Published in Environment International 30, issue 5, 701-720, 2004
which should be used for any reference to this work

# Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications

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## Abstract

Sustainable development requires methods and tools to measure and compare the environmental impacts of human activities for the provision of goods and services (both of which are summarized under the term “products”). Environmental impacts include those from emissions into the environment and through the consumption of resources, as well as other interventions (e.g., land use) associated with providing products that occur when extracting resources, producing materials, manufacturing the products, during consumption/use, and at the products’ end-of-life (collection/sorting, reuse, recycling, waste disposal). These emissions and consumptions contribute to a wide range of impacts, such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, and noise—among others. A clear need, therefore, exists to be proactive and to provide complimentary insights, apart from current regulatory practices, to help reduce such impacts. Practitioners and researchers from many domains come together in life cycle assessment (LCA) to calculate indicators of the aforementioned potential environmental impacts that are linked to products—supporting the identification of opportunities for pollution prevention and reductions in resource consumption while taking the entire product life cycle into consideration. This paper, part 1 in a series of two, introduces the LCA framework and procedure, outlines how to define and model a product’s life cycle, and provides an overview of available methods and tools for tabulating and compiling associated emissions and resource consumption data in a life cycle inventory (LCI). It also discusses the application of LCA in industry and policy making. The second paper, by Pennington et al. (Environ. Int. 2003, in press), highlights the key features, summarises available approaches, and outlines the key challenges of assessing the aforementioned inventory data in terms of contributions to environmental impacts (life cycle impact assessment, LCIA).

## 1. Introduction

Achieving “sustainable development” requires methods and tools to help quantify and compare the environmental impacts of providing goods and services (“products”) to our societies. These products are created and used because they fulfil a need, be it an actual or a perceived one. Every product has a “life,” starting with the design/development of the product, followed by resource extraction, production (production of materials, as well as manufacturing/provision of the product), use/consumption, and finally end-of-life activities (collection/sorting, reuse, recycling, waste disposal). All activities, or processes, in a product’s life result in environmental impacts due to consumption of resources,

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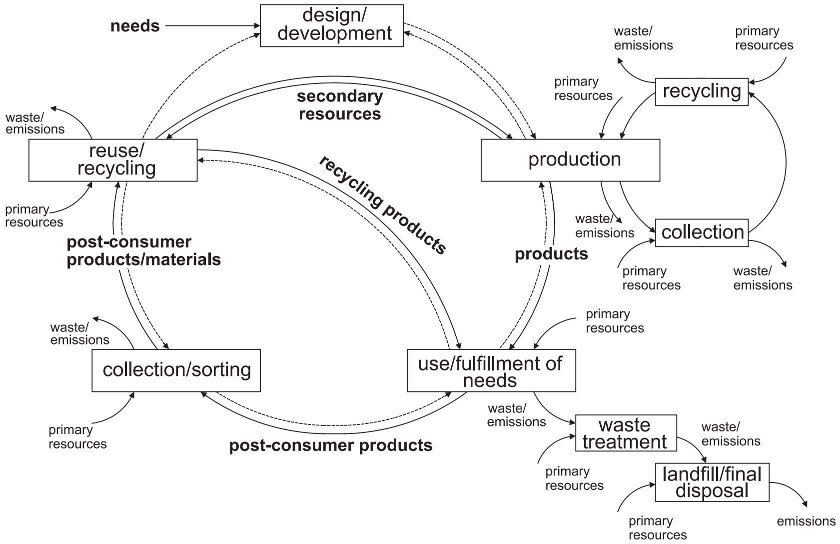

Fig. 1. Schematic representation of a generic life cycle of a product (the full arrows represent material and energy flows, while the dashed arrows represent information flows) (Rebitzer et al., 2000).

emissions of substances into the natural environment, and other environmental exchanges (e.g., radiation).

Fig. 1 presents a simplified scheme of the product life concept, which is usually referred to as a ‘‘life cycle,’’ as it includes loops between the several life phases. Examples of such loops are the reuse and recycling of post-consumer products (originating in the end-of-life phase) or recycling of production scrap.

Life cycle assessment (LCA) is a methodological framework for estimating and assessing the environmental impacts attributable to the life cycle of a product, such as climate change, stratospheric ozone depletion, tropospheric ozone (smog) creation, eutrophication, acidification, toxicological stress on human health and ecosystems, the depletion of resources, water use, land use, and noise—and others.

When conducting an LCA, the design/development phase is usually excluded, since it is often assumed not to contribute significantly. However, one has to note that the decisions in the design/development phase highly influence the environmental impacts in the other life cycle stages. The design of a product strongly predetermines its behaviour in the subsequent phases (e.g., the design of an automobile more or less determines the fuel consumption and emissions per kilometre driven in the use phase and has a high influence on the feasible recycling options in the end-of-life phase). Fig. 2 illustrates this interdependency between design/development and the other phases of the life cycle. Therefore, if the aim of an LCA is the improvement of goods and services, one of the most important LCA applications, then the study should be carried out as early in the design process as possible and concurrent to the other design procedures. This applies analogously to the design or improvement of a process within a life cycle of a product, especially if interactions with other processes or life cycle stages can occur.

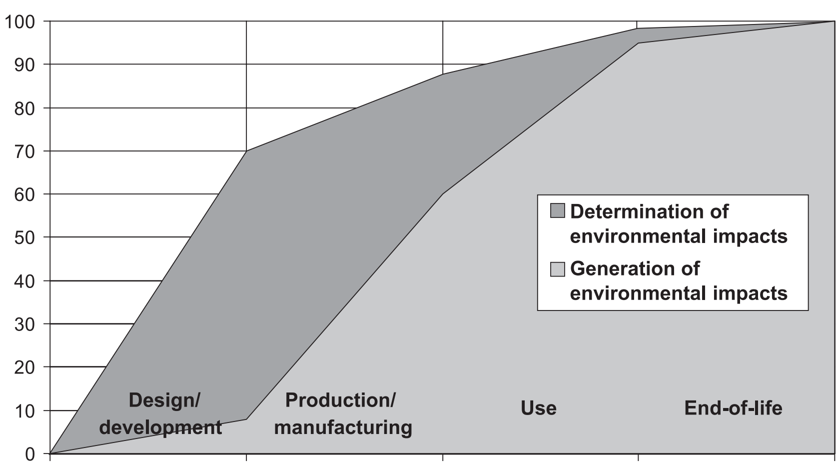

Fig. 2. Generalized representation of the (pre)determination and the generation of environmental impacts in a product’s life cycle (Rebitzer, 2002).

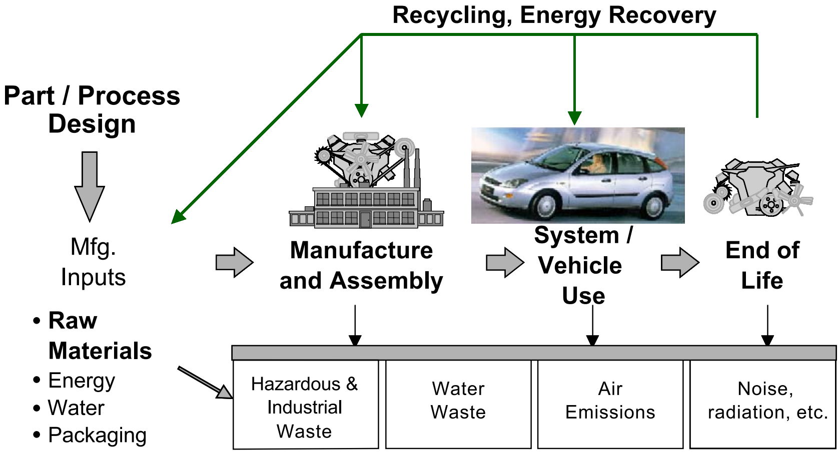

Fig. 3. Life cycle of an automobile (Adams and Schmidt, 1998).

Part 1 of this paper, which is targeted at decision makers in industry and policy, product developers, environmental managers, students, and other non-LCA specialists working on environmental issues, provides

- an overview of the objectives, characteristics, and components of an LCA,
- outlines selected applications of the LCA methodology, and
- provides a review of some of the challenging issues for LCA practitioners in the context of defining the goal and scope and compiling the life cycle inventory (LCI) of emissions and resource consumptions associated with a product's life cycle—the frame and foundation, respectively, of every LCA.

A second paper focuses on life cycle impact assessment (LCIA), the subsequent phase of an LCA for assessing the inventory data in terms of contributions to environmental impacts (life cycle impact assessment) (Pennington et al., 2004).

It should be stressed that LCA is still a young and evolving application, with its roots in research related to energy requirements in the 1960s (Curran, 1996) and pollution prevention, which was formally initiated in the 1970s (Royston, 1979). Environmental management, in general, is also a young discipline, from a political standpoint, with institutes such as the USEPA being created just over 30 years ago. For these reasons, and partly due to the methodology being applicable to many different study objectives, there is no absolute consensus on all the issues presented in this paper. There are therefore different approaches, depending on the specific question at hand, and ultimately depending on the decision that has to be supported by an LCA study. Given this, this article elaborates on some specific methodological choices and outlines alternatives, where relevant, that can be adopted depending on the goal of an LCA study, but also on the scientific perspectives of the researcher or practitioner.

## 2. The structure and components of LCA

An LCA practitioner tabulates the emissions and the consumption of resources, as well as other environmental exchanges at every relevant stage (phase) in a product's life cycle, from "cradle to grave"—including raw material extractions, energy acquisition, materials production, manufacturing, use, recycling, ultimate disposal, etc. (see Fig. 1). Indirect changes in other systems (other product life cycles) may also be accounted for (see 'consequential LCA' in Section 3). Fig. 3 provides an example of such a life cycle for an automobile. The complete life cycle, together with its associated material and energy flows, is called product system.

After the compilation, tabulation, and preliminary analysis of all environmental exchanges (emissions, resource consumptions, etc.), called the life cycle inventory (LCI), it is often necessary for practitioners to calculate, as well as to interpret, indicators of the potential impacts associated with such exchanges with the natural environment (life cycle impact assessment, LCIA).

While advances continue to be made, international and draft standards of the ISO 14000 series are, in general, accepted as providing a consensus framework for LCA:[1]

- International Standard ISO 14040 (1997) on principles and framework.
- International Standard ISO 14041 (1998) on goal and scope definition and inventory analysis.

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[1] These publications do not provide detailed methodological guidance. Comprehensive and detailed guidelines are supplied, e.g., by Consoli et al. (1993), Guinée et al. (2002), Hauschild and Wenzel (1998), Heijungs et al. (1992), Lindfors et al. (1995), and Wenzel et al. (1997).

- International Standard ISO 14042 (2000) on life cycle impact assessment.
- Iinternational Standard SO 14043 (2000) on life cycle interpretation.

There have also been developments on the standardization on the application of LCA-based methods for design purposes (International Standard/TR ISO TR 14062, 2000).

The Society of Environmental Toxicology and Chemistry's (SETAC) "Code of practice" originally distinguished four methodological components within LCA (Consoli et al., 1993): goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and life cycle improvement assessment. In ISO 14040 (1997) life cycle improvement assessment is no longer regarded as a phase on its own, but rather as having an influence throughout the whole LCA methodology. In addition, life cycle interpretation has been introduced. This is a phase that interacts with all other phases in the LCA procedure, as illustrated in Fig. 4.

The goal and scope definition of an LCA provides a description of the product system in terms of the system boundaries and a functional unit. The functional unit is the important basis that enables alternative goods, or services, to be compared and analysed. The functional unit is not usually just a quantity of material. Practitioners may compare, for example, alternative types of packaging on the basis of 1 $m^3$ of packed and delivered product—the service that the product provides. The amount of packaging material required, termed the reference flow, can vary depending on the packaging option selected (paper, plastic, metal, composite, etc.).

Life cycle inventory (LCI), the main focus of this paper, is a methodology for estimating the consumption of resources and the quantities of waste flows and emissions caused by or otherwise attributable to a product's life cycle. Consumption of resources and generation of waste/emissions are likely to occur

- at multiple sites and regions of the world,
- as different fractions of the total emissions at any one site (the fraction required to provide the specified functional unit; allocation amongst related and nonrelated co-products in a facility such as a refinery, etc.),
- at different times (e.g. use phase of a car compared to its disposal), and
- over different time periods (multiple generations in some cases, e.g. for landfilling).

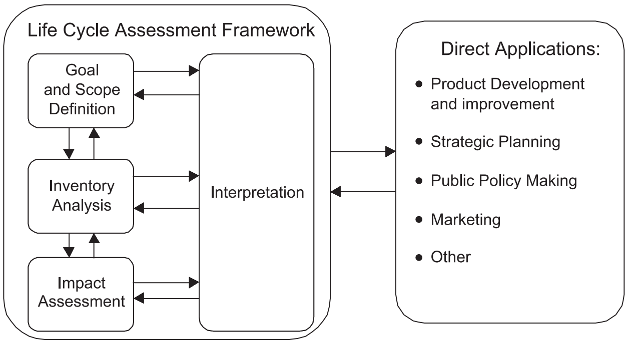

Fig. 4. Phases and applications of an LCA (based on ISO 14040, 1997).

The processes within the life cycle and the associated material and energy flows as well as other exchanges are modelled to represent the product system and its total inputs and outputs from and to the natural environment, respectively. This results in a product system model and an inventory of environmental exchanges related to the functional unit. Different aspects and challenges of special interest in modelling this product system and establishing the LCI are discussed in detail in Sections 3–5.

Life cycle impact assessment (LCIA)—the focus of the second part of this article series (Pennington et al., 2004)—provides indicators and the basis for analysing the potential contributions of the resource extractions and wastes/emissions in an inventory to a number of potential impacts. The result of the LCIA is an evaluation of a product life cycle, on a functional unit basis, in terms of several impacts categories (such as climate change, toxicological stress, noise, land use, etc.) and, in some cases, in an aggregated way (such as years of human life lost due to climate change, carcinogenic effects, noise, etc.—an option under ISO EN 14042 (2000) for some applications).

Life cycle interpretation occurs at every stage in an LCA. If two product alternatives are compared and one alternative shows higher consumption of each material and of each resource, an interpretation purely based on the LCI can be conclusive. A practitioner, however, may also want to compare across impact categories, particularly when there are trade-offs between product alternatives, or if it is desirable to prioritise areas of concern within a single life cycle study. For example, emissions of $CO_2$ in one life cycle may result in a higher climate change indicator than in another, but the alternative involves more pesticides and has a higher potential contribution to toxicological impacts. A stakeholder may therefore want more information to decide which difference is a higher priority. As outlined in part 2 (Pennington et al., 2004), resolving such issues is often an optional step, but one that clearly warrants attention, drawing not only on natural sciences but relying heavily on social science and economics.

The following section discusses the basis, as well as important aspects of specific interest for the LCA practitioner and researcher, in regards to goal and scope definition and to life cycle inventory analysis.

## 3. Modelling the product system

An LCI can be best described as a model of one or more product systems. Each product system fulfils a function that is quantified in functional units. The choice of functional units is discussed below. The aim of the LCI is to calculate the quantities of different resources required and emissions and waste generated per functional unit.

The model of the product system is typically a static simulation model. It is composed of unit processes, which each represent one or several activities, such as production processes, transport, or retail. For each unit process, data are recorded on the inputs of natural resources, the emissions, waste flows, and other environmental exchanges. The environmental exchanges are typically assumed to be linearly related to one of the product flows of the unit process. All unit processes are linked through intermediate product flows, what makes the typical process system model linear with respect to the quantity of function it provides. For product comparisons, the functional unit is translated to reference flows, which are specific product flows for each of the compared systems required to produce one unit of the function. The reference flow then becomes the starting point for building the necessary models of the product systems.

The choices and assumptions made during system modelling, especially with respect to the system boundaries and what processes to include within these boundaries, are often decisive for the result of an LCA study. An understanding of the importance of system modelling in LCA has been growing ever since "goal and scope definition" was identified as a separate phase in Heijungs et al. (1992) and statements such as "...depending on the goal and scope of the LCA" were liberally used throughout the ISO 14040 series. However, it has been less clear how the goal and scope of an LCA should affect the system modelling.

Heintz and Baisnée (1992) and Weidema (1993) suggested that two very distinct categories of LCA goals exist:

- to describe a product system and its environmental exchanges or
- to describe how the environmental exchanges of the system can be expected to change as a result of actions taken in the system.

In recent years, similar distinctions between types of LCA have been presented by many authors, although with slight variations and often with different sets of names (Ekvall, 2000). Here we use the term "attributional LCA" to denote a description of a product system and the term "consequential LCA" to denote a description of the expected consequences of a change.

The distinction between attributional and consequential LCA has important consequences for the way the product system should be modelled, as illustrated in the following sections. Therefore, careful attention has to be paid to the relationship between the goal of the specific LCA and the selection of the type of LCA model.

### *3.1. Defining the functional unit*

The functional unit is a quantitative description of the service performance (the needs fulfilled) of the investigated product system(s). For a refrigerator, the functional unit may, e.g., be described in "cubic meter years of cooling to 15 °C below room temperature."

An attributional LCI provides the set of total system-wide flows that are 'associated with' or 'attributed to' the delivery of a specified amount of the functional unit. Since the system is linearly modelled, the results all scale linearly with the functional unit, and its magnitude is of little importance. As an example, consider an LCA of electricity production. Attributional LCI results describe the environmental exchanges of the average electricity production in a geographic area and/or an electricity supplier. The results could, for instance, be presented as the emissions per megawatt hour produced. The magnitude of the functional unit (megawatt hour, smaller, or larger) does not affect the conclusions since the average emissions of the electricity system scale linearly with the functional unit.

A consequential LCI, in contrast, is an estimate of the system-wide change in pollution and resource flows that will result from a change in the level of the functional units produced. In this case, the results may depend on the magnitude of the change. The changes in emissions, etc. caused by a small increase or reduction in electricity production are described by environmental data for the marginal technologies (Azapagic and Clift, 1999, Weidema et al., 1999, Mattsson et al., 2004). These are, by definition, the technologies affected by small changes in the production. A large change in the electricity production can affect more technologies and, in addition, have substantial consequences for the structure of the electricity system. Since the consequences do not scale linearly with the magnitude of the change, the results of a consequential LCI are easier to interpret if the functional unit reflects the magnitude of the change investigated.

Differences in the functions provided by product system alternatives often appear when choosing a (too) narrow product perspective, i.e., when studying intermediate products, components, or products that are otherwise very dependent on other products. Such differences in functional output (performance of product system), and the consequent need for adjustments, can often be avoided by choosing a broader function-based perspective, i.e., based on the needs fulfilled by the products (e.g., "lighting" and "cooling of food") rather than based on the physical products themselves (e.g., "lamps" and "refrigerators"). Any remaining differences in the functional output between the compared systems can be avoided by expanding the system boundaries to include alternative ways to provide the same functions. Such system expansion is discussed in Section 3.3.

### *3.2. Identifying processes to include in the product system*

In an attributional LCA, the processes included are those that are deemed to contribute significantly to the studied product and its function. This typically implies that material and energy flows are followed systematically upstream from the process associated with the reference flow to the extraction of natural resources and downstream to the final disposal of waste. Typically, upstream supply is assumed to be fully elastic. The induced demand for one unit of product leads to the production and supply of one unit of product, with associated emissions and resource consumptions. Other customers/applications of the product are assumed not to be affected. In the same way, downstream demand is also assumed fully elastic (the induced supply of one unit of product leads to the consumption of one unit of product), and other producers of the same type product (fulfilling the same functional unit) are assumed not to be affected.

In a consequential LCA, the processes included are those that are expected to be affected on short and/or long term by the decisions to be supported by the study. Ekvall and Weidema (2004) describe in some detail how to decide what processes to include in a consequential LCI. In brief, the definition of system boundaries depends on how the markets can be expected to react to the studied change (Weidema, 2003, Ekvall, 2002), taking into account that

- neither production nor demand are always fully elastic, which means that the demand for one unit of product in the life cycle investigated affects not only the production of this product but also the consumption of the product in other systems,
- individual suppliers or markets may be constrained, which means that they are unaffected by an increase in demand for the product, and
- a change in demand for a product is often so small, compared to the total market for that product, that it only affects the marginal upstream production processes.

With respect to non-monetized aspects (flexibility, quality, knowledge), the marginal processes are likely to be the unconstrained processes with the lowest expected marginal production costs. An exception to this rule is when the total market for that good or service is shrinking faster than the replacement rate of production capital in that market. In this case, the marginal process is likely to be the existing process with the highest expected marginal production costs.

### *3.3. How to handle processes with multiple outputs*

When a unit process provides more than one product, one should question how exchanges should be partitioned and distributed among the multiple products. This has been one of the most controversial issues in the development of LCA (Klöpffer and Rebitzer, 2000). To answer this question, the ISO standards on LCA suggest a stepwise procedure. Other than the obvious solution of subdividing the unit process into separate processes each with only one product, whenever this is possible, the ISO procedure (ISO 14041, 1998, clause 6.5.3) consists of three consecutive steps.

The recommended option is to expand the studied systems “to include the additional functions related to the co-products,” implying that the systems can be easily expanded so that all are yielding comparable product outputs. The processes to include when making such system expansions are those processes actually affected by an increase or decrease in output of the by-product from the studied systems, as identified by the procedure outlined in Section 3.2 (Ekvall and Finnveden, 2001; Weidema 2001, 2003).

A second option in the ISO procedure is to theoretically separate the exchanges “in a way which reflects the underlying physical relationships between them, i.e., they shall reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.” This is a description of causal relationships that exist when the co-products can be independently varied (i.e., a situation of combined production).

The third option of the ISO procedure is to partition the exchanges “between the products and functions in a way which reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.” The concept is parallel to the second option, which suggests that the relationships referred to here should also be causal in nature. This is further emphasized by the only example provided, namely, that of the economic value of the products, which can be seen as the ultimate cause for the existence of the process. Economic value is, thus far, the only causal relationship that has been found to fit this last step of the ISO procedure.

In some LCIs, the environmental exchanges from processes with multiple outputs are partitioned in proportion to the physical quantity (mass, energy content, or similar) of the outputs without being justified by any causal relationship. This is only consistent with the ISO recommendations if the word “relationships” is more broadly interpreted to include also noncausal relationships, for example, the relation between the quantities of mass or energy in the outputs from the process. Such a broad interpretation would leave the system delimitation for attributional studies completely open.

## 4. Data collection and databases for LCI

In addition to methodological choices regarding the modelling of a product system, for each process of the product system, a data set is needed. This data set is a compilation of inputs and outputs related to the function or product generated by the process. Data collection and compilation are often the most work- and time-consuming steps in LCAs. Product systems usually contain process types common to nearly all studies, namely, energy supply, transport, waste treatment services, and the production of commodity chemicals and materials. As a cause of global markets, many of these process types are even similar or identical, be it oil extraction in the Middle East or steel manufacturing in Asia. Other processes show typical continental, national, or even regional properties—such as electricity generation, road transportation, cement manufacturing, and agricultural production, respectively. Therefore, databases providing high-quality (e.g., transparent and consistent) data of frequently used commodities for life cycle inventories are helpful and required, particularly if one wants to apply LCA on a routine basis, e.g., for product development purposes in a firm (see Section 6).

### *4.1. Challenges of data collection*

Both if data are to be compiled specifically for a given study, or if the compilation is made for the purpose of creating a database, a number of difficulties may arise. The list below provides some examples:

- The owner or operator of the activity has little or no previous experience in doing such compilations—traditionally, environmental data is recorded, if at all, on an organizational level rather than on a function level. Similarly, the LCA practitioner may have little previous knowledge of the process for which data is to be compiled. A process of mutual learning and awareness raising has to take place.
- The compilation is dependent on a set of methodological choices. In any process providing more than one unit of service or function, choices have to be made how to partition the overall inputs and outputs between the different functions (see Section 3.3).
- From an even more technical point of view, measurement points relevant to the question (i.e., input/output per unit of function, for instance, the electricity consumption for one single process) may be lacking.
- The compiled list and data for a unit processes can resemble the ‘environmental parallel’ to a cost statement (in the sense of product-related activity-based costing) or reveal proprietary technological data. For external LCA studies, companies often consider such information sensitive—although such barriers can be overcome, e.g., by using default approximations or industry averages in the absence of more specific data.

For the LCA practitioner, a number of additional problems will occur related to the overall structure of LCA:

- An LCA system usually consists of a large number of unit processes, hence, mutual learning of many process ‘owners’ may be necessary.
- The work often requires communication across several organizational borders, outside the regular business information flow.
- The quantity of each product, pollutant, resource, etc. needs to be measured in the same way in each unit process. The nomenclature used to denote the flows and other environmental exchanges also needs to be consistent throughout the product system.

Further examples are given by De Beaufort-Langeveld et al. (2003) and Middleton and McKean (2002).

### *4.2. Data documentation and establishment of standard databases*

In the 1990s, the LCA community realized that not only data but also data documentation is crucial. Meta information about, e.g., geographical, temporal, or technological validity of LCI data was rarely provided (neither in a structured way nor otherwise). The Society for the Promotion of Life Cycle Assessment Development (SPOLD) initiated the development of a data documentation format (Weidema, 1999), which facilitates extensive documentation of LCI data for processes and services. Several important LCA-software providers were included in the development of SPOLD in order to increase acceptance and data format compatibility. The result of a parallel, somewhat compatible, development was the SPINE data reporting and exchange format (Carlson et al., 1995). This was created concurrent to the establishment of the SPINE database (see below) and allows documentation of meta information using text data fields.

In 2001, the International Standards Organisation (ISO) agreed to publish a technical specification to describe the data documentation format for life cycle inventory data (ISO 14048, 2001). The format is structured in three areas, namely,

- process [Process description, Inputs and outputs (environmental exchanges)],
- modelling and validation, and
- administrative information.

Within these areas, ISO 14048 (2001) further specifies the kind of meta information that should be reported along with the input and output flows of any unit process or LCI result. The format consists of a long list of data fields, which accommodate information about the valid geography, the valid time span, a description of the technology, etc. The data format can be used for unit process raw data as well as for LCI results. No distinction is made, however, between mandatory and optional data fields, and the technical operation is not specified. Hence, implementation of the ISO 14048 data format requires further technical specification (e.g., which data fields are required to unequivocally identify a data set). The two examples for database systems mentioned in the following section (ecoinvent and SPINE) try to follow this technical specification. As an illustration, Fig. 5 presents an excerpt from the data format, as implemented in ecoinvent. A recent US

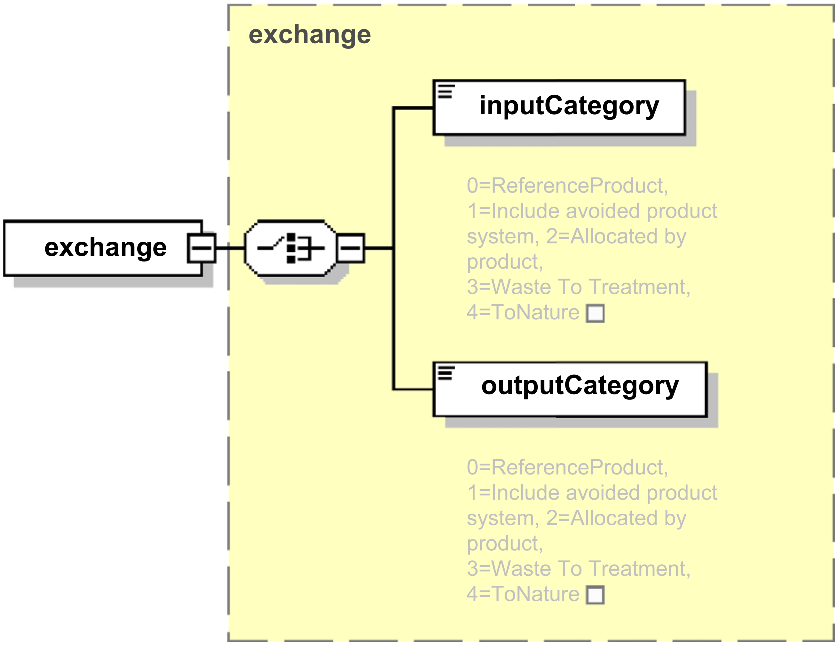

Fig. 5. Excerpt from an ISO 14048 compatible data format (EcoSpold, as part of ecoinvent 2000).

national LCI database project (NREL, 2002) similarly aims at ISO 14048 compliance.

### *4.2.1. Public database initiatives*

Through several publicly funded projects databases have been created that cover more commonly used goods and services. Many of these databases provide LCI data on the level of life cycle inventory results (e.g., the aggregated resource consumptions, wastes, and emissions per kilogram of material produced, also called "building blocks"). Some databases, such as the Swedish SPINE[2] and the Swiss "Ökoinventare von Energiesystemen" (Frischknecht et al., 1996), and its successor ecoinvent 2000[3] (Frischknecht, 2001), also offer data on a disaggregated unit process level (i.e., LCI data per technological process). Most of these databases follow the attributional (descriptive) approach (see Section 3), although if data are available on a unit process level, adjustments towards a consequential (change-oriented) approach are rather straightforward.

In addition to the aforementioned initiatives, several national-level database development activities in Japan, USA, Canada, Germany, Italy, Switzerland, and Sweden, as well as some international coordination projects are under way. For example, one of the goals of the LCI Program of the UNEP/SETAC Life Cycle Initiative is to establish "a peer reviewed and regularly updated database or information system for the life cycle inventory for a wide range of unit processes or subsystems ('building blocks') like electricity, transportation, or commonly used materials" (Udo de Haes et al., 2002).

### *4.2.2. Industry database initiatives*

Many industry sectors are proactively meeting requests for data to be used in LCAs. The Association of Plastics Manufacturers in Europe (APME) can be considered the pioneer in making data publicly available (Matthews and Fink, 1994), but also other industry associations have been actively collecting and providing data since the early 1990s. An indicative list of trade associations providing life cycle inventory data is given in Table 1.

### *4.3. LCA software*

For many (potential) users of LCA, it is appropriate to use a dedicated software. A rough division into three classes of software can be made:

- Generic LCA software, typically intended for use by researchers, consultants and other LCA specialists.
- Specialized LCA-based software of various types for specific decision makers, typically intended for use by designers in engineering or construction, the purchasing department, or environmental and waste managers.
- Tailored LCA software systems to be used for clearly defined applications in specific IT environments (as interfaces to business management software). These are usually firm-specific adaptations of generic software or software packages programmed directly for the needs of the firm.

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[2] www.globalspine.com.

[3] www.ecoinvent.ch.

Table 1
Indicative, nonexhaustive list of LCI data collected and published by industry associations

| Database 'name' (if any) or designation | Geographical scope | Managed by | 'Format' | Further information |
|---|---|---|---|---|
| Ecobalances of the European plastic industry | Europe | APME | text format | http://www.apme.org |
| Environmental profile report for the European aluminium industry | Europe | European Aluminium Association | hardcopy | http://www.aluminium.org |
| FEFCO European database for corrugated board—life cycle studies | Europe | FEFCO | hardcopy or 'Spold' | http://www.fefco.org |
| Life cycle assessment of nickel products | International | Nickel Development Institute | text format | http://www.nidi.org |
| LCA of the steel industry | International | IISI | hardcopy | http://www.worldsteel.org/env_lca.php |

According to a study by Jönbrink et al. (2000), who sent out questionnaires to 22 suppliers of generic LCA software, almost all software supplied from these organisations are delivered with a database by default. Most of the software packages in the survey are commercial, and the total number of licenses sold for all these were reported to be around 3000 worldwide. Specialized software is typically made to suit the needs of decision makers in specific sectors, such as designers in mechanical, electrical or construction industry (Lippiatt and Boyles, 2001) or waste managers (McDougall et al., 2001; Thorneloe and Weitz, 2003).

The data contained in these generic and specialized software packages are to a large extent secondary data, i.e., collected from public or industry sources (Sections 4.2.1 and 4.2.2). Some suppliers also supply data that have been collected directly, but this appears to be less common.

Tailored LCA software systems, on the other hand, usually contain databases with internal data of the firm as well as secondary data to account for background data or commodities. The specific implementation and the degree of overlap with public or other external databases vary highly from firm to firm. An example of such a system for a multinational company, which also comprises a methodological procedure to efficiently conduct LCAs on the basis of company internal and third party data, is given by Rebitzer and Buxmann (2004).

## 5. Different approaches for LCI

LCA, with its ambition to provide insights into the potential environmental effects of the complete and detailed system associated with the provision of goods and services, has evolved into a powerful and fairly robust methodological framework. Such a comprehensive LCA approach can be described as a "detailed LCA" when compared to simplification approaches (De Beaufort-Langeveld et al., 1997). For several applications, however, the time and costs for a detailed LCA study are judged not to correspond to the possible benefit of the results (SETAC Data WG, 1999). There is even concern "whether the LCA community has established a methodology that is, in fact, beyond the reach of most potential users" (Todd and Curran, 1999). These limitations are particularly acute within contexts where a rapid decision is required, such as during a Design for Environment (DfE) process (Brezet and van Hemel 1997, p. 200; De Beaufort-Langeveld et al., 1997, p. 10) or when a rough first overview of a system's impacts is needed in order to decide on further investigations. Therefore, in order to provide efficient and reliable decision support in a relatively brief period of time, for many applications, simplified LCAs and LCA thinking have to be employed. The term "streamlined LCA" is an often-used synonym to simplified LCA.

The LCA framework consists of goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation (see Section 2). De Beaufort-Langeveld et al. (1997, p. 19) argue that streamlining efforts should "focus on the life cycle inventory analysis, which is typically the most time consuming phase, with the greatest potential for savings." There are different strategies for the simplification of the inventory analysis, depending on the goal and scope of the study (the specific application and decision to be supported), the required level of detail (information on single technological processes or aggregated entities), the acceptable level of uncertainty, and the available resources (time, human resources, know-how and budget). In the following sections (Sections 5.1–5.3), three principal approaches of LCI/LCA simplification, with different strengths and weaknesses, are elaborated, namely,

- the direct simplification of process-oriented modelling, as outlined in the previous sections of this paper,
- LCA based on economic input–output analysis, and

Table 2
Analysis of LCA simplification methods (Hunt et al., 1998)

| Cut-off method | Description (applied to packaging, industrial chemicals, household cleaners, etc.) | Success rate (same ranking as detailed LCA) |
|---|---|---|
| Removal of upstream components | all processes prior to primary material production (e.g., polymerisation) are excluded | 58% |
| Removal of partial upstream components | as above, but the one preceding step is included (e.g., monomer production) | 70% |
| Removal of downstream components | all processes after primary material production are excluded (manufacturing, use, end of life) | 67% |
| Removal of up- and downstream components | only primary materials production is included (e.g., only polymerisation) | 35% |

- the so-called hybrid method, which combines elements of process LCA with input–output approaches.

### 5.1. Simplification of process-LCA

The U.S. Environmental Protection Agency (EPA) and the Research Triangle Institute (RTI) cooperated to examine various LCA simplification techniques (Hunt et al., 1998). Due to the aforementioned reasons, the analysis mainly looked at techniques that reduced the effort for the LCI by applying different cut-offs (i.e., deliberately excluding processes of the system from the inventory analysis). It was concluded that universal recommendations for horizontal cut-offs (based on the image of a flow chart where the flows start with resource extraction at the top and end with the final disposal at the bottom) cannot be given. The success rate of the simplification by different horizontal cuts, expressed as delivering the same ranking as detailed LCAs, was found to be rather arbitrary and depending on the single application and reference flows (see Table 2).

Hunt et al. (1998), concluded that a vertical cut, whereby data are collected for all relevant stages and stressors, but in lesser detail, is generally preferable to eliminating processes at any given stage. This implies that a screening, or preassessment, of the LCA is required prior to commencing a simplified inventory. The importance of this preassessment as a first step in simplification of LCA was also a major finding of the SETAC Europe Working Group on the subject of simplifying (De Beaufort-Langeveld et al., 1997). This result is reflected in their suggested overall procedure for simplification, see Fig. 6 (where the term simplification is used for the overall procedure and the term simplifying for the second step within simplification, see below).

*Screening*: For screening purposes the following concepts exist.

- Qualitative approaches: ABC hot spot screening (Fleischer and Schmidt, 1997); matrix methods, representing life cycle stages and stressors (Graedel et al., 1995; Todd, 1996; Hunkeler et al., 1998a,b); checklists and expert panels (De Beaufort-Langeveld et al., 1997).
- Semiquantitative methods: ABC/XYZ assessment, a statistically weighted hot-spot screening according to Fleischer et al. (2001); Environment-Failure Mode Effect Analysis (Environment-FMEA) method according to Schmidt (2001b), which is weighting severity, occurrence, and detection of an environmental issue (Quella and Schmidt, 2003).
- Quantitative approaches: Input–output LCA (see Section 5.2); assessment of single key substances; calculation of the cumulative energy demand (De Beaufort-Langeveld et al., 1997); LCA based on easily available data (Lindfors et al., 1995).

Qualitative matrix approaches and the use of energy demand as a screening indicator are the most widely applied screening approaches. Matrix methods are especially preferable if detailed LCAs of similar product systems exist, from which conclusions can be derived based on the identification of differences to a well-known system. Energy demand can be useful, because energy-related data are readily available for many single processes as well as in aggregated forms, and several environmentally important impacts are strongly linked to energy generation/consumption processes. For instance, when looking at global environmental impacts, on average, fossil energy use is responsible for about 90% of impacts on resource depletion, 70% on acidification, and 65% on global warming (Braunmiller et al., 2000). Further investigation is required to

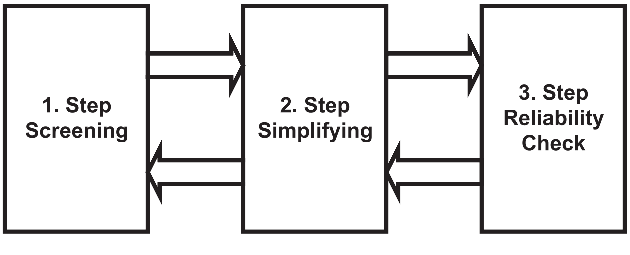

Fig. 6. Simplification procedure for LCA (based on De Beaufort-Langeveld et al., 1997).

ensure this holds true for the other impact categories outlined in part 2 of this paper (Pennington et al. 2004).

Complementing these systematic methodological options, one should also mention the experience of the LCA practitioner as an invaluable asset for providing screening insights (and simplifying, see below) and recommendations. However, even if sufficient know-how and experience for a product group is available, it is difficult to predetermine the important unit processes and environmental issues without the risk of neglecting relevant hot spots or trade-offs.

*Simplifying*: Following screening, it is necessary to simplify the model of the product system (Fig. 6), for which data have to be collected and compiled. This is the most critical, but least developed, step in the simplification of process-LCA.

Rebitzer and Hunkeler (2002) proposed criteria that should be met by simplifying methods:

- Relevance: That is to say, compatibility in regards to the decision to be supported by the LCA (e.g., in time to the materials selection step for product design/development and in the appropriate form so that the results can be easily communicated to product designers).
- Validity: Essentially, the simplified LCA should give the same ranking/insights for a given study as a detailed LCA, though lower resolution is acceptable.
- Compatibility with computational procedures: Only if a method can be implemented in software algorithms/expert systems is it possible to integrate the procedure into existing databases and existing information technology environments (as they exist for environmental management systems or product development, etc.). However, in principle also, manual simplification is possible if it is compatible with the organisational structure of the parties concerned.
- Reproducibility: A method should be designed in such a way that different practitioners arrive at the same ranking results (for the identical goal and scope definition).
- Transparency: In order to be credible and to identify improvement potentials, a method should be transparent, i.e., it should be feasible to understand the calculation of the final results and to find the most relevant environmental issues and processes.

As the area of simplifying is still in its infancy, no general methods are recommended at present. However, there are certainly a variety of specific simplifying methods for specific applications based on experience and detailed LCAs. Research on developing general methods, specifically for new applications, where similar detailed LCAs do not exist, mainly focuses on modelling restricted (i.e., smaller) product systems with cut-offs (Rebitzer and Fleischer, 2000; Raynolds et al., 2000a,b). Rebitzer (1999) also suggested to formalize typical systems behaviour, compared to characteristics of existing studies, to meet the aforementioned requirements (i.e., the transfer of cut-off procedures that apply to one specific product system or class of system to similar systems). In this development hybrid methods, as developed for example by Suh and Huppes (2001) (see below in Section 5.3), also play an important role.

*Reliability check*: After one or more simplifying procedures have been selected and carried out, a reliability check is rather straightforward. From a methodological point, there is no significant difference to conducting uncertainty and sensitivity analyses in a detailed LCA or for other analytical tools.

Finally, it has to be stressed that the procedure, as illustrated in Fig. 6, is not a linear step-by-step method, but the different steps interact, and the results of one step might lead to an adapted repetition of another (hence, the arrows in Fig. 6 point in both directions).

### *5.2. I/O-LCA*

An alternative to LCAs based on process modelling (‘process-LCA’), the focus of the previous sections of this paper, is industry/commodity level input/output (I/O) modelling (see e.g., Hall et al., 1992). With input/output modelling (I/O-LCA), the product system, which consists of supply chains, is modelled using economic flow databases (tables). These databases are collected and supplied by the statistical agencies of national governments. They financially describe the amount that each industrial sector spends on the goods and services[4] produced by other sectors. Emissions and associated impacts are then assigned to different commodity sectors. Process modelling, on the other hand, relies directly on inventory databases (see Section 3) that, for example, quantify requirements for manufacturing, transportation, energy generation processes, etc.

I/O-LCA is a specialized subset of the broader and continually growing field of “Integrated Environmental and Economic Accounting,” a field of methods and applications combining economic input–output data and modelling approaches with environmental and resource data and issues (UN, 2000). Economic input–output analysis, the basis for I/O-LCA, was developed by Wassily Leontief (1936), who published US tables for the years 1919 and 1929. I/O-LCA has been practiced in various forms for three decades, although originally it was simply referred to by terms such as “environmentally extended input/output analysis.” The general method was presented in depth, along with a review of energy-based I/O and environmental extensions through the mid-1980s, by Miller and Blair (1985). Joshi (2000) described the data sources and modelling assumptions involved in creating and applying a US I/O-LCA model.

Both I/O- and process-LCA have their strengths and weaknesses. I/O-LCA provides greater comprehensiveness

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[4] Collectively referred to as “commodities” in this approach, though equivalent to the term “products” as introduced in Section 1.

of the modelled supply chain (broader system boundaries) by usually considering a broader range of sectors, but at the expense of much more coarsely modelling commodities in terms of sectorial outputs and hence, the unit processes in a life cycle. The level of detail and the possible differentiation between similar products (e.g., when comparing two different designs for an electronic appliance) is very limited. Therefore, suitable applications for I/O-LCA are questions where the overall environmental impact of a system (e.g., impacts of new telecommunication technologies) or comparisons between very different options on a regional, national, or international level (e.g., impacts of introducing fuel cell vehicles compared to the current state) are the focus. Specific comparisons within one industrial sector, e.g., material selection in design for environment (DfE), cannot usually be answered by the I/O approach.

I/O-LCA is not mathematically different from process LCA: both are linear, constant coefficient models, which can be readily cast in matrix form (see e.g., Heijungs and Suh 2002). Instead, the principal differences are those of

- data sources (unit process data versus economic national accounts),
- commodity flow units (physical units versus economic value),
- level of process/commodity detail, and
- covered life cycle stages (complete life cycle vs. pre-use/consumption stages).

In regards to the latter point, the "unit processes" in the I/O-LCA model are actually industrial sectors, rather than technological entities as in the process-LCA. The ISO standards for life cycle inventory analysis describe the construction of LCI process chain models by combining data of unit processes (see also Section 3). ISO 14040 (1997) defines a unit process as "the smallest portion of a product system for which data are collected when performing a life cycle assessment." Thus, using the national accounts as a data source, these industrial sectors are indeed the unit processes in an ISO-consistent sense.

There are three main stages of data compilation and modelling/analysis involved in I/O-LCA:

- Creation of a direct requirements matrix from economic data, generally from make and use tables from national accounts (see below);
- Linkage of data for environmental exchanges (e.g., pollutant releases and resource consumption flows) to the direct requirements matrix;
- Calculation of a cradle-to-gate inventory (up to the finished/sold product) using the direct requirements matrix and environmental exchange data.

As introduced by Leontief (1941), the original input–output account was already in the form of a direct requirements matrix, specifying the flows of the output from each type of production process as inputs required by each of the others. However, the modern national accounts do not directly provide a direct requirements matrix. Instead, they employ the "make and use framework" pioneered by Stone (1961) and standardized in the United Nations' series of handbooks on national accounting (e.g., United Nations, 1968, 1993). Rather than specify flows from process to process, the make and use framework separately describes the output and consumption of commodities by industries. The "use" matrix tabulates the annual expenditures by each industry (that is, a group of production operations whose primary output is alike) for inputs of each commodity (that is, a good or service bought or sold in the economy), and the 'make" matrix tabulates annual production output of commodities by industries.

Since the tables are published, LCA researchers need not necessarily compile their own direct requirement accounts from make and use tables, but can use the appropriate available data, where necessary after mathematical conversions, for linking them to the environmental exchanges and the subsequent calculation of the life cycle inventory as explained above. From a practitioner's perspective, a number of I/O tools are now available that perform all necessary calculations through to impact assessment.

Results of I/O-LCA can be used either for screening purposes (see Section 5.1) or to roughly estimate the overall environmental impacts of goods and services on a regional, national, or even international level.

### *5.3. Hybrid LCA*

An LCA based on unit processes is specific and detailed, while generally based on incomplete system boundaries due to the effort for compiling "all" data of the product system. On the other hand, I/O-LCAs are more complete in system boundaries but lack process specificity (see Section 5.2). Attempts to overcome the disadvantages, while combining the advantages of both methods are generally referred to as hybrid approaches (Suh and Huppes, 2001).

In energy analysis, both process modelling (or vertical analysis) and input–output-based energy analysis are used in parallel under slightly different conditions (International Federation of Institutes for Advanced Studies, IFIAS, 1974). Process analysis is employed when assessing an atypical product that cannot be represented by an aggregated industry sector and thus requires process-specific data, while input–output analysis is used for assessing a typical product that is well approximated by an input–output classification. It was Bullard and Pillati (1976) and Bullard et al. (1978) who first combined the advantages of the two approaches by adding input–output-based results that cover far upstream processes (far from the process which delivers the reference flow of the system) to process analysis results that cover near upstream processes. This type of approach is referred to as a tiered hybrid method.

The tiered hybrid method was introduced into LCA in the early 1990s. Moriguchi et al. (1993) analysed life cycle $CO_2$ emission of an automobile by both process-LCA and input–output analysis using this method. Since the input–output-based results show only pre-use stages of a product's life cycle, Moriguchi et al. added the use phase and end-of-life phase emissions based on process modelling techniques. One available tool for supporting LCAs based on this tiered hybrid approach is the Missing Inventory Estimation Tool (MIET)[5]—a spreadsheet database tool that is publicly available (Suh, 2001; Suh and Huppes, 2002).

It is notable that I/O-LCA does not always guarantee a complete upstream system boundary, especially when the national economy, on which an input–output table is based, heavily relies upon imports. This problem led to other types of tiered hybrid approaches with different procedures. Hondo et al. (1996), in a study for Japan for instance, employed process modelling for far upstream processes such as coal mining, which are not covered by the Japanese national input–output table, because the processes do not exist in Japan, and used input–output analysis for the remaining sectors.

Another form of hybrid analysis starts from the input–output side. Joshi (2000) disaggregated part of an input–output table to improve process specificity. This type of hybrid approach is referred to as input–output based hybrid method (Suh and Huppes, 2001; Suh et al., 2004). The input–output based hybrid method, however, is not fully independent from the tiered hybrid method, since, even disaggregated, input–output tables do not cover the complete product life cycle. Use and end-of-life stages still need to be modelled based on the tiered hybrid method. Thus, input–output-based hybrid methods can be considered as a special form of tiered hybrid method, where the resolution of the input–output element is improved.

Tiered hybrid methods generally treat the process-based analysis part with the (graphical) process flow diagram approach and use mathematical representation only for input–output elements. This separation in computational structure has led to difficulties in modelling interactions between the two systems and applying analytical tools in a consistent way. Suh (2004) therefore proposed a hybrid model where both the process-based model and the input–output-based model are merged into one matrix. This approach is referred to as the integrated hybrid method (Suh, 2004).

Hybrid approaches in general provide more complete system definitions while preserving process specificity with relatively small amounts of additional information and inventory data. Different methods in hybrid approaches, however, vary in level of sophistication, additional data, and resource requirements, etc. Therefore, the specific choice of the method has to be made by the LCA practitioner depending on goal and scope of the study, as well as on the available resources, including time, and the necessary or desired level of confidence (see Suh and Huppes, 2001a).

A simple guidance would be that if a process-LCA has been done already and an LCA practitioner is to expand the system with minimal efforts, then a tiered hybrid analysis using, for instance, MIET can quickly deliver the results without much efforts. If an LCA study is being planned with very restricted amount of budget and time, it can be recommended to start with a few processes and link cut-off flows using tiered hybrid analysis. Then the uncertainty can be further reduced by collecting process-specific data for those inputs that are identified as key contributors in the I/O-LCA. By iterating the procedure, an LCA practitioner can efficiently direct efforts to achieve both higher level of completeness and accuracy. If a detailed LCA study is planned, which requires high-level completeness and accuracy, with possible applications of sophisticated analytical tools such as perturbation analysis or Monte Carlo simulation, the choice could be the integrated hybrid approach where the same aforementioned iterative process can be applied.

## 6. Applications of LCA

As mentioned in Section 1, LCA is a method to help quantify and evaluate the potential environmental impacts of goods and services. This implies that LCA can be applied to any kind of product and to any decision where the environmental impacts of the complete or part of the life cycle are of interest. Figure 4 lists a number of example applications. Additionally, LCA can be applied by different stakeholders and actors associated with the life cycle. LCA has been applied by governmental organizations, nongovernmental organizations, and industry in a wide variety of sectors, either autonomously or with the help of research institutes or consultants.

This review paper cannot extensively elaborate all application opportunities. However, due to the important roles of industry and government, the following sections primarily focus on industry-orientated applications of LCA and the corresponding LCA-derived methodologies as well as the role of LCA in/for governmental activities. While noting the growing importance of LCA in policy and public procurement instruments, activities in various industrial sectors, in conjunction with changes in consumer behaviour, are ultimately the most crucial factors for reducing the environmental impacts associated with products (Frankl and Rubik, 2000). As small and medium enterprises (SMEs) and multinational corporations play prominent roles in the economic system, but have distinctively different characteristics, they are discussed separately.

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[5] www.leidenuniv.nl/cml/ssp/software/miet/.

### *6.1. LCA at a multinational corporation*

Besides aspects being valid for all private corporations, there are specific characteristics valid for multinational corporations that make the application of life cycle tools, and LCA in particular, both, easier and more difficult, as described in the following. Multinational corporations are organizations with suppliers, facilities, and customers literally throughout the world. The elaborations in this section apply in particular to those corporations having strong entities (production and product design/development) in at least two continents. Due to the natural size of multinational organizations, there are typically dedicated resources available to apply LCA (time, money, software tools, knowledge, databases, etc.). In most multinational corporations, there are teams, groups, or even departments that are responsible to conduct LCAs and/or to coordinate the correct application throughout the company. Ideally, they have—in addition to external databases (see the discussions in Section 4)—their own data inventories for their processes and products, as well as clear internal tools and standards on how (by whom and when) to apply LCA and related methods. In some cases, they also include in these LCA efforts their suppliers, industrial customers, and other life cycle stakeholders (Schmidt, 2001a).

These promoting aspects are often found, for example, in all major American and European, as well as most of the Asian, automotive and electronics manufacturers. In addition, several (not all) multinational suppliers have established LCA groups, databases, standards, tools, etc. On this basis joint projects (USCAR, EUCAR, JAMA) have been established that cover complex products and include the life cycle stakeholders (EUCAR, 1998; Sullivan et al., 1998; Kobayashi et al., 1998). Several hundreds of studies on various levels (components, subsystems, investments, vehicles, etc.) have been conducted, e.g., within Ford Motor Company, DaimlerChrysler, and Volkswagen. Other multinational organizations, from the automotive and other sectors (e.g., 3M), have demonstrated similar efforts.

The challenge for multinational organizations in applying LCA lies, perhaps more than for smaller (national) organizations, in the methodological area of how to conduct simplification (see Section 5), what to focus on (what is important?), and how to weight certain environmental aspects against each other (optional weighting across impact categories being addressed in part 2, Pennington et al., 2004). These issues reflect the diverse cultural approaches to environmental problems in different continents, nations, or regions (e.g., customer acceptance, legislation/liability, monetary valuation, existing LCA weighting sets, etc.) as outlined in previous papers (e.g., Schmidt and Sullivan, 2002, Beyer and Kaniut, 1997, Hunkeler et al., 1998). For example, no global consensus on weighting across impact categories (such as climate change versus resource consumption) is currently available and perhaps no global generic weighting set can be foreseen (Schmidt and Sullivan, 2002, Hofstetter, 2002). Therefore, multinational organizations sometimes have to establish—based mainly on their own culture and values—their own standards to deal with the aforementioned methodological issues. These standards have to be flexible enough for regional or brand-specific interpretation.

Looking at the example of Ford Motor Company, the various LCA experts in the different countries and brands have been successful in reaching a consensus in the past years (Schmidt and Sullivan, 2002). The consensus is an agreed upon set of minimum and optional criteria for detailed and simplified LCAs. The optional recommendations outline what can be included depending on the goal and scope of the study and regional/brand-specific needs. Based on these guidelines, studies shall be conducted and reviewed by a global LCA expert team. Other multinational organizations have been using different approaches. Examples are organizational structures where LCA methodology development and application are centralized in one group for the global company or where LCAs are carried out independently in various regions and/or sub-organizations/brands.

This points to another important challenge for the application of LCA in multinational corporations: how to organize the application of LCA and how to integrate life cycle thinking and approaches throughout the organization—avoiding that life cycle approaches are reserved to the exclusive circles of LCA/environmental departments. Due to their size, many multinational organizations are still in the phase of conducting isolated LCAs without any, or regular, links across departments of the corporation.

Ideally, the main driver to apply LCAs should be to further improve a company's own products and processes, making a strong interaction with, e.g., design/development and manufacturing necessary. Experiences show that various factors support the integration of life cycle approaches in multinational corporations (Beyer and Kaniut, 1997; Louis and Wendel, 1999), specifically

- senior management commitment,
- link to economics (e.g., environmental business cases based on LCA and life cycle costing; Schmidt, 2003) and support by and/or commitment of non-environmental departments,
- training (e.g., Design-for-Environment training),
- procedures (e.g., product development process that integrates LCA aspects to establish Environmental Product Declarations),
- objectives and strategies (e.g., for development teams to reach certain LCA-related targets),
- simple (software) tools that can be applied also by nonexperts following a short training,
- intensive internal communication and exchange, and
- patience and flexibility.

At least in the case of Ford, these factors have been of help and are resulting in a reasonable level of internal applications where an added value can be anticipated. These applications have mainly supported (Louis and Wendel, 1998, Adams and Schmidt, 1998)

- material choices (typical application as in all industries),
- technology choices (comparison of different propulsion systems, comfort/feature approaches, vehicle comparisons, etc.),
- product and process evaluation, target setting and benchmarking, and
- infrastructure and location choices.

In summary, the application of LCA has significantly contributed to the sustainability efforts of multinational companies, though there are many untapped potentials that still have to be exploited. One can expect an increasing relevance of LCA applications in the future.

### *6.2. The potential of LCA and related concepts in SMEs and start-ups*

While the acceptance of the need for environmental management practices, voluntary certification such as to ISO 14001 (1996), supply chain coordination, and to a lesser extent, life cycle assessment/engineering/costing/thinking, has grown in multinationals, the need for incorporation in smaller firms is often doubted. Specifically, SMEs, and start-ups, are often discouraged from focusing on anything other than time to market, time to cash, and core competencies. However, several small- and medium sized firms and trade associations alike have begun their approaches to systemic environmental management, based on simplified LCA approaches, by examining win–win solutions where both environmental improvements and economic benefits can be reaped. This is true in design/development and in new product introduction (Hunkeler and Vanakari, 2000), as well as in process improvement (Biswas et al., 1998). Such firms have taken various approaches to reduce the scope of life cycle assessment (simplifying, see also Section 5), and, following the development of databases and software (see also Section 3), identify key indicators, validated metrics or grey lists so that further design, or assessment, can be streamlined (Biswas et al., 1998), or benchmarked (Hunkeler, 2003). One could even question to what extent some of these approaches may not only be useful for the environmental performance of SMEs and start-ups, but also for reducing risks of bankruptcy and improving credit terms.

SMEs, and in particular entrepreneurial projects in high technology, can be characterized by the following attributes:

- long periods of negative cash flow,
- growing markets which can be difficult to penetrate,
- lack of familiarity with regulatory restrictions, which slow the installation of production, and
- high expenditures on research and development relative to industrial norms.

Therefore, the consequences for incorrect resource allocation decisions can be catastrophic for the firm in question. Simply, SMEs, particularly those in developing or southern regions, and start-ups cannot afford to make an incorrect decision without risking the future of the firm. Indeed, the risk–reward trade-off is very similar for firms of different sizes, who have restricted, or conditional, capital. If one adds to this the common environmental risk evaluation which large financial institutes impose on small firms and start-ups, then the potential penalty, often an additional 2% in debt carrying charges per annum, can be a significant burden, and cost, given the high ratio of debt to equity in SMEs (Hunkeler, 2003). Furthermore, start-ups typically have capital limitations. Therefore, their cost of having to redesign or reinstall a facility could lead to the destabilization, or collapse, of the firm. The need for careful planning which will not have to be corrected is a driver with particular relevance to SMEs. Therefore, if anything, environmental management, including life cycle assessment applications, and the potential risks associated without it, are more important as the size of the firm decreases.

The tangible benefits to SMEs and start-ups, in regard to advanced environmental business policies, which take the complete life cycle of their products into account, include (Hunkeler et al., 2004)

- reduced operating costs via the supply chain coordination of transports to reduce the fraction of vehicles travelling with light or empty loads;
- new product introduction by considering unused raw materials as a marketable asset rather than a cost-centred waste stream;
- improved relations with authorities, and reduced disposal costs, linked with the installation of near-zero discharge facilities, which are much easier to implement for small scales if planned from the outset;
- favourable image to local and regional politicians which can provide loan guarantees for promising firms without any significant operational or environmental risks;
- improved credit terms with major financial institutions;
- reduced costs to certify to ISO 9001 and 14001, which also brings indirect benefits via improved stakeholder coordination (requirements from industrial customers);
- reduced overhead by having in place an environmental management system, which permits the SME in question to correspond to clients and suppliers programs.

Several of these benefits, which have been documented (Hunkeler et al., 2002), may seem like luxuries for only the most highly funded, venture capital supported, firms. However, experience shows that top management commitment is the most important driver, for multinationals and SMEs alike, in regards to implementing LCA and related concepts. Furthermore, the various cases reveal that firms as small as 10–100 people, in "old-economy" sectors such as manufacturing, often take the lead and identify the most significant benefits.

The accumulation of the items listed also is important for firms in the IPO (initial public offering) stage, as well as when seeking external capital. It seems, indeed, that start-ups have a better chance to grow, and survive, if from the outset, they behave like the organization they want to become. If access to key advisors is a critical success factor for small firms, as it is generally recognized to be, the sustained presence of directors or board members who are aware, and can develop and implement, environmental policies and life cycle applications for start-ups, and SMEs, will likely become essential over the coming decade. Though the space in this brief review is too limited to document specific cases, market share, profitability, and operating margins have all been shown to increase, for firms with sales ranging from $10,000 to $10,000,000 per annum, with the addition of, and buy-in to, life cycle-oriented environmental management programs (Huang and Hunkeler, 1996, Hunkeler et al., 2004, Schmidheiny and Zorraquin, 1996).

### *6.3. LCA, government, and policy*

Governments have a key role in establishing the frameworks and conditions for production and consumption patterns of goods and services in our societies. As a tool addressing the environmental pillar within the concept of sustainable development, LCA is of importance in setting and supporting related strategies to help reduce wastes, emissions, and the consumption of resources that are attributable to the provision and consumption of goods and services. This section of the paper outlines some of the ongoing government activities in regards to LCA.

#### *6.3.1. General development*

Governments have, thus far, primarily been involved in promoting methodological developments and capacity building by sponsoring research programs and workshops, producing illustrative case studies, developing supporting tools, databases, etc. This has typically resulted in nationally managed databases (Section 4), several methodologies and concepts, as well as tools for LCIA (see Pennington et al., 2004).

In Japan, the Ministry of the Environment, Ministry of Agriculture, Forestry and Fisheries (MAFF), Ministry of Land, Infrastructure and Transport (MLIT), Ministry of Economy, Trade and Industry (METI), and Ministry of Education, Culture, Sports, Science and Technology (MEXT) organized a joint committee composed of LCA experts and have conducted LCA activities since the beginning of the 1990s. Among these activities, METI started the national Japanese LCA project in 1998. This national project included provision of life cycle inventory data from 23 industrial partner associations and the development of a national life cycle impact assessment methodology. The results (an inventory database and characterization factors for LCIA) of this project will be available on a web site managed by JEMAI (Japan Environmental Management Association for Industry) (Itsubo and Inaba, 2003).

Several US governmental bodies, such as the Environmental Protection Agency (EPA), the Department of Energy (DoE), and the Department of Defence (DoD), are active in supporting methodological LCA development, promoting data availability, and conducting case studies.[6] Available LCA tools from these federal agencies include the impact assessment method and tool TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) (Bare et al., 2003), the life cycle inventory tool for the assessment of various solid waste management strategies (Thorneloe and Weitz, 2003), and the BEES (Building for Environmental and Economic Sustainability) software for analysing the environmental and economic performance of building products (Lippiatt and Boyles, 2001). To encourage the use of LCA, the webpage LCAccess provides comprehensive information related to LCA,[7] and an important focus is now to establish a national LCI database.[8]

In addition to such supportive activities, and especially in Europe, a movement promoting product-oriented environmental policy has evolved (Heiskanen, 2002). Therefore, the next section provides examples of the various governmental drivers and activities in the European Union (EU), followed by an outline of the complimentary life cycle oriented activities within the United Nations Environment Programme (UNEP).

#### *6.3.2. Policy developments in the European Union*

Environmental labelling, the inclusion of environmental aspects in public purchasing, linking process- and plant-focused environmental management with the life cycle perspective (products and indirect effects in addition to the direct emissions of a plant or facility), and making life cycle data available are some of the instruments of the product-oriented environmental policy being promoted by, for example, the EU's Integrated Product Policy (IPP) (European Commission, 2003a). The adoption of life cycle thinking in a product policy context also implies that stakeholders are made more responsible for a broader range of environmental interventions throughout a product's life cycle, recognising that overall improvements in a product's environmental performance are best accomplished when all stakeholders contribute to a shared responsibility (Schmidt, 2001b).

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[6] www.epa.gov/opptintr/dfe/tools/lca.htm.

[7] www.epa.gov/ORD/NRMRL/lcaccess.

[8] www.nrel.gov/lci/pdfs/final_phase1_report.pdf.

In a broader context, the life cycle approach is a central theme also in the recent EU communications related to waste prevention, recycling, and the sustainable use of resources (European Commission, 2003b,c). Another, more specific, example is the ongoing policy development process relating to energy-using products (EuP), where it is suggested that manufacturers "shall perform an assessment of the environmental aspects of a representative EuP model throughout its lifecycle" (European Commission, 2003c). The proposal explicitly notes that it does not want to introduce an obligation for an ISO 14040 type LCA and leaves flexibility in the choice of tools. A third example is that the circumstances under which elements of LCA might support future chemicals legislation are now under investigation (Christensen and Olsen, 2004).

The "Packaging and Packaging Waste directive, PWD" (OJ, 1994) has been implemented in most EU member states through producer responsibility schemes in the form of legally binding directives for recycling and recovery targets. As such directives are traditional in the sense that they address only the waste issue in the post-user phase and are not based on LCA results, they could therefore be open to criticism for not taking into account the issue of potential problem transfers from one environmental problem to another. Therefore, in this directive, there is a reference to LCA stating that "life-cycle assessments should be completed as soon as possible to justify a clear hierarchy between reusable, recyclable and recoverable packaging" (OJ, 1994). In the process of updating the targets in the Packaging and Packaging Waste directive, the European Commission took into account a Cost–Benefit Analysis (CBA) to evaluate existing schemes. Here, LCA was explicitly used to evaluate the environmental impacts and benefits of various schemes and scenarios (RDC-Environment and PIRA International, 2003).

In a few instances, national authorities in the EU have also applied LCA to justify legislative measures to discriminate between packaging systems. However, in most cases, the differences between systems were found to be too small to support the regulatory conclusions when considering the variability in modelling choices (Schmitz, 2002).

In this context, it is important to note that clear rules have to be respected if LCA, as with any tool, is to be used in national and international policymaking support. All affected stakeholders should be included from the very beginning of the process (BDI, 1999) and requirements of ISO 14040–14043 with respect to comparative assertions disclosed to the public have to be met (Vroonhof et al., 2002). As policy questions are often related to macroeconomic, generalized issues (not referring to a specific, well-defined product variant), difficult methodological challenges occur. These include, e.g., the definition of precise functional units, system boundaries, specific assumptions regarding use and recycling patterns, etc., as well as the limitations of transferring conclusions from specific cases, where considered, to support national or international decisions. Depending on the policy area and the applications, LCA will always be complimented by other tools to a more or less high degree. Rehbinder (2001), for example, points also to different issues if LCA has more direct legal implications. He stresses the problem of potentially divergent conclusions given the lack of international harmonisation of methodologies and data, the need for proper mechanisms of participation, and the need to ensure transparency.

### *6.3.3. United Nations Environment Programme (UNEP) and a global life cycle approach.*

When UNEP's Industry and Environment Programme Activity Centre launched its Cleaner Production Programme in 1990, understanding of the environmental impacts of products throughout their life cycles was identified as an important component (de Larderel, 1993). The launch of the Life Cycle Initiative in 2002 further emphasised the importance of the life cycle approach (Solgaard and de Leeuw, 2002).

The Life Cycle Initiative is a response to the call from governments for a life cycle economy in the Malmö Declaration (2000). It contributes to the 10-year framework of programs to promote sustainable consumption and production patterns, as requested at the 2002 World Summit on Sustainable Development (WSSD) in Johannesburg. The mission of the Life Cycle Initiative is to help "develop and disseminate practical tools for evaluating the opportunities, risks, and trade-offs associated with products and services over their entire life cycle to achieve sustainable development."[9]

The initiative aims to promote the adoption of the life cycle approach on a worldwide scale—also reflecting the global relevance of many product systems (supply and end-of-life chains, etc.). In particular, it is seen as crucial to reach out to, and assist the adoption of, LCA approaches among decision makers in developing countries, in countries with economies in transition, and in small- and medium-sized companies (Töpfer, 2002). These target groups can possibly benefit the most by adopting life cycle insights in the early stages of their product development and organisational activities.

## 7. Conclusions and outlook

By helping to support new business opportunities, in conjunction with the drive towards sustainable development, LCA is becoming an essential part of most organisations' toolbox. Life cycle assessment (LCA) is a powerful set of tools for quantifying, evaluating, comparing, and improving goods and services in terms of their potential environmental impacts. LCA supports the identification of opportunities for pollution prevention and for reducing resource consumption through systematic analyses, thus

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[9] www.uneptie.org/pc/sustain/lcinitiative/home.htm.

avoiding dogmatic objectives which can be, while intuitive, incorrect even in their general tangent.

If combined with life cycle costing (LCC), which can be most efficiently based on LCA, though is not elaborated in this paper, two of the three pillars of sustainable development, environment and economics, are represented. For more insights into LCC and the connection to LCA see Rebitzer and Hunkeler (2003). LCA and related approaches are essential elements in the efforts to make sustainable development a reality.

Research on and application of LCA, though still very young domains, have progressed significantly in their aim to achieve a common understanding of the goals, structure, challenges, and procedural issues. This is most prominently demonstrated by the establishment of the ISO 14040 series, as well as associated continuous expansion and improvement activities. In this framework, the goal and scope definition and the inventory analysis outlined in this paper provide the basis of any LCA study. The paper elaborated on the current state-of-development of these two basic elements and introduced areas of practical applications of LCA. The second part of this paper (Pennington et al., 2004) expands on the assessment of the resultant resource consumption and waste/emissions inventories in the context of contributions to impacts.

In summary, modelling life cycle inventories is a robust, and possibly unique, approach to evaluating, together with the life cycle impact assessment phase (see the second part of this paper by Pennington et al., 2004), the environmental impacts of products in a holistic way—as required by sustainable development. However, there remain many open questions to be solved, and dissemination strategies to be elaborated. These include education, awareness raising, and mutual learning as well as suitable and easily accessible tools and appropriate international databases, which are needed for a global proliferation of this relatively new methodology.

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