2) – Amount of disposal(1) reduced by recycle(1)×0.5 + Amount of disposal(2) reduced by recycle(2)×0.5 = 200/kg×0.2kg–200/kg×0.8kg×0.5 +200/kg×0.8kg×0.5 = 40
	Recycling	Amount recycled(1)×0.5 + Amount recycled(2) = 100/kg×0.8kg×0.5 + 100/kg×0.8kg×0.5 = 80
3	Raw material acquisition	Net virgin material use(3) + raw material recovered by recycling(2) ×0.5 = 300/kg×0.2kg + 300/kg×0.8kg×0.5 =180
	Disposal	Amount disposed of(3) – Amount of disposal(2) reduced by recycling(2) ×0.5 = 200/kg×1.0kg–200/kg×0.8kg×0.5 = 120
	Recycling	Amount recycled(2) × 0.5 = 100/kg×0.8kg×0.5 = 40

Figure 3.9 Allocation by the 50/50 method

Results of allocation of the environmental load by the 50/50 method are shown in Table 3.5.

Table 3.5 Allocation results by the 50/50 method

Life cycle stage	Product system		
	1	2	3
Raw material acquisition	180	60	180
Disposal	120	40	120
Recycling	40	80	40
Sum	340	180	340

3) The avoided impact approach

Recycled material from one product system is used to substitute for virgin material use in an adjacent product system. By expanding the system boundary of the first product system to include the processes related to the substituted virgin raw material, allocation can be avoided. This is one of two methods recommended to avoid allocation, see ISO 14041.

The environmental load of raw material acquisition is proportional to the amount of virgin raw material used minus the amount of material recycled for use as raw material in other product systems. Here the environmental load of the virgin raw material is subtracted from the total environmental load of the raw material used in the product system. The environmental load of disposal is proportional to the amount of waste disposed of after subtracting the amount of waste recycled. Finally, the environmental load of recycling is proportional to the amount of waste recycled.

Allocation of environmental load by the avoided impact approach is shown in Figure 3.10. For simplicity, only the first product system is shown here.

Product system	Life cycle stage	EL allocation (Credit due to the recycled amount)
1	Raw material acquisition	Net virgin material use – substituted virgin raw material use = 300/kg×1.0kg – 300/kg×0.8kg = 60
	Disposal	Amount disposed of = 200/kg×0.2kg = 40
	Recycling	Amount recycled = 100/kg×0.8kg = 80

Figure 3.10 Avoided impact approach

For instance, assume that wastes from a paper mill are incinerated in an incinerator where heat is recovered and used to supplement heating of the paper mill. As a result the heating fuel consumption, LNG, is reduced in the paper mill. The reduction in the LNG consumption is attributed to the incineration of the waste. Thus, the paper mill is entitled to claim environmental credit for the reduction in environmental load associated with the quantity of LNG saved. The environmental load of LNG includes raw material extraction, transportation and processing of the fuel. Figure 3.11 shows system boundary for the case cited here.

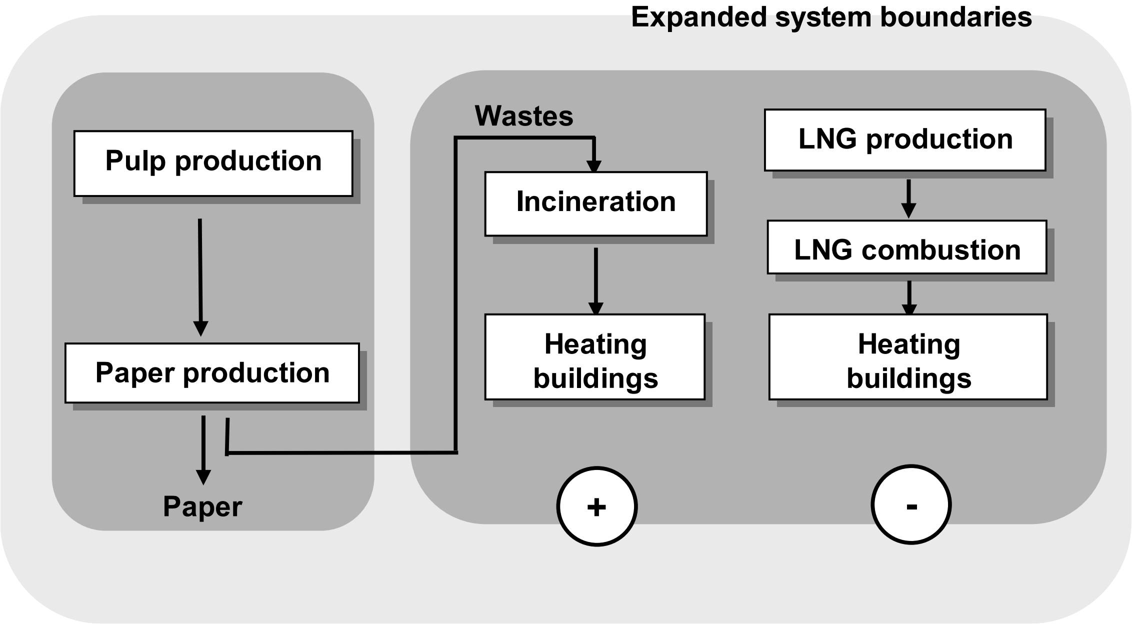


Figure 3.11 System boundary for the paper mill waste heat case using the avoided impact approach

Example of Life cycle inventory analysis: hair drier case

1) Life cycle data

Manufacturing data (including component manufacturing)	*Manufacturing is mostly dominated by injection molding of body / power cord / packaging / motor.* *Note: The weight of each component is shown in material composition Table E2.1 in chapter 2. Up to 80% cumulative weight is considered in this study (20% decision rules for mass contribution).*	*Two products are assembled at the site, model A and model B. Total electricity consumed in manufacturing is 5,040 kWh per year.* *Note: This will be allocated to Model (A) based on economic value.*

↓

Distribution data	*The distribution distance is approximately 3,000 km within Eastern China by 20 ton trucks.*	

↓

Use data	*Use scenario* *- drying hair in 5 minutes (requires 83.33 Wh)* *- once a day* *- 6 days a week* *- 50 weeks a year* *- the total uses add up to 1,200 over the 4 year lifetime of the product*	*Electricity consumed 0.083 kWh/time.* *Note: Electricity consumption is data based on a scenario, which should be checked in the sensitivity analysis described in Chapter 5, Life Cycle Interpretation.*

↓

Disposal data	*Disposal via municipal waste (waste incineration only)*	*There are two scenarios (A and B) for disposal.* *- Scenario A (Old fashioned way): Incineration 50%, the rest is landfill.* *- Scenario B (by WEEE directive): The ratio of recycling, incineration, and landfill is 50%, 20%, and 30%, respectively.*

Data quality of the background data

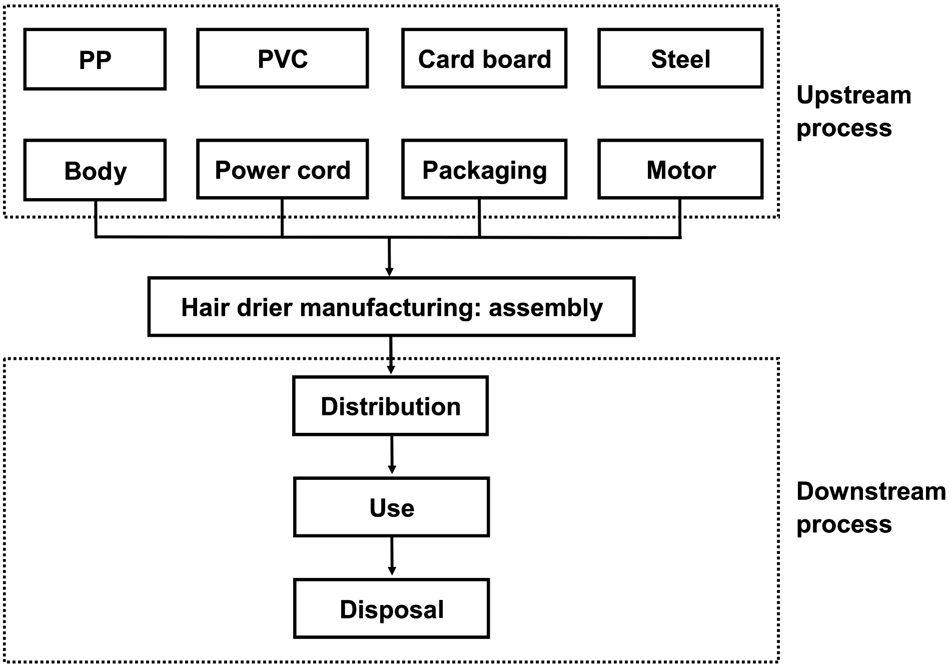
Time related coverage: within the last 5 years
Geographical coverage: manufactured, used and disposed of in Eastern China
Technological coverage: current average technologies

Data category and parameter

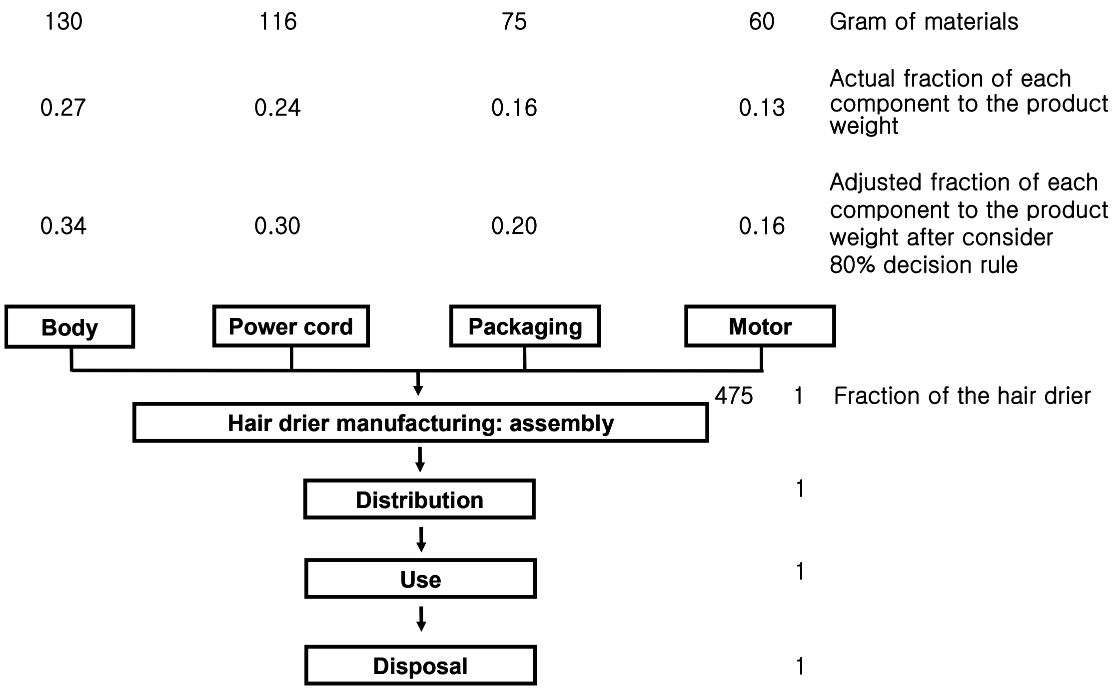
Input data:
Raw materials: iron ore, crude oil, etc
Ancillary materials: not known
Energy: electricity, diesel fuel

Output data:
Emissions to air: CO_2, *VOC,* CH_4
Emissions to water: not known
Emissions to land: solid waste
Product: hair drier Model (A)
Co-/by- products: Model (B)

2) *Process tree*



3) Process tree with material balance



4) Example of the LCI database: hair drier case

The following data base is used as the background data of this study

Database

	Substance	Category	Unit	Total
PP (1 kg)	Crude oil	Raw	g	1.20E+03
	CO_2	Air	g	1.80E+03
	NO_X (as NO_2)	Air	g	1.00E+01
	SO_X (as SO_2)	Air	g	1.10E+01
	VOC	Air	g	9.60E+00
Cardboard (1 kg)	Crude oil	Raw	g	1.14E+02
	CO_2	Air	g	4.67E+02
	NO_X	Air	g	3.96E+00
Steel (1 kg)	Crude oil	Raw	g	3.60E+01
	Coal	Raw	g	3.84E+02
	Iron ore	Raw	g	9.79E+02
	CO_2	Air	g	1.52E+03
PVC	Crude oil	Raw	g	3.70E+02

(1 kg)	Coal	Raw	g	1.30E+02
	CO_2	Air	g	1.94E+03
	VOC	Air	g	1.43E+01
Electricity (1 kWh)	Coal	Raw	g	4.95E+01
	CO_2	Air	g	2.90E+02
	Methane	Air	g	5.32E-01
	SO_2	Air	g	1.18E+00
Transportation (20t Truck, 1ton-km, 50% loaded)	Crude oil	Raw	g	2.81E+01
	CO	Air	g	5.08E-01
	CO_2	Air	g	9.25E+01
Incineration (50%) (1 kg waste)	Coal	Raw	g	1.89E-01
	Crude oil	Raw	g	2.76E+00
	CO_2	Air	g	7.09E+02
	NO_X (as NO_2)	Air	g	1.57E-01
Landfill (50%) (1 kg waste)	Coal	Raw	g	4.33E-02
	Crude oil	Raw	g	1.90E+00
	CO_2	Air	g	3.07E+01
	Methane	Air	g	3.07E+00
	SO_X(as SO_2)	Air	g	1.51E-01
Incineration (20%) (1 kg waste)	Coal	Raw	g	1.61E-01
	Crude oil	Raw	g	7.02E-01
	CO_2	Air	g	3.56E+00
	NO_X (as NO_2)	Air	g	1.27E-01
Landfill (30%) (1 kg waste)	Crude oil	Raw	g	9.54E-01
	CO_2	Air	g	1.87E+01
	Methane	Air	g	1.97E+00
	SO_X (as SO_2)	Air	g	3.24E-02
Recycling (50%) (1 kg waste)	Coal	Raw	g	7.88E+00
	Crude oil	Raw	g	-7.49E+01
	Iron ore	Raw	g	-1.06E+02
	CO_2	Air	g	-2.00E+02

Note: A negative value for recycling means there is an environmental benefit or positive environmental impact accrued from recycling, not adverse environmental impacts.

5) Data from raw material acquisition to components manufacturing

Just prior to main product (hair drier) manufacturing (assembly), assume process scraps generated during manufacturing will be reused as raw material in the same process.

a) Body manufacturing

Data collected per unit body	Electricity	0.27 kWh
	PP	130 g
	Calculation of environmental load (EL): DB electricity/kWh×0.27 kWh/unit body DB PP/kg×0.13 kg/unit body	

b) Power cord manufacturing

Data collected per unit power cord (PVC)	Electricity	0.5 kWh (Data allocated by physical mass)
	PVC	116 g
	Calculation of environmental load (EL): DB electricity/kWh× 0.5 kWh/unit power cord (PVC) DB PVC/kg× 0.116 kg/unit power cord (PVC)	

c) Packaging manufacturing

Data collected per unit packaging	Electricity	0.1 kWh
	Paper carton (Cardboard)	75 g
	Calculation of environmental load (EL): DB electricity/kWh× 0.1 kWh/unit packaging DB Cardboard/kg× 0.075 kg/unit packaging	

d) Motor manufacturing

Data collected per unit motor (steel)	Electricity	0.6 kWh (Data allocated by physical mass)
	PVC	60 g
	Calculation of environmental load (EL): DB electricity/kWh×0.6 kWh/unit motor DB Steel/kg× 0.06 kg/unit motor	

d) Total EL from the upstream processes

Sum of EL from body (1), power cord (2), packaging (3), and motor manufacturing (4)

We took the 80% decision rules for mass contribution; therefore, we must adjust the data for the weight of a hair drier.

Adjusted EL; actual EL × 1/decision rules for mass contribution factor
(Sum of body (1), power cord (2), packaging (3), and motor manufacturing (4))/0.8

6) Data from manufacturing process (hair drier assembly)

- Electricity used during assembly is the only source of input.
- Assume no wastes or emissions to air and water, or by-products.
- As Model(A) and Model(B) are manufactured in the same manufacturing process in the same factory, electricity consumed in the process must be allocated to each model. In this study, allocation based on economic value was used.

Allocation

a) Manufacturing of hair drier: Model (A) and Model (B) in same factory

Product	*Model (A)*	*Model (B)*
Amount of product (piece)	*6,420*	*7,469*

b) Allocation factor by Economic value

Type of model	*Model (A)*	*Model (B)*	*Total*
Sale price (dollar/EA)	*14*	*17*	*31*
Total sale price (dollar)	*89,880*	*126,970*	*216,853*
Allocation factor	*41.4*	*58.6*	*100.0*

c) Calculation of electricity consumed for Model (A)

Electricity consumed	*Allocation factor*	*Electricity consumed (Allocated)*	*Electricity consumed (Allocated)/reference flow*
5,040 kWh	*0.414*	*2,089 kWh for Product A*	*0.33 kWh*

5,040 kWh x (0.414)/(6,420unit) = 0.33 kWh/one unit of Model(A)

Calculation of environmental load (EL): DB electricity/kWh× 0.33 kWh/unit hair drier

7) Data from distribution process

Data collected from distribution process	*Distance*	*3,000 km*
	Location	*within Eastern China*
	Transportation means	*20 tons*
	Calculation of environmental load (EL): DB 20 ton truck/(ton-km) × distance traveled (3,000 km) × hair drier weight (0.475 kg/(1,000 kg/ton))	

In calculating the EL of distribution, a single hair drier is considered.

8) Data from use stage

- *Electricity used for drying hair was the only source of input.*
- *No consideration was given to water.*

Use scenario

- *Drying hair in 5 minutes (requires 83.33 Wh)*
- *Once a day*
- *6 days a week*
- *50 weeks a year*

The total uses add up to 1,200 times over the 4 year lifetime of the product.

Data collected from use stage	*Electricity consumed*	*0.0833 kWh/each use*
	Calculation of environmental load (EL): DB electricity/kWh× 0.0833 kWh/each use× 1,200 uses	

9) Data from disposal stage

Scenario A - Assume that 50% of the hair drier by mass is combustible parts, while the remaining 50% is non combustible. The combustible parts are incinerated and the rest is landfilled.

Scenario B - Assume that 20% of the hair drier will go into incineration, 30% to landfill and the remaining 50% into recycling. (This is to reflect the requirements set in the WEEE directive)

In this example, the two disposal scenarios will be compared to determine the impact of different scenarios on the environmental load of disposal of the hair drier.

- Assume that the environmental load associated with the collection of waste hair drier is negligible.

Scenario A	*Scenario B*
Landfill – 50%	*Landfill – 20%*
Incineration – 50%	*Incineration – 30%* *Recycling – 50%*
Calculation of environmental load (EL): *DB incineration (50%)/kg × 0.475 kg/unit hair drier* *DB landfill (50%)/kg × 0.475 kg/unit hair drier*	*Calculation of environmental load (EL):* *DB incineration (20%)/kg × 0.475 kg/unit hair drier* *DB landfill (30%)/kg × 0.475 kg/unit hair drier* *DB recycling (50%)/kg × 0.475 kg/unit hair drier*

10) LCI of hair drier

Sum of EL from the upstream, manufacturing, distribution, use and disposal stages:

a) EL from the upstream processes

Parameter	*Body (housing)*		*Power cord manufacturing*		*Packaging manufacturing*		*Motor manufacturing*		*Total (EL /0.80)*
	PP	*Electricity*	*PVC*	*Electricity*	*Cardboard*	*Electricity*	*Steel*	*Electricity*	
Crude oil	*1.56E+02*		*4.29E+01*		*8.57E+00*		*2.16E+00*		*2.62E+02*
Coal		*1.34E+01*	*1.51E+01*	*2.48E+01*		*4.95E+00*	*2.30E+01*	*2.97E+01*	*1.39E+02*
Iron ore							*5.87E+01*		*7.34E+01*
CO_2	*2.34E+02*	*7.83E+01*	*2.25E+02*	*1.45E+02*	*3.50E+01*	*2.90E+01*	*9.12E+01*	*1.74E+02*	*1.26E+03*
Methane		*1.44E-01*		*2.66E-01*		*5.32E-02*		*3.19E-01*	*9.78E-01*
CO									
VOC	*1.25E+00*		*1.66E+00*						*3.63E+00*
NO_x (Air)	*1.30E+00*				*2.97E-01*				*2.00E+00*
SO_x (Air)	*1.43E+00*	*3.19E-01*		*5.90E-01*		*1.18E-01*		*7.08E-01*	*3.96E+00*

Note: 0.80 is the mass fraction included in the product system as defined by the decision rule for mass contribution, 80%.

b) EL from the manufacturing, distribution, and use stage

Parameter	*Manufacturing*	*Distribution*	*Use*	*Total*
	Electricity	*Transportation*	*Electricity*	
Crude oil		*4.00E+01*		*4.00E+01*
Coal	*1.61E+01*		*4.95E+03*	*4.96E+03*
Iron ore				
CO_2	*9.43E+01*	*1.32E+02*	*2.90E+04*	*2.92E+04*
Methane	*1.73E-01*		*5.32E+01*	*5.34E+01*
CO		*7.24E-01*		*7.24E-01*
VOC				
NO_x (Air)				
SO_x (Air)	*3.84E-01*		*1.18E+02*	*1.18E+02*

c) EL from the disposal stage

Parameter	*Scenario A*			*Scenario B*			
	Incineration (50%)	*Landfill (50%)*	*Total*	*Incineration (20%)*	*Landfill (30%)*	*Recycling (50%)*	*Total*
Crude oil	*1.31E+00*	*9.02E-01*	*2.21E+00*	*3.33E-01*	*4.53E-01*	*-3.56E+01*	*-3.48E+01*
Coal	*8.98E-02*	*2.05E-02*	*1.10E-01*	*7.65E-02*		*3.74E+00*	*3.82E+00*
Iron ore						*-5.03E+01*	*-5.03E+01*
CO_2	*3.37E+02*	*1.46E+01*	*3.52E+02*	*1.69E+00*	*8.89E+00*	*-9.52E+01*	*-8.46E+01*
Methane		*1.46E+00*	*1.46E+00*		*9.36E-01*		*9.36E-01*
CO							
VOC							
NO_x (Air)	*7.48E-02*		*7.48E-02*	*6.03E-02*			*6.03E-02*
SO_x (Air)		*7.18E-02*	*7.18E-02*		*1.54E-02*		*1.54E-02*

Comparison of EL, during the disposal stage only, between scenario A and B:

As shown in Figure E3.1, scenario B reduces environmental load of the disposal stage by increasing the recycling rate of the waste. A negative EL indicates reduction in environmental load, i.e., beneficial, not adverse, impact on the environment.

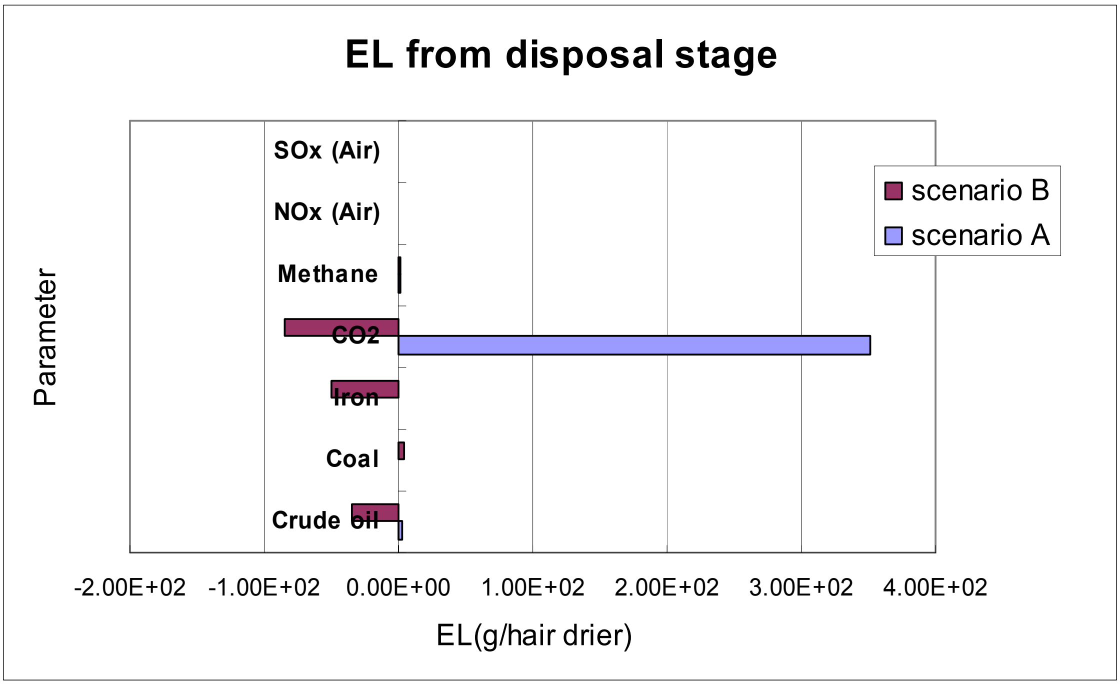


Figure E3.1 Environmental load in the disposal stage for scenarios A and B

f) Sum of EL

Parameter	*Upstream*	*Manufacturing*	*Distribution*	*Use*	*Disposal*		*Sum of EL (g/hair drier)*	
					Scenario A	*Scenario B*	*Scenario A*	*Scenario B*
Crude oil	*2.62E+02*		*4.00E+01*		*2.21E+00*	*-3.48E+01*	*3.04E+02*	*2.67E+02*
Coal	*1.39E+02*	*1.61E+01*		*4.95E+03*	*1.10E-01*	*3.82E+00*	*5.10E+03*	*5.11E+03*
Iron ore	*7.34E+01*					*-5.03E+01*	*7.34E+01*	*2.32E+01*
CO_2	*1.26E+03*	*9.43E+01*	*1.32E+02*	*2.90E+04*	*3.52E+02*	*-8.46E+01*	*3.08E+04*	*3.04E+04*
Methane	*9.78E-01*	*1.73E-01*		*5.32E+01*	*1.46E+00*	*9.36E-01*	*5.58E+01*	*5.53E+01*
CO			*7.24E-01*				*7.24E-01*	*7.24E-01*
VOC	*3.63E+00*						*3.63E+00*	*3.63E+00*
NO_x (Air)	*2.00E+00*				*7.48E-02*	*6.03E-02*	*2.07E+00*	*2.06E+00*
SO_x (Air)	*3.96E+00*	*3.84E-01*		*1.18E+02*	*7.18E-02*	*1.54E-02*	*1.22E+02*	*1.22E+02*

Comparison of EL between product system scenarios A and B:

For the environmental load over the entire product system, the difference between scenario A and B does not appear to be significant, as shown in Figure E3.2. This is because EL from the disposal stage is minor compared to the combined EL of the other life stages. The reduction in EL in the case of scenario B over that of scenario A, though small, is demonstrated in Figure E3.2. Recycling of waste should, therefore, be encouraged in order to reduce EL from a product system.

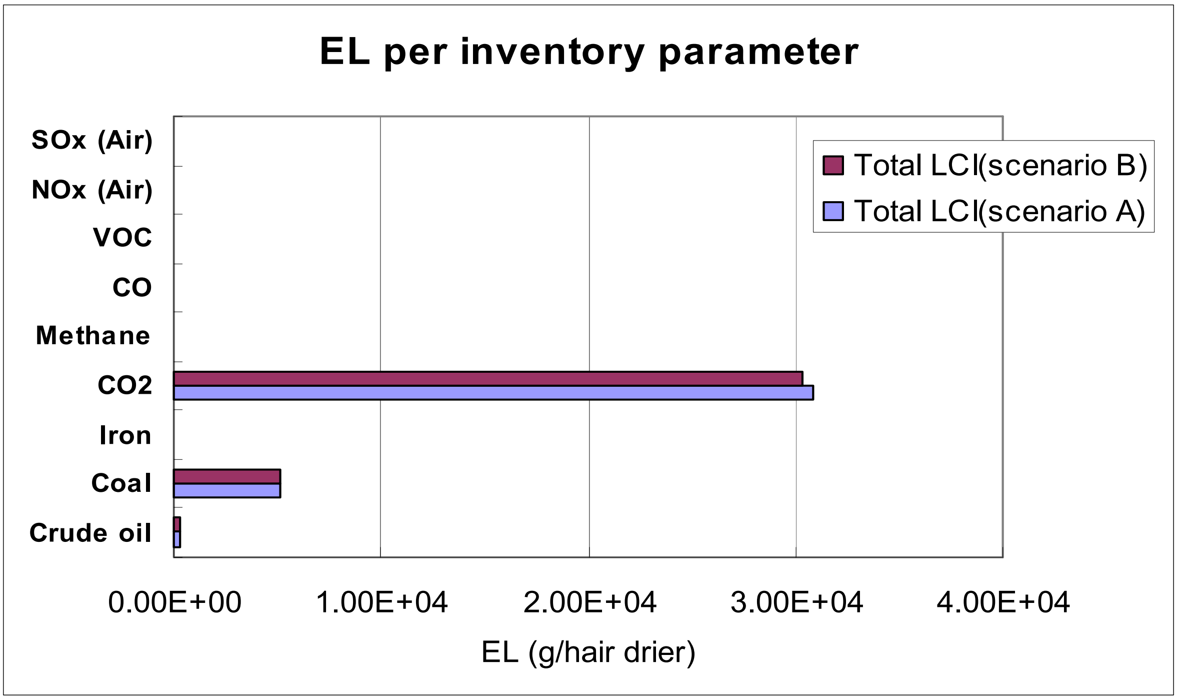


Figure E3.2 Environmental load of the entire product system per inventory parameter for scenarios A and B

4 Life cycle impact assessment

The significance of potential environmental impacts of a product system based on life cycle inventory results is evaluated by using LCIA. The LCIA consists of several elements. They are classification, characterization, normalization, and weighting. Of these four elements, normalization and weighting are considered optional, while the first two are mandatory elements in LCIA. For details, see ISO 14042, 2000. Figure 4.1 shows the elements and the relationship among them in LCIA, with an illustrated example.

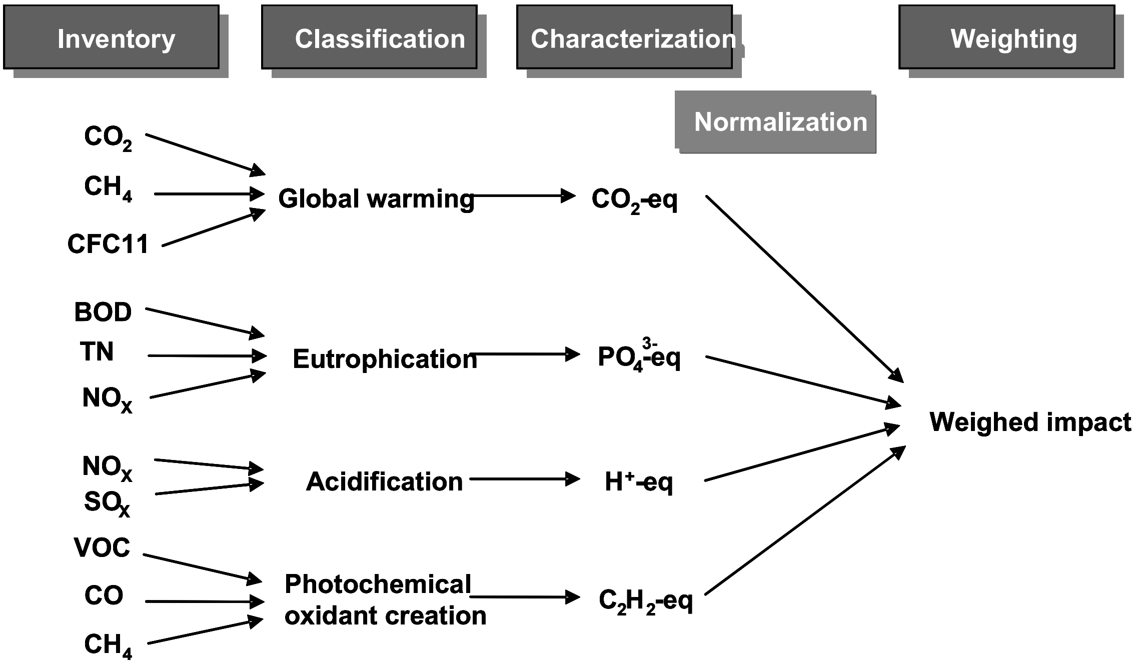


Figure 4.1 Elements and relationship among the elements of LCIA

Below are explanations of all four elements in LCIA. In addition, LCIA examples using the hair drier case follow.

4.1 Classification

Inputs and outputs listed in LCI results are assigned to impact categories based on expected types of impact on the environment. The expected types of environmental impact for each input and output parameter in the inventory results are the key points to address here. The types of environmental impacts to be considered in LCIA are another key point.

Common impact categories often considered in LCIA are listed below. This list is arranged in the order of scale of impact, from global to local.

- Abiotic and biotic resource depletion
- Global warming
- Ozone depletion
- Photochemical oxidant formation (Ozone) or smog formation
- Acidification
- Eutrophication
- Human toxicity
- Ecotoxicity
- Solid waste, hazardous and radioactive waste

Some of these impact categories are well defined and thus allow quantitative estimation of impacts by inventory parameters on the said impact category. However, most of them are not well defined and quantitative estimation of the environmental impact is difficult. Discussion on LCIA in this book will be limited to those well defined impact categories with established characterization or equivalency factors. In the LCA field, impact categories considered in the classification section include global warming, ozone depletion, acidification, eutrophication, photochemical oxidant formation, abiotic resource depletion, human toxicity, ecotoxicity, and solid waste. Of these, the last three categories do not have reliable characterization factors; thus, they will not be discussed in the characterization steps and beyond.

Once impact categories are chosen for an LCA study, the next step is to link life cycle inventory parameter to corresponding impact categories based on the cause-effect relationship. This requires prior knowledge of this relationship. It should be noted that one parameter can affect more than one impact categories. For instance, NO_X can affect not only acidification but also eutrophication, and even smog formation. A cause-effect relationship is described in Figure 4.2 for the case of green house gas emission, causing so called "global warming" effect to the environment.

Cause-Effect Chain - Example: Global Warming

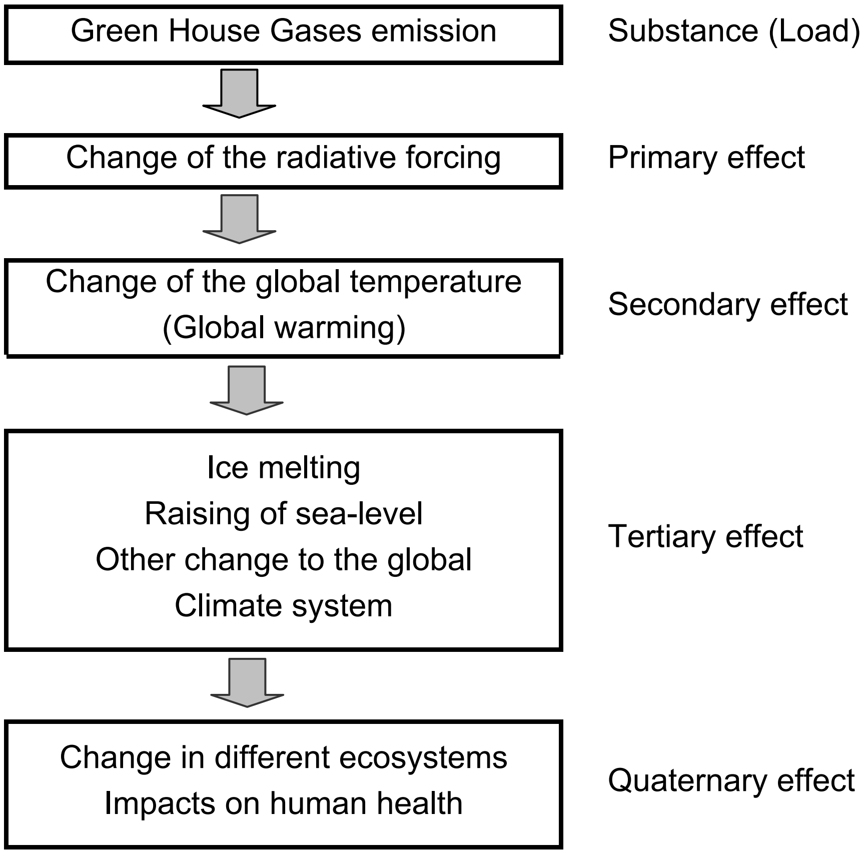


Figure 4.2 Cause-effect chain of green house gases in the environment

There are four cases where multiple impacts occur from a single inventory parameter. They are parallel impacts, serial impacts, indirect impacts, and combined impacts.

In parallel impacts, a single inventory parameter causes more than two distinctively different impacts. The case of NO_X is a good example of this. A logical step to take, after the linking, is to assign a quantity of inventory parameter in proportion to its contribution to each impact category. However, no information is available about these proportions most of the time. Thus, it is customary to assign the total amount of inventory parameter to all types of impact category in the parallel impact case. This may create concern about double counting, however, LCA seeks to consider the worst possible case, therefore, double counting is not a serious problem.

The second case of multiple impacts is serial impacts. Here, one inventory parameter causes two or more different types of impact in series. An example of this is a heavy metal that causes ecotoxicity which then becomes human toxicity. Toxic chemicals released into the environment affect the ecosystems first and then these ecosystems affect eventually impact on humans. In this case, there is no double counting problem. The question that needs to be addressed is how far this serial impact chain goes.

The third case involves indirect impacts. Here impact is induced by an inventory parameter, but not caused by the inventory parameter itself. An example is the case of ozone formation in the photochemical smog where NO_X acts as a catalyst. The root cause of smog is volatile organic compounds (VOC) and Carbon monoxide.

The final case is combined impacts, where emissions of substances have a mutual influence on each other's impacts, e.g., synergistic or antagonistic impacts of mixtures of toxic substances, or NO_x and VOC, both of which are required for photo-oxidant formation (Guinée et al., 2001).

Figure 4.3 shows classification of life cycle inventory results consisting of four parameters, CO_2, BOD, NO_X, and methane.

Inventory parameter	Impact category (i)							
	GW	OD	AD	EU	POC	HT	ET	ARD
CO_2	●							
BOD				●				
NO_X			●	●	●	●		
Methane	●				●			

Figure 4.3 Classification of inventory parameters for illustrative purpose

4.2 Characterization

Once the classification step is completed as shown above, quantification of environmental impacts by each inventory parameter on the impact category is assessed. A characterization factor that characterizes contribution of a given inventory parameter to the assigned impact category provides practical means for the quantification. It should be noted that quantification is only made within a given impact category. In other words, characterization factors only address relative contribution among inventory parameters assigned to a given impact category. Once the contribution of each parameter is quantified, the quantified impacts can be aggregated or added within the same impact category because all individual quantified impacts have the same dimension or unit. Thus, environmental impacts of a given impact category can be calculated from the life cycle inventory results of a product system.

Key to the quantification of the environmental impacts exerted by inventory parameters on a given impact category is the characterization or equivalency factor. A characterization factor is based on the equivalency principle used in chemistry. This principle can best be explained by citing an example. Both CO_2 and CH_4 contribute to global warming, but in differing degrees. Atmospheric research revealed that contribution to global warming of 1 g of CH_4 is the same as that of 23 g of CO_2. In this case, 1 g of CH_4 is equivalent to 23 g of CO_2 in terms of global warming impact. If the contribution to global warming of 1 g CO_2 is defined as unit global warming, then contribution to global warming of 1 g of CH_4 can be expressed as 23 g CO_2 equivalent. Thus, the equivalency or characterization factor of CH_4 is 23 g CO_2 equivalent (eq), and this value is identified as the global warming potential (GWP) of CH_4.

The equivalency factor, however, has limitations. It does not take into account thresholds so a linear relationship is assumed to exist between inventory parameter concentration and its impact on the environment. It also assumes that a given emission causes the same environmental impact wherever and however the emission occurs, notably no consideration is given to the environmental impact as a function of the rate of emission over time. However, it allows for consideration of geographical effects in terms of zone of influence, e.g., local or regional, and sensitivity of the areas to the emissions.

Once characterization factors are available, then environmental impacts by inventory parameters on a given impact category can be quantified using the approach in equation (1).

$$CI_{i,j} = Load_j \times eqv_{i,j} \qquad (1)$$

Where,

$CI_{i,j}$ = the magnitude of characterized impact by the jth inventory parameter in the ith impact category, g x-eq/ fu,

fu = functional unit,

$Load_j$ = the quantity of the jth inventory parameter, g/fu,

$eqv_{i,j}$ = equivalency (characterization) factor of the jth inventory parameter in the ith impact category, g x-eq/g

When summed up over all inventory parameters, jth parameters, then total environmental impact to the ith impact category is obtained as shown in equation (2).

$$CI_i = \sum CI_{i,j} = \sum Load_j \times eqv_{i,j} \qquad (2)$$

Figure 4.4 shows an example of the calculation of characterized impacts using a fictitious example.

Inventory parameter (j)	$Load_j$ (g/fu)	$eqv_{i,j}$ (g CO_2 eq/g)	$CI_{i,j}$ (g CO_2 eq/fu)
CO_2	1,000	1	1,000
CH_4	10	23	230
CFC 11	0.01	4,500	45
Sum ($\sum CI_{i,j}$)	$CI_i = \sum CI_{i,j}$		1,275

Figure 4.4 Illustrative example showing characterization

Prior to characterization, no information is available on the environmental impact caused by three inventory parameters, CO_2, CH_4, and CFC11, except for their impact on global warming. Load information on the three parameters does not provide information on the degree of environmental impact of the three parameters. Once the characterization step is completed, quantitative environmental impact information for each individual parameter, as well as their total impact, is available.

Figure 4.5 shows typical impact categories with symbols and units for the characterization factors.

Impact category	Symbol	Unit
Global warming	GWP	g CO_2 eq/g
Ozone layer depletion	ODP	g CFC11 eq/g
Acidification	AP	g SO_2 eq/g
Eutrophication	EP	g PO_4^{3-} eq/g
Photochemical Oxidant	POCP	g C_2H_4 eq/g
Abiotic resource depletion	ADP	U_j/D_j

Note; U_j = worldwide use of the j^{th} resource, kg/yr

D_j = the size of the deposit of the j^{th} resource, economically extractable, kg

Figure 4.5 Typical impact categories with symbols and units

4.3 Normalization

Normalization is a process that divides a characterization value (characterized impact) of an impact category of a product system by the normalization reference of the same impact category. A normalization value (normalized impact), which is the outcome of the normalization step, represents the fractional contribution of the product system to a given impact category in a geographical region for a given time period as defined in the normalization reference.

What is the normalization reference? The normalization reference is another form of characterization. The only difference is in the geographical and temporal system boundary. Characterization is limited to a product system, while the normalization reference covers the entire region where the product system is located. The temporal boundary in a product system spans from raw material acquisition to the product's final disposal such that the time interval in the product life cycle stages can be quite long, typically more than one year. The temporal boundary in a normalization reference, however, is typically set at one year.

The normalization reference of the i^{th} impact category (N_i) can be calculated just as the characterization value is calculated.

$$N_{i,k} = Load_k \times eqv_{i,k} \quad (3)$$

Where,

$N_{i,k}$ = the magnitude of characterized impact of the k^{th} inventory parameter in the i^{th} impact category, g x-eq/ yr,

$Load_k$ = the quantity of the k^{th} inventory parameter, g/yr,

$eqv_{i,k}$ = equivalency (characterization) factor of the k^{th} inventory parameter in the i^{th} impact category, g x-eq/g

When summed up over all inventory parameters, k^{th} parameters, then total environmental impact, or normalization reference, to the i^{th} impact category is obtained as shown in equation (4).

$$N_i = \sum N_{i,k} = \sum Load_k \times eqv_{i,k} \quad (4)$$

Where,

N_i= normalization reference of the i^{th} impact category, g x-eq/yr

It is a normal practice to define normalization reference as person equivalent (PE). This is to take into account the impact of different geographical scales of impact categories on the environment. Three different geographical scales are considered: global, regional, and local. Impact categories such as global warming, ozone layer depletion and abiotic resource depletion are global impacts, acidification and eutrophication regional impacts, and photochemical oxidant creation is a local impact. Geographical system boundaries for global, regional and local impacts are; the entire globe, a region (such as East Asia or Western Europe), and an individual country or part of a country or a city.

A normalization reference based on person equivalent is calculated as shown in Equation (5).

$$N_i = (\sum Load_k \times eqv_{i,k})/(\text{population size of the geographical system boundary}) \quad (5)$$

Where,

N_i = normalization reference of the i^{th} impact category, g x-eq/(pe-yr),

pe-yr= person equivalent per year

In this book, normalization reference calculated as person equivalent (equation 5) will be used instead of the conventional normalization reference (equation 4).

A normalization value (normalized impact) is then calculated as shown in equation (6):

$$NI_i = CI_i/N_i \qquad (6)$$

Where,

NI_i = Normalized impact of the i^{th} impact category, (pe-yr)/fu

Table 4.1 shows an example calculation of a normalization reference using a fictitious example. Since eutrophication is a regional impact, the population of Korea was used to calculate the normalization reference.

i = Eutrophication
Region (area) = Korea
Population = 47,000,000
Time period = one year (2002)

Table 4.1 Illustrative example showing normalization reference calculation of Eutrophication in Korea

Inventory parameter (k)	$Load_k$ (kg/yr)	$eqv_{i,k}$ (g PO_4^{3-} eq/g)	$N_{i,k}$ (kg PO_4^{3-} eq/(pe-yr))
NO_x	1.19E+09	0.13	3.30
BOD	7.18E+08	0.022	0.34
TN	1.94E+08	0.42	1.73
TP	2.10E+07	3.06	1.37
Sum	$N_i = \sum N_{i,k}$		6.72 kg PO_4^{3-} eq/(pe-yr)

Assume that in a product system A, only NO_x (air) was inventoried in its entire life cycle as 52.9 g/fu. NO_x (air) affects on the eutrophication impact category and its characterized impact was calculated as: CI_i= (52.9 g NO_x/fu) (0.13 g PO_4^{3-} eq/g NO_x) = 6.87 g PO_4^{3-} eq/fu. Normalized impact of the eutrophication impact category of this product system is then:

$$NI_i = CI_i/N_i = (6.87\text{ g }PO_4^{3-}\text{ eq/fu})/(6.72\text{ kg }PO_4^{3-}\text{ eq/(pe-yr)})=1.022E\text{-}03\text{ pe-yr/fu}$$

Note that NI_i has "year" in its unit, however this is misleading because the functional unit includes the time dimension. Since the time dimension is included in the inventory data itself, there is no explicit display of the time dimension in the inventory data. This fact is a weakness of LCA because inventory data are compiled from a wide time-span, however, no information is available as to this time span. This poses a problem in estimating environmental impacts from the inventory parameters as time cannot be ignored in estimating environmental impacts.

There are reasons for performing the normalization step in an LCA study, even if ISO 14042 does not recommend doing normalization. Normalization:

- enables a check for error of inventory data and characterization values,
- allows a better interpretation of the characterized impact values with respect to the characterized impact values of other impact categories
- provides a starting point for the subsequent weighting step.

There is a problem associated with normalization in that there is no objective criterion in selecting geographical and temporal system boundaries for normalization reference calculation. It is arbitrary in nature; thus, normalized impact values from the normalization step can also be arbitrary. When normalized results are used for comparison, it can lead to misleading conclusion. There is an implicit assumption that all impact categories are equally important built-in in the normalization process, thus the weight of each impact category is assumed equal or 1, which is not true.

Although the choice of system boundaries for normalization reference is rather arbitrary, it is not subject to social preference or value, as is the case with weighting. Thus, well defined and justifiable system boundaries for normalization reference can add value to the normalization process. However, due to the inherent limitation of the normalization process, i.e., equal weight among impact categories, the weighted impact of each impact category and subsequently of a product system needs to be calculated. In this sense, the normalization step can be considered an intermediate step between characterization and the weighting step.

4.4 Weighting

Weighting is a process that assigns relative significance to impact categories. Relative significance is termed weight, and the act of assigning weight is termed weighting. There are two approaches in weighting, for the broader perspective approach, the outcome is qualitative, while for the narrower perspective it is quantitative taking the form of a single value or weighted impact of a product system. In both approaches, however, the same principles apply, i.e., social, ethical, and political values dictate weighting process.

The qualitative approach is often used for a comparative study between two systems - product, process, materials, design options, etc. Using a life cycle matrix, as shown in Figure 4.6, an evaluation between a reference system and an alternative system is made based on evaluation criteria. Evaluation results are often expressed in descriptive language (e.g., better, worse, or equal), sign (e.g., +, ++, -, --), or number (e.g., 1, 2, …, 10). Frequently used evaluation criteria can include the precautionary principle (Udo de Haes et al., 1996), social preference, the technical and financial capability of a corporation, etc.

Life cycle stage	Impact categories				
	GW	OD	AD	EU	ARD
Upstream Processes					
Manufacturing					
Distribution					
Use					
Disposal					
Sum					

Figure 4.6 Illustrative example of a qualitative approach using life cycle matrix

The quantitative approach is commonly conceived as the weighting step in LCA. Weighted impact as shown in equation (7) is calculated in the weighting step.

$$WI_i = W_i \times CI_i \qquad (7)$$

Where,
WI = weighted impact of the ith impact category,
W_i = weight of the i^{th} impact category,
CI_i = characterized impact of the i^{th} impact category.

In equation (7), an assumption is made that a linear relationship exists between characterized impact value and weight. When summed up over the all impact categories, the weighted impact of a product system is obtained, as shown in equation (8).

$$WI = \sum (W_i \times CI_i) \qquad (8)$$

There are three categories of weighting methods commonly employed in the quantitative weighting process. They are panel method, monetization method, and target method.

The panel method is similar to qualitative methods because a group of people are asked for their opinion about the relative significance of impact categories. There is, however, a major difference in that they are asked to frame their responses in a quantitative way. One of the most widely known panel methods is the Delphi-like panel method. It begins with the normalized impacts and follows a four step approach.

The first step in the panel method is to gain a common understanding among the panel members on the importance of the impact categories. Typically a precautionary principle is given to the panel members for this purpose. The precautionary principle has four key elements. They are:

- the degree of scientific uncertainty,
- scale of the impact,
- duration of the impact, and
- the degree of irreversibility.

In general, reversible impacts are considered less serious than irreversible impacts. An impact with shorter recovery time is considered less serious than that with longer recovery time. Those impacts with scientifically known consequences are considered less serious than those with scientifically uncertain consequence (Udo de Haes et al., 1996). This principle has frequently been applied to determine the relative significance of impact categories when using the panel method.

The second step is to have each panel member assess the relative significance of each impact category based on common understanding. Giving a weighing factor to each impact category is the same as comparing the relative significance among different impact categories. Typically panel members are representatives from industry, government, environmental NGOs, academia, and consumers.

The third step is to assess the results from the panel members and then presents the results back to the members.

The last step is to ask panel members to re-assign relative significance to the impact categories based on the group's results. The weight can be maintained or changed. Results from the panel members are collected, averaged, and the results become the weight of the impact categories.

Monetization methods are similar to the panel methods because a group of people are asked to assign values to different impact categories. A major difference, however, is that the value assigned should be monetary value on impact category. The approach in common use in LCIA is based on willingness to pay (WTP) concept.

The following two paragraphs contain detailed information on the monetization method for beginners.

The willingness to pay concept is related to the avoidance of something along the cause-effect chain. In the early part of the chain, something to avoid is an environmental load such as emissions to air, water, and land. In the latter part of the chain, it is the damage to the environment such as human health, crop yields, etc. Here, monetary value is based on total economic value of something to avoid as shown in equation (9).

$$\text{Total economic value} = \text{user values} + \text{non user values} \qquad (9)$$

And, user value consists of two component values as shown in equation (10).

$$\text{User values} = \text{direct user value} + \text{indirect user value} \qquad (10)$$

An example of total economic value of avoiding destruction of a forest is shown below.

Direct user value = the timber value of a forest
Indirect user value = the recreational value of the forest
Non user value = existence value (land cost)

A well known weighting method based on the WTP concept is the Environmental Priority Strategy (EPS) system (Steen, 1999). It is based on society's willingness to pay to avoid damage resulting from environmental loads. An inventory parameter is assigned monetary value and expressed as an environmental load unit (ELU). For instance, 1 g of CO_2 has xxx ELU/kg, iron yyy ELU/kg, etc. Thus, weighted impact of a product system or any segment of a system can be readily obtained from the inventory results. However, the EPS method suffers from lack of transparency in the assignment of monetary value to impacts caused by inventory parameters.

The target method differs from the two previous methods discussed here. It relates relative significance of impact category to some sort of target. There are differences among various target methods that stem mainly from the structure of the equation relating the targets to weighting factor (W_i), the choice of targets, and the use of data for the targets (i.e., characterized impact or inventory data).

The weighting factor in the target method is related to the target as shown in equation (11).

$$W_i = 1/T_i \qquad (11)$$

Where,
W_i = weighting factor of the i^{th} impact category,
T_i = target value of the i^{th} impact category.

Equation (11) is quite similar to the normalized impact calculation shown in equation (6). The only difference is that N_i in equation (6) is replaced by T_i in equation (11). If N_i is multiplied by numerator and denominator of equation (11), the same equation results as shown in equation (12).

$$W_i = (1/N_i) \times (N_i/T_i) \qquad (12)$$

It is important to understand the meaning of N_i/T_i. Since N_i represents present, actual impact while T_i represents target impact, the ratio between N_i and T_i is in fact the reduction factor of the ith impact category. Let's assume that N_i is 20 kg PO_4^{3-} eq/yr and T_i = 10 kg PO_4^{3-} eq/yr. Then eutrophication impact has to be reduced by 20/10 or 2 times between present and target year. Thus, N_i/T_i becomes the reduction factor.

The calculation of a weighted impact of a product system can be made using equations (7) and (12).

$$WI_i = W_i \times CI_i = CI_i \times (1/N_i) \times (N_i/T_i) = (CI_i/N_i) \times (N_i/T_i) \quad (13)$$

Sometimes, target values are based on inventory values, not impact values as is the case in the Ecoscarcity method (Baumann et al., 1994). In this method, the weighting factor of the j^{th} inventory parameter is expressed as in equation (14).

$$W_j = (1/F_c) \times (F_{tot}/F_c) \quad (14)$$

Where,
W_j = weighting factor of the j^{th} inventory parameter,
F_c = annual load (mass of inventory parameter) target (political target),
F_{tot} = annual actual load.

This is quite similar to equation (12) in that F_{tot}/F_c represents the reduction factor of the j^{th} inventory parameter, and $1/F_c$ as a normalizing factor. However, a major difference exists in $(1/F_c)$ where F_c represents target, future value, while N_i represents present, actual value. The advantage of the Ecoscarcity method is that there is no need for characterization or normalization. As shown in equation (15), environmental impact of the j^{th} inventory parameter can be obtained readily by simply multiplying the weighting factor (W_j) by the inventory value.

$$WI_j = Load_j \times W_j \quad (15)$$

It should be noted that there is an implicit assumption in equation (11) that targets in all impact categories are equally important. To overcome this problem, a subjective weighting factor has been introduced to the target method as shown in equation (16).

$$W_i = v_i \times (1/T_i) \quad (16)$$

Where,
v_i = subjective weighting factor.

Distance-to-target method is based on the weighting factor in equation (16) for the calculation of the weighted impact of the i^{th} impact category and that of a product system. Weighted impact of the i^{th} impact category is calculated, in the distance-to-target method, as:

$$WI_i = CI_i \times v_i \times (1/T_i) = CI_i \times v_i \times (1/N_i) \times (N_i/T_i) = v_i \times (CI_i/N_i) \times (N_i/T_i)$$

This calculation can be simplified as in equation (17) for the calculation of the weighted impact by the distance to target method.

$$WI_i = v_i \times NI_i \times (N_i/T_i) \qquad (17)$$

Equation (17) simply shows that a subjective weighting factor representing the relative significance of the i^{th} impact category, v_i, was added into the weighted impact calculation. A well known distance-to-target method is Ecoindicator 95. (Goedkoop, 1995)

Example of life cycle impact assessment: hair drier case

1) Classification

Inventory parameter	*Global Warming* ***(GW)***	*Ozone Depletion* ***(OD)***	*Acidification* ***(AD)***	*Eutrophication* ***(EU)***	*Photochemical Ozone Creation* ***(POC)***	*Abiotic Resource Depletion* ***(ARD)***
Crude oil						●
Coal						●
Iron ore						●
CO_2	●					
Methane	●				●	
CO					●	
VOC					●	
NO_x (Air)			●	●	●	
SO_x (Air)			●			

Note: Since the hair drier does not exert impact on OD, the environmental impact on OD will not be dealt with here.

2) Characterization

a) Characterization (equivalency) factor

Parameter	Characterization factor				
	GWP ($g\ CO_2\ eq/g$)	AP ($g\ SO_2\ eq/g$)	EP ($g\ PO_4^{3-}\ eq/g$)	POCP (g ethene eq/g)	ADP (1/yr) Reserve-to-Use method
	$eqv_{i,j}$	$eqv_{i,j}$	$eqv_{i,j}$	$eqv_{i,j}$	$eqv_{i,j}$
Crude oil					*2.48E-02* *(BP 2001)*
Coal					*3.44E-03* *(BP 2001)*
Iron ore					*7.21E-03* *(USGS 2001)*
CO_2	*1.00E+00* *(IPCC 2001)*				
Methane	*2.30E+01* *(IPCC 2001)*			*6.00E-03* *(Heijungs et al., 1992)*	
CO				*2.70E-02* *(Derwent et al., 1996)*	
VOC				*4.16E-01* *(Heijungs et al., 1992)*	
NO_x *(Air)*		*7.00E-01* *(Hauschild et al., 1999)*	*1.30E-01* *(Heijungs et al., 1992)*	*2.80E-02* *(Derwent et al., 1996)*	
SO_x *(Air)*		*1.00E+00* *(Hauschild et al., 1999)*			

b) Characterization

Parameter	$Load_{i,j}$	Characterized Impact (CI_i)				
		GW (g CO_2 eq / hair drier)	AD (g SO_2 eq / hair drier)	EU (g PO_4^{3-} eq / hair drier)	POC (g ethene eq / hair drier)	ARD (g/hair drier -yr)
Crude oil	3.04E+02					7.55E+00
Coal	5.10E+03					1.76E+01
Iron ore	7.34E+01					5.29E-01
CO_2	3.08E+04	3.08E+04				
Methane	5.58E+01	1.28E+03			3.35E-01	
CO	7.24E-01				1.95E-02	
VOC	3.63E+00				1.51E+00	
NO_x (Air)	2.07E+00		1.45E+00	2.69E-01	5.80E-02	
SO_x (Air)	1.22E+02		1.22E+02			
Total		3.21E+04	1.24E+02	2.69E-01	1.92E+00	2.56E+01

c) Characterized Impact (CI_i)

Impact category		Life cycle stage						Total	
		Upstream	Manu-facturing	Distri-bution	Use	Disposal			
						Scenario A	Scenario B	Scenario A	Scenario B
GW	g CO_2 eq/ hair drier	1.29E+03	9.83E+01	1.32E+02	3.02E+04	3.85E+02	-6.31E+01	3.21E+04	3.17E+04
AD	g SO_2 eq/ hair drier.	5.35E+00	3.84E-01		1.18E+02	1.24E-01	5.76E-02	1.24E+02	1.24E+02
EU	g PO_4^{3-} eq/ hair drier	2.60E-01				9.72E-03	7.84E-03	2.69E-01	2.67E-01
POC	g ethene eq/ hair drier	1.57E+00	1.04E-03	1.95E-02	3.19E-01	1.08E-02	7.30E-03	1.92E+00	1.92E+00
ARD	g/ hair drier-yr	7.51E+00	5.54E-02	9.93E-01	1.70E+01	5.52E-02	-1.21E+00	2.56E+01	2.44E+01

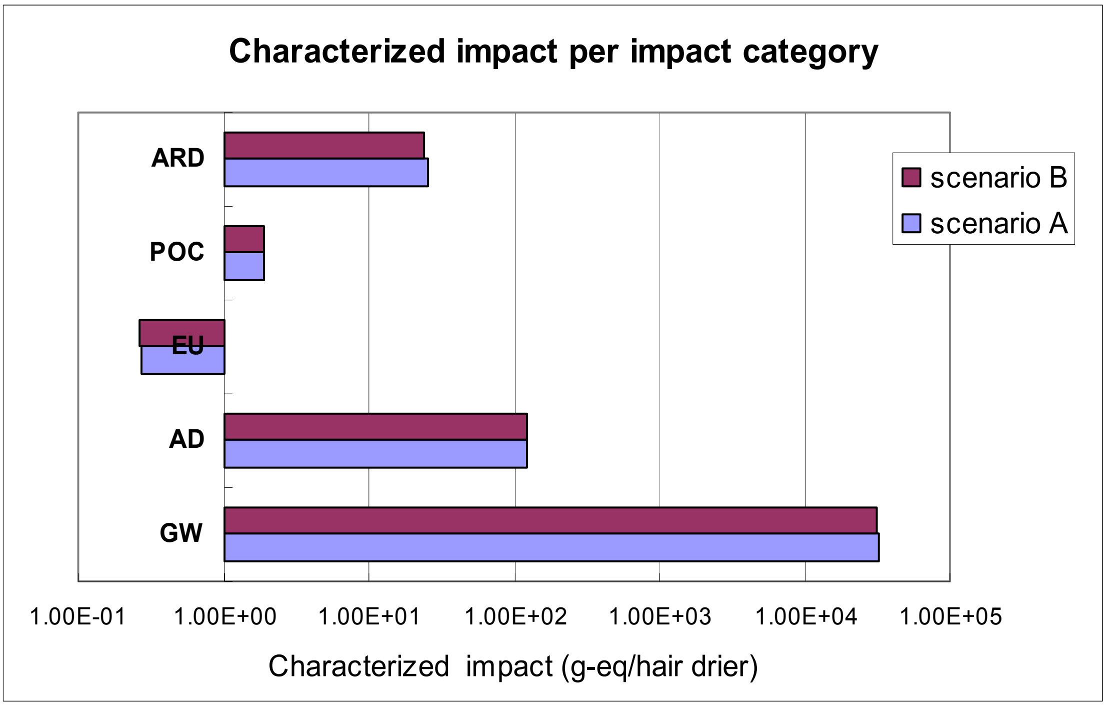


Figure E4.1 Characterized impact of hair drier in its entire life cycle per impact category

Comparison of characterized impact of a product between scenario A and B:

For the characterized impact in the five impact categories over the entire product system, the difference between scenario A and B does not appear to be significant as shown in Figure E4.1. This is because characterized impact from the disposal stage is minor compared to the sum of the other life stages. Nonetheless, scenario B shows a reduction in the characterized impact for all impact categories from those of scenario A. Thus, recycling of waste is conducive to the reduction of environmental impact from a product system.

3) Normalization

a) Normalization reference (N_i)

Impact category	*Geographical boundary*	*Value*	*Unit*
GW	*Global*	*5.66E+06*	*g CO_2 eq/pe·yr*
AD	*Regional*	*5.64E+04*	*g SO_2 eq/pe·yr*
EU	*Regional*	*8.90E+03*	*g PO_4^{3-} eq/pe·yr*

POC	*Regional*	*7.37E+03*	*g ethene eq/pe·yr*
ARD	*Global*	*1.87E+04*	*g/pe·yr^2*

Note:
1. Reference year = 1995
2. World population = 5,675,675,676
3. Regional population (certain region in Eastern China) = 45,093,000

b) Normalized Impact

Normalized Impact (NI_i) = CI_i / N_i

Impact category		*Life cycle stage*						*Total*	
		Upstream	*Manu-facturing*	*Distri-bution*	*Use*	*Disposal*			
						Scenario A	*Scenario B*	*Scenario A*	*Scenario B*
GW	*pe·yr/ hair drier*	*2.27E-04*	*1.74E-05*	*2.33E-05*	*5.34E-03*	*6.80E-05*	*-1.11E-05*	*5.67E-03*	*5.59E-03*
AD	*pe·yr/ hair drier*	*9.49E-05*	*6.80E-06*		*2.09E-03*	*2.20E-06*	*1.02E-06*	*2.20E-03*	*2.19E-03*
EU	*pe·yr/ hair drier*	*2.92E-05*				*1.09E-06*	*8.81E-07*	*3.03E-05*	*3.00E-05*
POC	*pe·yr/ hair drier*	*2.13E-04*	*1.41E-07*	*2.65E-06*	*4.33E-05*	*1.47E-06*	*9.91E-07*	*2.61E-04*	*2.61E-04*
ARD	*pe·yr/ hair drier*	*4.01E-04*	*2.96E-06*	*5.31E-05*	*9.10E-04*	*2.95E-06*	*-6.48E-05*	*1.37E-03*	*1.30E-03*

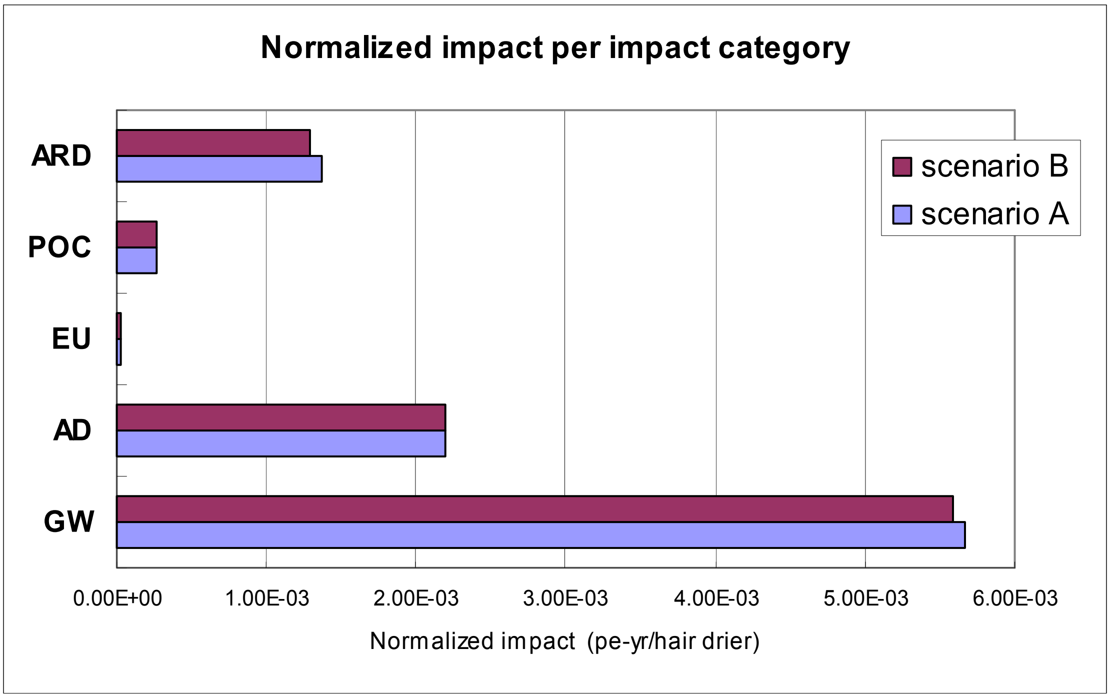


Figure E4.2 Normalized impact of hair drier for its entire life cycle per impact category

Comparison of normalized impact of a product system between scenario A and B:

For the normalized impact in the five impact categories over the entire product system shown in Figure E4.2, the difference between scenario A and scenario B appears to be significant in the global warming and acidification categories. Scenario B shows a reduction in the normalized impact for all impact categories over that of scenario A, illustrating that recycling of waste is conducive to the reduction of environmental impact from a product system.

4) Weighting

a) Weight of impact categories (W_i) based on the panel method

Impact category	GW	AD	EU	POC	ARD
Weight (W_i)	0.29	0.16	0.14	0.13	0.28

Note: weighting factors given here are for illustrative purpose only. Readers should not use these factors for their own work.

b) Weighted impact (WI_i) = $NI_i \times W_i$

Impact category	Normalized impact (NI_i) = CI_i/N_i (pe·yr/ hair drier)		Weighted Impact (WI_i) (pe·yr/hair drier)	
	Scenario A	Scenario B	Scenario A	Scenario B
GW	5.67E-03	5.59E-03	1.67E-03 (68.6%)	1.65E-03 (68.9%)
AD	2.20E-03	2.19E-03	3.46E-04 (14.2%)	3.46E-04 (14.4%)
EU	3.03E-05	3.00E-05	4.35E-06 (0.2%)	4.32E-06 (0.2%)
POC	2.61E-04	2.61E-04	3.30E-05 (1.4%)	3.29E-05 (1.4%)
ARD	1.37E-03	1.30E-03	3.81E-04 (15.6%)	3.62E-04 (15.1%)
Total			2.44E-03 (100.0%)	2.39E-03 (100.0%)

c) Weighted impact per life cycle stage

	Upstream	*Manufacturing*	*Distribution*	*Use*	*Disposal*		*Total*	
					Scenario A	*Scenario B*	*Scenario A*	*Scenario B*
GW	*6.70E-05*	*5.12E-06*	*6.86E-06*	*1.57E-03*	*2.01E-05*	*-3.28E-06*	*1.67E-03*	*1.65E-03*
AD	*1.50E-05*	*1.07E-06*		*3.30E-04*	*3.47E-07*	*1.61E-07*	*3.46E-04*	*3.46E-04*
EU	*4.19E-06*				*1.57E-07*	*1.27E-07*	*4.35E-06*	*4.32E-06*
POC	*2.70E-05*	*1.78E-08*	*3.35E-07*	*5.47E-06*	*1.86E-07*	*1.25E-07*	*3.30E-05*	*3.29E-05*
ARD	*1.11E-04*	*8.22E-07*	*1.47E-05*	*2.53E-04*	*8.20E-07*	*-1.80E-05*	*3.81E-04*	*3.62E-04*
Total	*2.25E-04*	*7.03E-06*	*2.19E-05*	*2.16E-03*	*2.16E-05*	*-2.09E-05*	*2.44E-03*	*2.39E-03*

Sum of WI_i *= WI of the hair drier system for Scenario A = 2.44E-03*
for Scenario B = 2.39E-03

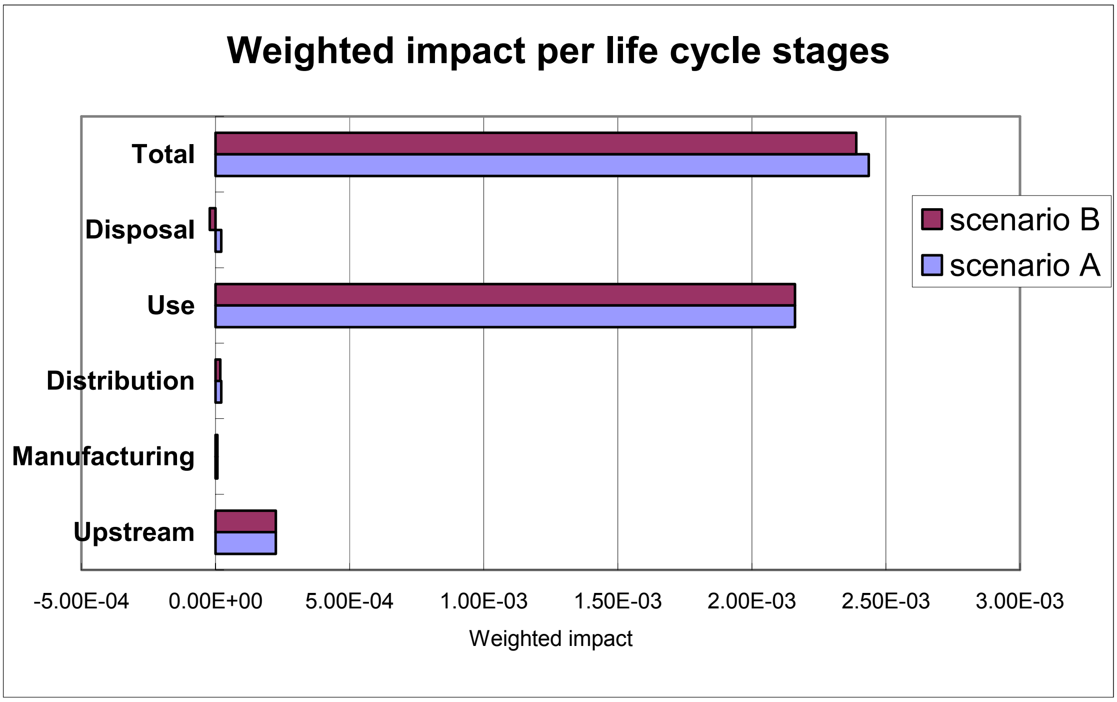


Figure E 4.3 Weighted impact per life cycle stage

Comparison of weighted impact of a product system between scenario A and B:

For the weighted impact in the five life cycle stages shown in Figure E4.3, the difference between scenario A and B is clear in the disposal stage. Scenario B exhibits a negative weighted impact value or beneficial environmental impact while scenario A causes adverse impact on the environment. For other life cycle *stages, no differences exist because the two scenarios were created only for the disposal stage. The results shown in Figure E4.3 strongly indicate that recycling of waste is conducive to the reduction of environmental impact from the disposal of a product, in this case, a hair drier.*

Note: Results shown here depend strongly on the weighting factors used for the comparison.

5 Life cycle interpretation

Results of life cycle inventory analysis and life cycle impact assessments are analyzed with respect to various aspects such as completeness, sensitivity, and consistency. In addition, key issues that contribute significantly to the environmental impact of the product system are also identified. Key issues in this context can mean key processes, materials, activities, and components or even a life cycle stage.

From these analyses, conclusions are drawn and recommendations made as to the environmental aspects of the product, possible areas for improvement or key environmental information that could be communicated to the consumer, all depending on the goal of the LCA study.

There are three key elements in life cycle interpretation as defined by ISO 14043. First is the identification of key issues, second is the evaluation (including checking completeness, sensitivity and consistency), and third is development of conclusions together with recommendations. All three elements defined in the ISO standard on life cycle interpretation are discussed here.

5.1 Identification of key issues

Key issues are activities, processes, materials, components, or life cycle stages which have a significant impact on the total impact of a product system, usually greater than 1%. One of the objectives of performing LCA is to identify weak points of a product system, and then to improve those weak points through ecodesign of a product. The identification of key issues is a must in any LCA aimed at improving environmental aspects of the product.

A method called "contribution analysis" has been used for the identification of key issues or weak points of a product system. LCA results used in the identification of key issues can be characterized impact, weighted impact or inventory results. Of these, characterized impact results are most often used.

Characterized impact results are, in general, expressed in matrix format, where rows list inventory items and columns identify unit processes and activities shown in the process tree. Table 5.1 shows characterized impact for the global warming impact category of a fictitious product system.

Table 5.1 Characterized impact of the global warming impact category of a fictitious product system (unit: g CO_2 eq/fu)

Inventory parameter	Unit processes and activities						Sum
	Paint manu-facturing	Al manu-facturing	Packaging manu-facturing	Trans-portation	Use	Disposal	
CO_2	4	1,370	1,240	53	74	39	2,780
CH_4	0.22	120.05	58.8	22.05	22.05	2.45	226
CFC11	31.5	28,800	27,450	450	11,250	0	67,981
Sum	36	30,290	28,749	525	11,346	41	70,987

The total impact of global warming of the product system shown in Table 5.1 is 70,987 g CO_2 eq/fu. Every entry of the characterized impact matrix is now divided by the total impact of the product system and expressed as a percentage of the total. Table 5.2 shows the results of this division. The percentage value in each entry on the matrix is the contribution made by each unit process, or activity associated with a specific inventory parameter, to the total global warming impact of the product system.

Table 5.2 Percent contribution by each entry on the matrix to the total global warming impact category of a fictitious product system (unit: %)

Inventory parameter	Unit processes and activities						Share (%)
	Paint manu-facturing	Al manu-facturing	Packaging manu-facturing	Transp-ortation	Use	Disposal	
CO_2	0.01	1.93	1.74	0.07	0.10	0.05	3.91
CH_4	0.00	0.17	0.08	0.03	0.03	0.00	0.32
CFC11	0.04	40.52	38.62	0.63	15.83	0.00	95.64
Sum	0.05	42.68	40.50	0.74	15.96	0.07	100.00
Share(%)	0.05	42.68	40.50	0.74	15.96	0.07	

An arbitrarily chosen criterion, such as "contribution greater than 1% of the total impact" can be applied in identifying key issues from the matrix shown in Table 5.2. First, key unit processes and activities identified from Table 5.2 include Al manufacturing, packaging manufacturing, and use. Key inventory parameters include CFC11 and CO_2. Inventory parameters accompanying key unit processes and activities include CO_2 and CFC11 from the Al manufacturing process, CO_2 and CFC11 from the packaging manufacturing process, and CFC 11 from the use stage. The identified key issues are then reflected in the generation of improvement options for ecodesign.

The same method as shown above can also be applied if inventory results or weighted impact results are used for the identification of key issues. Of these two, weighted impact results are often used to identify key issues. Since weighted impact is derived from all the impact categories the identified key issues differ from those in the characterized impact case. In general, the number of key issues identified from the weighted impact case is fewer than those identified from the characterized impact case. However, key issues from the weighted impact case reflect the entire product system's perspective by aggregating all impact categories of the product system. It is recommended that key issues be identified from both the characterized impacts and weighted impacts of a product system and that key issues identified from both approaches are used as the key issues of the product system.

5.2 Evaluation of completeness, sensitivity and consistency

Basic premises for performing an LCA study such as data quality, goal, major assumptions, system boundary setting, etc have been determined during the goal and scope definition phase. Data are then collected during the inventory analysis phase, and their impact on the environment assessed during the life cycle impact assessment phase. During the first part of the life cycle interpretation phase, key issues were also identified. However, all these results are based on basic premises defined earlier, such as assumptions, data quality, and methodologies employed. It is necessary to perform a systematic evaluation of all these results in order to check completeness, sensitivity and consistency. Each of these three elements of the evaluation is described below, together with an example.

1) Completeness check

The objective of a completeness check is to ensure that all information and data required for life cycle interpretation are complete. In particular, the check aims at ensuring that identified key issues reflect life cycle inventory results as well as life cycle impact assessment results sufficiently and accurately. If particular data are missing or judged incomplete, goal and scope definition of the LCA study must be reevaluated to determine whether missing or incomplete data should cause modification of the initial goal and scope definition. If the data that are missing or incomplete influence significantly the key issues identified, then the goal and scope of the LCA study must be revised accordingly.

2) Sensitivity check

The objective of a sensitivity check is to evaluate sensitivity and uncertainty analysis results performed during the life cycle inventory analysis and life cycle impact assessment phases. Topics for sensitivity and uncertainty analyses include allocation methods, uncertainties in input data, and assumptions made in the LCA studies, among others. The outcome of the sensitivity check is the degree of reliability of the LCA results, including identified key issues.

The influence on the results of varying the assumptions and data by some range (e.g., 25%) is assessed in a sensitivity analysis. Results achieved using various values are then compared. Sensitivity can be expressed as the percentage of change or as the absolute deviation from the results. In general, a change in the result greater than 10% is considered significant. (ISO 14043, 2000)

One of the most widely adopted method in the sensitivity check is the use of a scenario (e.g., data range, assumption range, best and worst case) to derive LCA results and key issues. If there is a change in the identified key issues before and after the sensitivity check, then the corresponding scenario is judged sensitive and in-depth investigation of the underlying data begins.

In general items for the sensitivity analysis include:

- Rules for allocation, criteria used for decision rules for mass contribution
- Boundary setting process and system definition
- Judgments and assumptions concerning data
- Selection of impact categories

- Assignment of inventory results (classification)
- Calculation of characterized impacts (characterization)
- Calculation of normalized impacts (normalization)
- Calculation of weighted impacts (weighting)
- Weighting method
- Data quality

The sensitivity may be assessed using methods such as elasticity. Depending on the magnitude of the elasticity, defined as C_R/C_D (Change in results/Change in data), the sensitivity of the item is judged empirically. However, there are no clear cut criteria that can be used in judging the sensitivity. (ISO 14043, 2000)

3) Consistency check

The objective of a consistency check is to evaluate whether methods, procedures, data, and assumptions employed in the LCA study are applied with consistency throughout the entire LCA. In particular, any inconsistency between what has been applied and what was defined in the scope definition are scrutinized in the consistency check.

Topics for a consistency check would include:
i) Have the regional and/or temporal differences been consistently applied?
ii) Have allocation rules and system boundaries been applied consistently to all product systems, in particular, for the case of open loop recycling?
iii) Have elements of the life cycle impact assessment, such as characterization factors and methods, been consistently applied?
iv) Is data quality, as defined in the scope definition, consistent throughout the LCA study?
v) Have weighting method and factors been applied consistently?

4) Data Quality requirements

Collected data must be checked with respect to requirements set earlier, during the goal and scope definition phase. While collecting data in subsequent phases (LCI and LCIA) the data quality must be checked and, if it does not meet the requirements, the data should be collected again or the requirements should be modified. In other words, the data quality requirements check is an iterative process.

Descriptions of data quality are important in order to understand the reliability of the study results and properly interpret the outcome of the study. As a minimum, the following parameters should be included in assessing data quality requirements.

Time related coverage: within the last 5 years
Geographical coverage: manufactured, used and disposed of in Eastern China
Technological coverage: average current technologies

In addition, it is necessary to define factors including precision, completeness, representativeness, consistency, and reproducibility of the data. These factors are yardstick in judging quality of the life cycle inventory data and are explained briefly below.

Precision: measurement of the variability of the data values for each data category expressed
Completeness: percentage of locations reporting primary data subtracted from the potential number in existence for each data category in a unit process
Representativeness: qualitative assessment of the degree to which the data set reflects the true population of interest
Consistency: qualitative assessment of how uniformly the study methodology is applied to the various components of the analysis
Reproducibility: qualitative assessment of the extent to which information about the methodology and data values allows an independent practitioner to reproduce the results reported in the study

Where the use of the LCA study is intended to make a comparative assertion that is disclosed to the public, a critical review shall be conducted.

5.3 Conclusions and recommendations

The objective of this section is to draw conclusions from the LCA study and then make recommendations based on those conclusions for the intended audience.

There are logical steps to reaching the conclusions.

First, identify key issues of the product system. Second, evaluate the results for completeness, sensitivity and consistency. Third, draw preliminary conclusions from the LCA study and assess whether the conclusions are in line with the requirements for data quality and the assumptions defined in the goal and scope definition phase. If all three of these requirements are met, then draw final conclusions, make pertinent recommendations, and prepare an LCA report as suggested in ISO 14040.

Example of life cycle interpretation: hair drier case

(1) Contribution Analysis

a) Key issue identification of each impact category based on characterized impact

GW

	Upstream									Downstream				Total (%)	
	PP (%)	Body (%)	PVC (%)	Power cord manufacturing (%)	Card board (%)	Packaging (%)	Steel (%)	Motor manufacturing (%)	Manufacturing (Assembly) (%)	Distribution (%)	Use (%)	Disposal (%)			
												SCA	SCB	SCA	SCB
CO_2	2.93E+02	9.79E+01	2.81E+02	1.81E+02	4.38E+01	3.63E+01	1.14E+02	2.18E+02	9.43E+01	1.32E+02	2.90E+04	3.52E+02	-8.46E+01	3.08E+04	3.04E+04
	(100.00)	(95.95)	(100.00)	(95.95)	(100.00)	(95.95)	(100.00)	(95.95)	(95.95)	(100.00)	(95.95)	(91.30)	(134.13)	(96.00)	(95.99)
Methane		4.13E+00		7.65E+00		1.53E+00		9.18E+00	3.98E+00		1.22E+03	3.35E+01	2.15E+01	1.28E+03	1.27E+03
		(4.05)		(4.05)		(4.05)		(4.05)	(4.05)		(4.05)	(8.70)	(-34.13)	(4.00)	(4.01)
Total	2.93E+02	1.02E+02	2.81E+02	1.89E+02	4.38E+01	3.78E+01	1.14E+02	2.27E+02	9.83E+01	1.32E+02	3.02E+04	3.85E+02	-6.31E+01	3.21E+04	3.17E+04
	(0.91)	(0.32)	(0.88)	(0.59)	(0.14)	(0.12)	(0.35)	(0.71)	(0.31)	(0.41)	(94.08)	(1.20)		(100.00)	
	(0.92)	(0.32)	(0.89)	(0.60)	(0.14)	(0.12)	(0.36)	(0.72)	(0.31)	(0.42)	(95.41)		(-0.20)		(100.00)

Note: SCA means scenario A, SCB means scenario B

AD

	Upstream								Manufacturing (Assembly) (%)	Downstream				Total (%)	
	PP (%)	Body (%)	PVC (%)	Power cord manufacturing (%)	Card board (%)	Packaging (%)	Steel (%)	Motor manufacturing (%)		Distribution (%)	Use (%)	Disposal (%)			
												SCA	SCB	SCA	SCB
NO$_X$	1.14E+00				2.60E-01							5.23E-02	4.22E-02	1.45E+00	1.44E+00
	(38.89)				(100.00)							(42.15)	(73.29)	(1.17)	(1.16)
SO$_X$	1.79E+00	3.98E-00		7.38E-01		1.57E-01		8.85E-01	3.84E-01		1.18E+02	7.18E-02	1.54E-02	1.22E+02	1.22E+02
	(61.11)	(100.00)		(100.00)		(100.00)		(100.00)	(100.00)		(100.00)	(57.85)	(26.71)	(98.83)	(98.84)
Total	2.93E+00	3.98E-00		7.38E-01	2.60E-01	1.57E-01		8.85E-01	3.84E-01		1.18E+02	1.24E-01	5.76E-02	1.24E+02	1.24E+02
	(2.36)	(0.32)		(0.60)	(0.21)	(0.13)		(0.71)	(0.31)		(95.26)	(0.10)		(100.00)	
	(2.36)	(0.32)		(0.60)	(0.21)	(0.13)		(0.72)	(0.31)		(95.31)		(0.05)		(100.00)

Note: SCA means scenario A, SCB means scenario B

EU

	Upstream								*Manufacturing (Assembly) (%)*	*Downstream*				*Total (%)*	
	PP (%)	*Body (%)*	*PVC (%)*	*Power cord manufacturing (%)*	*Card board (%)*	*Packaging (%)*	*Steel (%)*	*Motor manufacturing (%)*		*Distribution (%)*	*Use (%)*	*Disposal (%)*			
												SCA	*SCB*	*SCA*	*SCB*
NO_X	*2.11E-01*				*4.83E-02*							*9.72E-03*	*7.84E-03*	*2.69E-01*	*2.67E-01*
	(100.00)				*(100.00)*							*(100.00)*	*(100.00)*	*(100.00)*	*(100.00)*
Total	*2.11E-01*				*4.83E-02*							*9.72E-03*	*7.84E-03*	*2.69E-01*	*2.67E-01*
	(78.46)				*(17.93)*							*(3.61)*		*(100.00)*	
	(79.01)				*(18.05)*								*(2.93)*		*(100.00)*

Note: SCA means scenario A, SCB means scenario B

POC

	Upstream									*Downstream*				*Total (%)*	
	PP (%)	*Body (%)*	*PVC (%)*	*Power cord manufacturing (%)*	*Card board (%)*	*Packaging (%)*	*Steel (%)*	*Motor manufacturing (%)*	*Manufacturing (Assembly) (%)*	*Distribution (%)*	*Use (%)*	*Disposal (%)*			
												SCA	*SCB*	*SCA*	*SCB*
Methane		*1.08E-03*		*2.00E-03*		*3.99E-04*		*2.39E-03*	*1.04E-03*		*3.19E-01*	*8.74E-03*	*5.61E-03*	*3.35E-01*	*3.32E-01*
		(100.00)		*(100.00)*		*(100.00)*		*(100.00)*	*(100.00)*		*(100.00)*	*(81.00)*	*(76.87)*	*(17.40)*	*(17.27)*
CO										*1.95E-02*				*1.95E-02*	*1.95E-02*
										(100.00)				*(1.02)*	*(1.02)*
VOC	*6.49E-01*		*8.63E-01*											*1.51E+00*	*1.51E+00*
	(93.45)		*(100.00)*											*(78.57)*	*(78.72)*
NO_X	*4.55E-02*				*1.04E-02*							*2.09E-03*	*1.69E-03*	*5.80E-02*	*5.76E-02*
	(6.55)				*(100.00)*							*(19.00)*	*(23.13)*	*(3.01)*	*(3.00)*
Total	*6.94E-01*	*1.08E-03*	*8.63E-01*	*2.00E-03*	*1.04E-02*	*3.99E-04*		*2.39E-03*	*1.04E-03*	*1.95E-02*	*3.19E-01*	*1.08E-02*	*7.30E-03*	*1.92E+00*	*1.92E+00*
	(36.10)	*(0.06)*	*(44.84)*	*(0.10)*	*(0.54)*	*(0.02)*		*(0.12)*	*(0.05)*	*(1.02)*	*(16.59)*	*(0.56)*		*(100.00)*	
	(36.16)	*(0.06)*	*(44.92)*	*(0.10)*	*(0.54)*	*(0.02)*		*(0.12)*	*(0.05)*	*(1.02)*	*(16.62)*		*(0.38)*		*(100.00)*

Note: SCA means scenario A, SCB means scenario B

ARD

	Upstream								*Manufacturing (Assembly) (%)*	*Downstream*				*Total (%)*	
	PP (%)	*Body (%)*	*PVC (%)*	*Power cord manufacturing (%)*	*Card board (%)*	*Packaging (%)*	*Steel (%)*	*Motor manufacturing (%)*		*Distribution (%)*	*Use (%)*	*Disposal (%)*			
												SCA	*SCB*	*SCA*	*SCB*
Crude oil	*4.84E+00*		*1.33E+00*		*2.66E-01*		*6.70E-02*			*9.93E-01*		*5.48E-02*	*-8.63E-01*	*7.55E+00*	*6.63E+00*
	(100.00)		*(95.35)*		*(100.00)*		*(9.63)*			*(100.00)*		*(99.31)*	*(-71.17)*	*(29.45)*	*(27.21)*
Coal		*5.72E-02*	*6.48E-02*	*1.06E-01*		*2.13E-02*	*9.91E-02*	*1.28E-01*	*5.54E-02*		*1.70E+01*	*3.80E-04*	*1.31E-02*	*1.76E+01*	*1.76E+01*
		(100.00)	*(4.65)*	*(100.00)*		*(100.00)*	*(14.25)*	*(100.00)*	*(100.00)*		*(100.00)*	*(0.69)*	*(1.08)*	*(68.49)*	*(72.10)*
Iron ore							*5.29E-01*						*-3.62E-01*	*5.29E-01*	*1.67E-01*
							(76.13)						*(-29.91)*	*(2.07)*	*(0.69)*
Total	*4.84E+00*	*5.72E-02*	*1.40E+00*	*1.06E-01*	*2.66E-01*	*2.13E-02*	*6.95E-01*	*1.28E-01*	*5.54E-02*	*9.93E-01*	*1.70E+01*	*5.52E-02*	*-1.21E+00*	*2.56E+01*	*2.44E+01*
	(18.87)	*(0.22)*	*(5.44)*	*(0.42)*	*(1.04)*	*(0.08)*	*(2.71)*	*(0.50)*	*(0.22)*	*(3.87)*	*(66.41)*	*(0.22)*		*(100.00)*	
	(19.85)	*(0.24)*	*(5.73)*	*(0.44)*	*(1.09)*	*(0.09)*	*(2.85)*	*(0.52)*	*(0.23)*	*(4.08)*	*(69.86)*		*(-4.97)*		*(100.00)*

Note: SCA means scenario A, SCB means scenario B

b) Key issue identification based on weighted impact

	Upstream									Manufacturing (Assembly) (%)	Downstream				Total (%)	
	PP (%)	Body (%)	PVC (%)	Power cord manufacturing (%)	Card board (%)	Packaging (%)	Steel (%)	Motor manufacturing (%)	Sub total (%)		Distribution (%)	Use (%)	Disposal (%)			
													SCA	SCB	SCA	SCB
GW	1.52E-05	5.31E-06	1.46E-05	9.83E-06	2.28E-06	1.97E-06	5.94E-06	1.18E-05	6.70E-05	5.12E-06	6.86E-06	1.57E-03	2.01E-05	-3.28E-06	1.67E-03	1.65E-03
	(13.78)	(72.80)	(29.20)	(72.80)	(28.83)	(72.06)	(36.50)	(72.80)	(29.83)	(72.80)	(31.28)	(72.80)	(93.00)	(15.74)	(68.64)	(68.88)
AD	8.17E-06	1.11E-06		2.06E-06	7.26E-07	4.40E-07		2.47E-06	1.50E-05	1.07E-06		3.30E-04	3.47E-07	1.61E-07	3.46E-04	3.46E-04
	(7.40)	(15.25)		(15.25)	(9.18)	(16.11)		(15.25)	(6.67)	(15.25)		(15.25)	(1.61)	(-0.77)	(14.21)	(14.45)
EU	3.41E-06				7.79E-07				4.19E-06				1.57E-07	1.27E-07	4.35E-06	4.32E-06
	(3.09)				(9.85)				(1.86)				(0.73)	(-0.61)	(0.18)	(0.18)
POC	1.19E-05	1.85E-08	1.48E-05	3.42E-08	1.78E-07	6.84E-09		4.11E-08	2.70E-05	1.78E-08	3.35E-07	5.47E-06	1.86E-07	1.25E-07	3.30E-05	3.29E-05
	(10.77)	(0.25)	(29.49)	(0.25)	(2.25)	(0.25)		(0.25)	(12.01)	(0.25)	(1.53)	(0.25)	(0.86)	(-0.60)	(1.35)	(1.38)
ARD	7.18E-05	8.53E-07	2.07E-05	1.58E-06	3.94E-06	3.16E-07	1.03E-05	1.90E-06	1.11E-04	8.22E-07	1.47E-05	2.53E-04	8.20E-07	-1.80E-05	3.81E-04	3.62E-04
	(64.96)	(11.70)	(41.31)	(11.70)	(49.88)	(11.58)	(63.50)	(11.70)	(49.62)	(11.70)	(67.20)	(11.70)	(3.80)	(86.24)	(15.62)	(15.30)
Total	1.11E-04	7.30E-06	5.02E-05	1.35E-05	7.91E-06	2.73E-06	1.63E-05	1.62E-05	2.25E-04	7.03E-06	2.19E-05	2.16E-03	2.16E-05	-2.09E-05	2.44E-03	2.39E-03
	(4.54)	(0.30)	(2.06)	(0.55)	(0.32)	(0.11)	(0.67)	(0.67)	(9.22)	(0.29)	(0.90)	(88.71)	(0.89)		(100.00)	
	(4.62)	(0.30)	(2.10)	(0.56)	(0.33)	(0.11)	(0.68)	(0.68)	(9.38)	(0.29)	(0.92)	(90.28)		(-0.87)		(100.00)

Note: SCA means scenario A, SCB means scenario B

From the above results, we find key parameters, impact category, and activity. They are:

Key parameter = CO_2
Key impact category = GW
Key activity = Use stage

Figures E5.1 and E5.2 are graphical representation of the weighted impact per life cycle stage of the entire product system, and per unit processes in the upstream stage of the reference product, scenario A, respectively. Analysis of both figures lead to the identification of key issues of the hair drier product system for the improvement of its environmental aspects.

As shown in Figure E5.1, the use stage dominates most of the impact caused by the hair drier product system, followed by upstream stage. From this, every effort must be given to reduce environmental impact during the use stage by implementing improvement measures such as increasing energy efficiency of the hair drier drying system. This is clear because majority of the environmental impact during the use stage is due to global warming. In the case of Figure E5.2, the polypropylene unit process is a major contributor to the environmental impact in the upstream stage. Thus, consideration must be given whether polypropylene can be replaced with other material whose environmental impact is less than polypropylene.

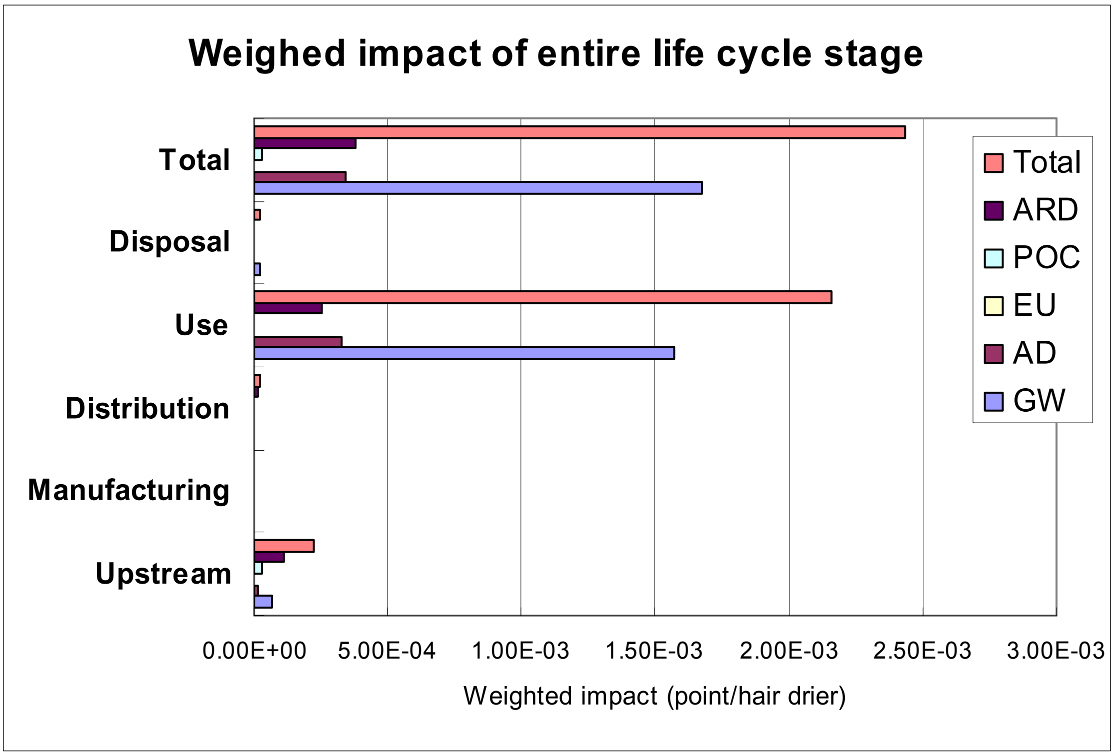


Figure E5.1 Weighted Impact of life cycle stage

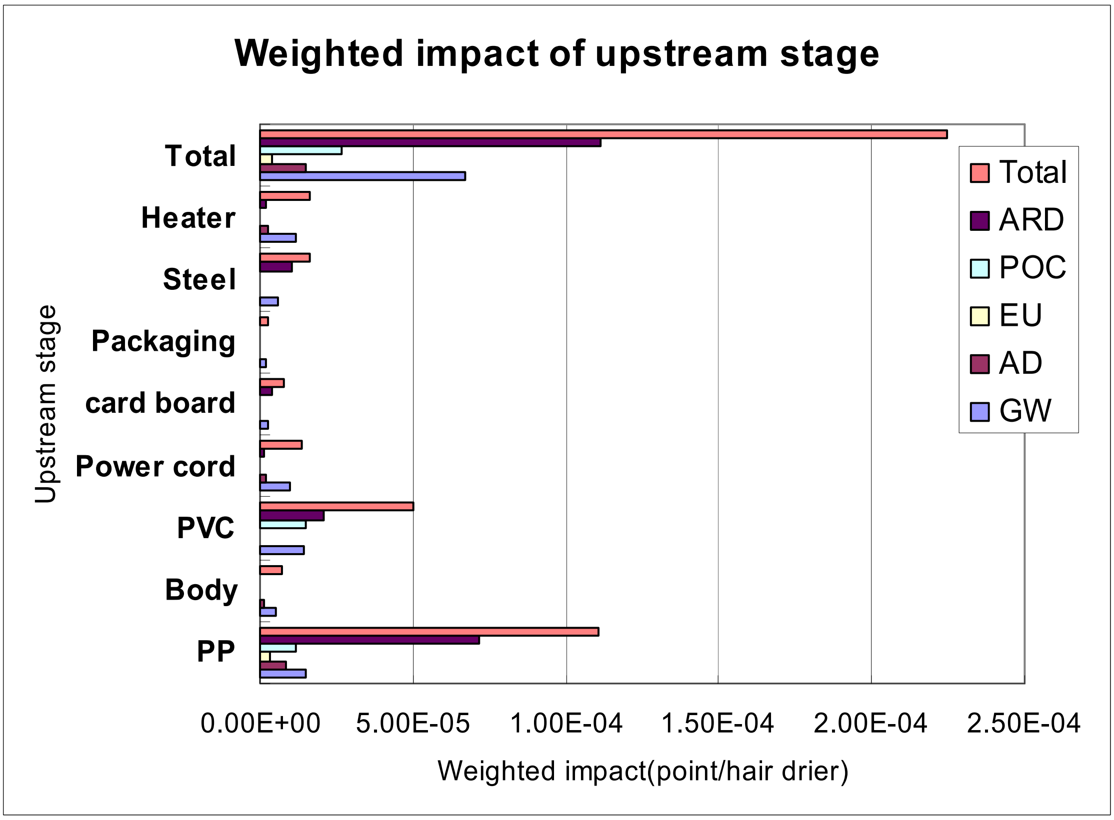


Figure E5.2 Weighted Impact of upstream stage *c) Comparison of weighted impact of a product system between scenarios A and B:*

For the weighted impact in the five life cycle stages, the difference between scenario A and B is clear in the case of disposal, where scenario B exhibits negative weighted impact value or beneficial environmental impact while scenario A causes adverse impact on the environment. For other life cycle stages, no differences exist because the two scenarios were made only for the disposal stage. Weighted impact per impact category shown in table below and Figure E5.3 for the disposal stage only and Figure E5.4 for the entire product system indicate that most benefit from waste recycling occurs in the abiotic resource depletion followed by global warming. This is expected because recycled material will replace virgin material, thus reducing virgin material requirement. Reduction in global warming occurs because of reduced emission of CO_2 during the incineration and landfill operation. These results strongly indicate that recycling of the waste is conducive to the reduction of environmental impact from a product, in this case, hair drier.

Impact category	Weighted Impact (WI_i)					
	Disposal stage		Reduction rate	Entire life cycle stages		Reduction rate
	Scenario A	Scenario B		Scenario A	Scenario B	
GW	2.01E-05	-3.28E-06	116.38%	1.67E-03	1.65E-03	1.40%
AD	3.47E-07	1.61E-07	53.59%	3.46E-04	3.46E-04	0.05%
EU	1.57E-07	1.27E-07	19.31%	4.35E-06	4.32E-06	0.70%
POC	1.86E-07	1.25E-07	32.61%	3.30E-05	3.29E-05	0.18%
ARD	8.20E-07	-1.80E-05	2295.22%	3.81E-04	3.62E-04	4.94%
Total	2.16E-05	-2.09E-05	196.78%	2.44E-03	2.39E-03	1.74%

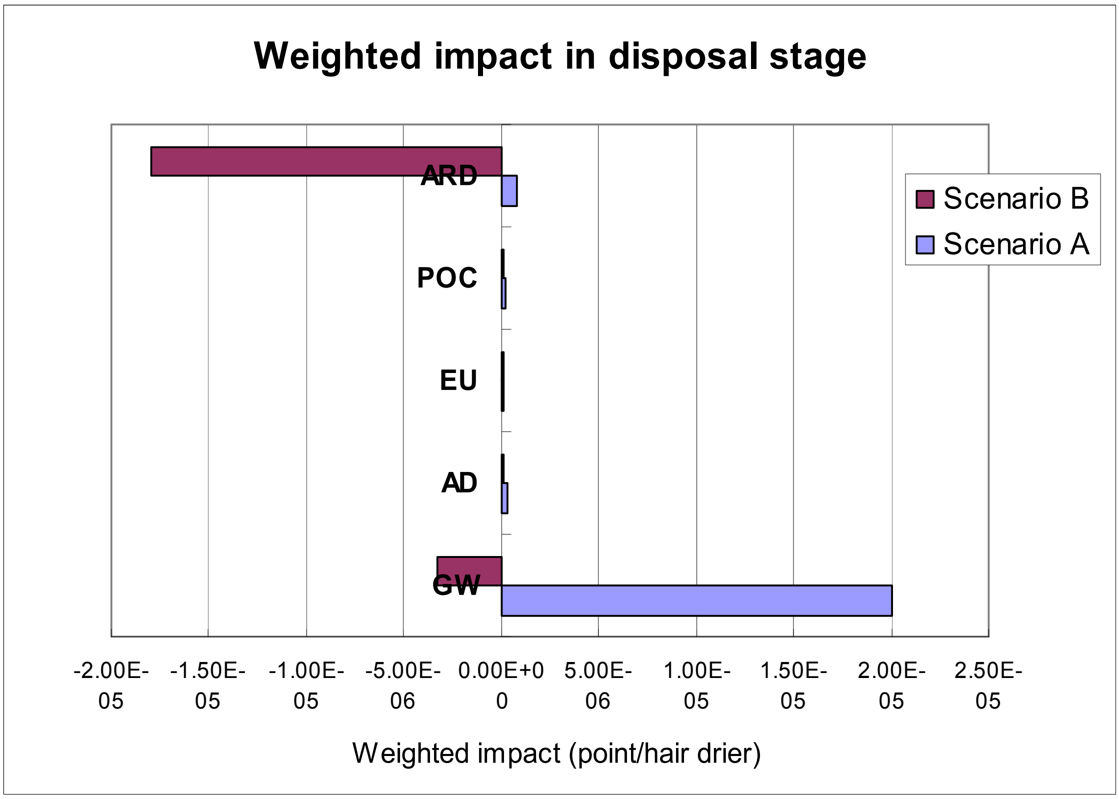


Figure E5.3 Weighted impact in the disposal stage for scenarios A and B

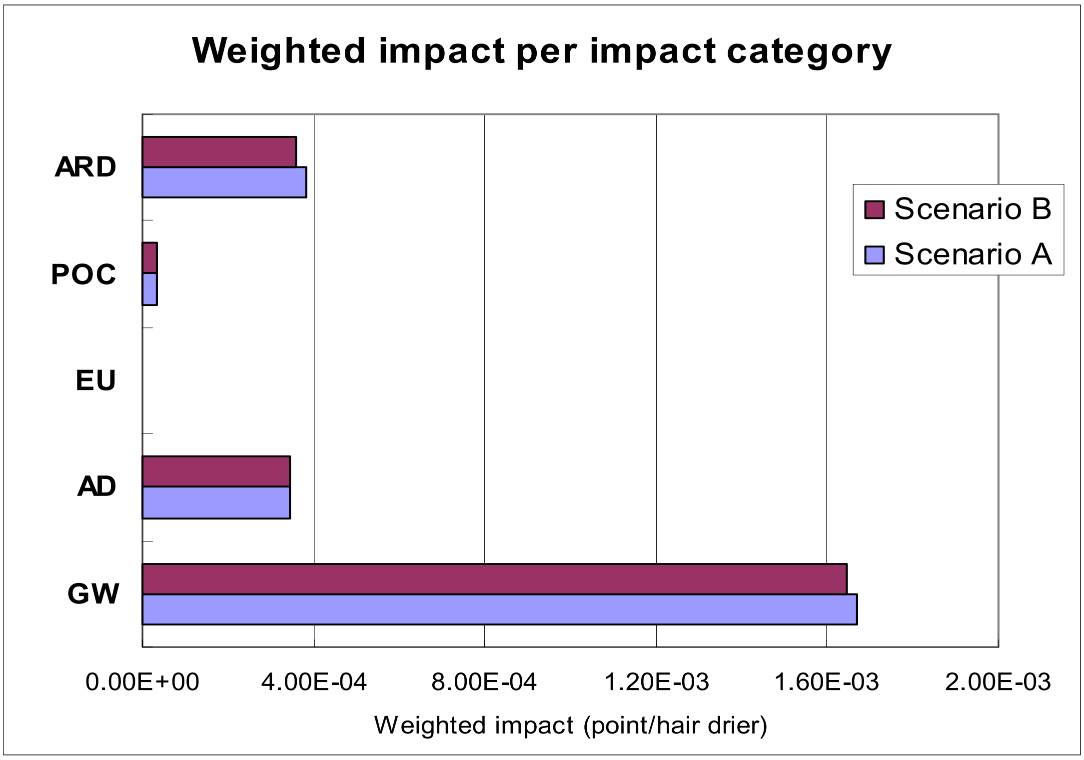


Figure E5.4 Weighted impact of the entire life cycle stages for scenarios A and B

(2) Completeness check

Figure E5.5 shows the result of the completeness check of the hair drier case. It lists all unit processes identified in the process tree from the upstream stage to the disposal stage. Comparison was made between two scenarios with respect to completeness of the data used, based on a qualitative scale from A to E (100% to 0%).

Unit process	*Scenario A*		*Scenario B*	
	Complete?	*Action required*	*Complete?*	*Action required*
PP	*A*		*A*	
Body	*B*	*Check inventory*	*B*	*Check inventory*
PVC	*A*		*A*	
Power cord manufacturing	*B*	*Check inventory*	*B*	*Check inventory*
Card board production	*A*		*A*	
Packaging	*B*	*Check inventory*	*B*	*Check inventory*
Steel	*A*		*A*	
Motor manufacturing	*A*		*A*	
Electricity	*B*	*Check inventory*	*B*	*Check inventory*
Manufacturing	*C*	*Check inventory*	*C*	
Distribution	*D*	*Check inventory*	*D*	*Check inventory*
Use	*B*	*Check inventory*	*B*	*Check inventory*
Incineration	*C*	*Check inventory*	*C*	*Check inventory*
Landfill	*C*	*Check inventory*	*C*	*Check inventory*
Recycling	*E*	*Compare B*	*C*	*Compare A*

Completeness: 100% ↔ 0%
(A B C D E)

Figure E5.5 The completeness check of the hair drier case

(3) Sensitivity check: allocation method and data uncertainty

a) Allocation method

Figure E5.6 shows results of the sensitivity check for the allocation rule based on economic value and physical mass.

	Weighted impact (WI_i)	
	Scenario A	*Scenario B*
Allocation By physical mass	*2.44E-03*	*2.39E-03*
Allocation By economic value	*2.43E-03*	*2.38E-03*
Sensitivity, %	*0.41*	*0.42*

Figure E5.6 The result of the sensitivity check for two scenarios

b) Data uncertainty

Implement the sensitivity analysis by chosen key issue in the use stage

Scenario: In use stage, assume that electricity use is increased by 10%.

Scenario

Impact category	*Scenario*			*Reference*
	CI_i	*NI_i*	*WI_i*	*WI_i*
GW	*3.51E+04*	*6.21E-03*	*1.83E-03*	*1.67E-03*
AD	*1.36E+02*	*2.40E-03*	*3.79E-04*	*3.46E-04*
EU	*2.69E-01*	*3.03E-05*	*4.35E-06*	*4.35E-06*
POC	*1.96E+00*	*2.65E-04*	*3.35E-05*	*3.30E-05*
ARD	*2.73E+01*	*1.46E-03*	*4.06E-04*	*3.81E-04*
Total		*2.65E-03*		*2.44E-03*

Elasticity = C_R/C_D

C_R = (WI of scenario -WI of reference)/WI of referenceX100, C_R = 8.87 %

C_D = (Data of scenario – Data of reference)/Data of referenceX100, C_D = 10.00%

Elasticity = 8.87/10 = 0.887

Elasticity less than 1 is considered acceptable.

(4) Consistency check

Figure E5.7 shows results of the consistency check for two scenarios.

Check	*Scenario A*		*Scenario B*		*Compare A and B*	*Action*
Data source	*Database*	*OK*	*Database*	*OK*	*Consistent*	*No action*
Data accuracy	*Good*	*OK*	*Good*	*OK*	*Consistent*	*No action*
Database age	*5 years*	*OK*	*5 years*	*OK*	*Consistent*	*No action*
Characterization factor	*OK*		*OK*		*Consistent*	*No action*
Weighting factor	*OK*		*OK*		*Consistent*	*No action*
Weighting method	*Panel method*	*OK*	*Panel method*	*OK*	*Consistent*	*No action*

Figure E5.7 The result of the consistency check

(5) Data quality requirements check

For the LCA of the hair drier example chosen here you need to answer data quality requirements for the process group as shown in Table E5.1.

Table E5.1 Data quality requirements check

Process group	Unit process	Collected data	Literature data	Boundaries		
				Time	Geo	Techno
Upstream processes (Materials)	PP		v	o	o	o
	PVC		V	o	o	o
	Cardboard		v	o	o	o
	Steel		v	o	o	o
Upstream processes (energy)	Electricity		v	o	o	o
	Diesel		v	o	o	o
Manufacturing processes	Raw material	v		o	o	o
	Energy	v		o	o	o
Downstream processes (distribution, use, disposal)	Transportation	v		o	o	o
	Electricity	v		o	o	o
	Incineration		v	o	o	o
	Landfill		v	o	o	o
	Recycling		v	o	o	o

v : corresponding data, o : meeting the requirements

(6) Conclusions and recommendations

The goal of performing LCA for a hair drier is to identify environmental weak points of the hair drier product system as well as comparing environmental impacts of the product system based on two different disposal scenarios. Major conclusions of the LCA study are:

1) Key issues identified by the contribution analysis

Key issues include key parameters, impact category, and activity. They are:

Key parameter = CO_2
Key impact category = Global Warming
Key activity = Use

The environmental impact from the use stage contributes to 88.71% of the total impact of the product system.

The global warming impact category comprises 68.64% of the total impact of the product system.

The impact accrued from CO_2 in the use stage was more than 96.00% of the impact of the use stage. This is due to the electricity consumption of the hair drier during the use stage.

2) Two different disposal scenarios were tested in order to do a comparison of the environmental impact of the product system.

- Disposal scenario A: landfill 50%, incineration 50%
- Disposal scenario B: landfill 30%, incineration 20%, recycling 50%

As shown in Table E5.2, scenario B reduces the environmental impact by 1.74% compared to scenario A. This is clearly the benefit of increased recycling of waste products.

Table E5.2 Environmental impact of the hair drier system for two different disposal scenarios

	Environmental impact (point /hair drier)		*Difference*	
	Disposal stage	*Total life cycle stage*	*Environmental impact (point /hair drier)*	*Relative difference (%)*
Scenario A	*2.16E-05*	*2.44E-03*	*4.24E-05*	*1.74*
Scenario B	*-2.09E-05*	*2.39E-03*		

Table E5.3 shows the completeness, sensitivity, and consistency check of the LCA results. The test results show that completeness, sensitivity and consistency requirements of the LCA study are all met.

Table E5.3 Completeness, sensitivity and consistency check of the hair drier LCA results

		Scenario A	*Scenario B*	*Comparison*
Completeness check		*Ranging between A and C*		*completeness is verified*
Sensitivity check	*Allocation rules (physical mass and economic value)*	*0.41 %*	*0.42%*	*Not affected by the allocation methods*
	Elasticity (electricity consumption during the use stage)	*0.89*		*Not sensitive*
Consistency check		*OK*	*OK*	*Consistency is verified*

Recommendations of the LCA study based on the conclusions drawn above are:

1) The CO_2 emission during the use of the hair drier must be reduced to improve the environmental aspects of the product. Thus, the hair drier must be designed to reduce electricity consumption during its use.

2) The environmental impact of the hair drier product system is reduced by 1.74% when the recycling rate increased to 50% from 0%. Thus, the environmental impact of the hair drier product system can be reduced by designing the product for easy recycling.

As the last step, an LCA report is prepared in accordance with the requirements given in ISO 14040.

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