LCANET Theme report
Databases and Softwares

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Paris, March 1997

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Introduction

The following report has been written by a group of European LCA experts, combining several fields of activities and competences:

- software design and development,
- application of LCA in industry, as internal experts or as consultants,
- data providing,
- research in Universities and research centres.

As such, it reflects both the needs of the users and of the practitioners. The overall aim of all the research topics described in this report is three fold:

1. to reduce the cost of LCA by increasing the data availability (1, 2)
2. to increase the credibility of LCA by increasing quality of data (5.1, 5.3) and calculation tools (5.2)
3. to expand the usage of LCA by allowing interaction with other fields (3), the development of modelling capabilities (4) and the development of expert systems (6).

All on-going debates in the Life Cycle Assessment field are mirrored in the discussion about softwares and databases and this report have therefore been influenced by these debates. For instance, the LCA is actually developing toward "life-cycle management", both by more frequent application to business and policy decisions and by the connection to other "life cycle" and / or environmental tools. This implies the development of interface with new and heterogeneous
data as well as their integration into LCA databases. Such operations imply also the taking into account of qualitative data, which is quite new in the LCA field. Several research topics presented below are linked to these new trends.

Prior to any research or development being undertaken some fundamental prerequisites are needed, among them is the development of common understanding between practitioners on the structure and semantics of any database and software. These prerequisites have not been developed in this report, for two main reasons:

- they have been established, even if not sufficiently and accurately, in the frame of SETAC and ISO;
- they do not constitute a field of research as such.

However, when they have not been enough clearly established, the need for further consensus developments arises and hampers the development of research. Hence, such points of discussion are sometimes identified in the report.

Some topics, for example, data uncertainties, have not been presented as research topics, since some LCA experts have already implemented them [Note 1: For instance, read J. Besnainou and R. Coulon, "Uncertainty, complexity and decision in Life Cycle Assessment", Proceedings of the Second International Conference on Ecobalance, Tsukuba, Japan; Dale J. Kennedy, Douglas C. Montgomery and Beth H. Quay, "Data Quality, Stochastic Environmental Life Cycle Assessment Modelling", Int. J. Life Cycle Assessment 1 (4), 199-207, 1996.]. But some other research topics have been reported, although very close to actual practices, e.g. in the chapter 2, "Generation of LCI-data sets". In this case, rather than "pure research", there is clearly a need to formalise the practice and to enhance the reproducibility of the studies. If no common "applied" research program is launched in this area, there is a risk of confusion
and considerable losses of time, money and credibility. Some other research topics reported in this report belong to the future, e.g. the development of expert systems.

The research topics identified are quite numerous (13). But all of them are necessary for a steadily development of LCA, as a decision tool in industry and policy. However, priorities must be determined, for helping co-operation and efficiency in research effort. The criteria for defining such priorities can be listed as follows:

- capability to help sound decisions in environmental fields which is covered by reproducibility, quality of data and softwares, modelling capabilities,
- need proven by LCA users (industry, authorities, citizens), which request, at the same time, a reduction of costs, widening applications and increase the credibility.

Based on these criteria, the following priorities are proposed:

- research on the integration of data provided by other environmental techniques and, more largely, the integration of existing data (3.1, 3.2),
- research on the quality monitoring in the maintenance of existing databases and the development of new databases (5.1),
- research on the validation of softwares (5.2).

However, the expert members of the working group believe that all the identified research topics must be funded, since they are vital for the development of LCA, and they are volunteering for co-operation in these areas.

1. What are the barriers for data exchange and how can these be eliminated

LCA's are often hampered by the lack of public available data. This
problem is due to on the one hand reluctance by data owners (industry) to share data and on the other hand reluctance by industry to generate data.

1.1 State-of-the-art

Industry's attitude towards LCA and publication of LCA data differs highly. While a significant number of suppliers, mostly of commodity materials, put much effort in the generation and publication of generic data for their products, manufactures of products further down the supply chain are less willing to share their generated LCA data. Some industry's have set up public industry wide databases of generic data, e.g. the plastic industry, the corrugated board industry, while other industry wide databases of generic data have not been published, e.g. the aluminium industry. Some possible reasons for this difference in attitude are summarised in table 1.

Table 1: Possible reasons for companies/industry motive/reluctance to carry out/generate and publish LCA (data).

<table>
<thead>
<tr>
<th>Pro-active companies/industries</th>
<th>Re-active companies/industries</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Why carry out/generate LCA (data)?</strong></td>
<td><strong>Why LCA (data) is not carried out/generated?</strong></td>
</tr>
<tr>
<td>Improvement of company image, advertising of own products</td>
<td>No confidence in LCA - outcome is arbitrary</td>
</tr>
<tr>
<td>Better understanding of own processes, ecological optimisation, identification of weak points, increasing eco-efficiency, portfolio optimisation</td>
<td>LCA is too costly (time and effort) and lack of expertise</td>
</tr>
<tr>
<td>Customers request LCA data</td>
<td>LCA is not (yet) an issue in certain industries</td>
</tr>
<tr>
<td>Authorities request LCA data</td>
<td>Lack of commitment in authorities</td>
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1.2 Research needs

The two main questions to be addressed under this research need are:

1. What are the barriers for data exchange?
2. How can the barriers be overcome?

In order to answer the first question, the incentives as well as the reasons for reluctance for carrying out and publishing LCA (data) need to be investigated. Table 1 provides some possible answers, however, the driving force (the most significant perceived benefit/danger) needs to be identified in order to answer the second question.

The research should address the following points:

- Identification of motives for not disclosing data;
- Identification of relationship between and ranking of the motives;
- Identification of possible solutions, including their classification (e.g. as technical or communication related).

<table>
<thead>
<tr>
<th>Ecolabelling requirements</th>
<th>Why is LCA (data) published?</th>
<th>Why is LCA (data) not published?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Improvement of company image, advertising of own products</td>
<td>Lack of benefit of the publication of LCA data and fear of exposure towards environmentalists and to wake &quot;sleeping dogs&quot; in the general public</td>
</tr>
<tr>
<td></td>
<td>To counteract the misuse of incorrect data</td>
<td>Fear to lose technical or economical trade secrets to competitors</td>
</tr>
<tr>
<td></td>
<td>Avoidance of imminent regulation and proactive participation in the regulation process to avoid oversimplification</td>
<td>Fear of increased regulation (by authorities)</td>
</tr>
</tbody>
</table>
From the above analysis, it will be possible to propose strategies to overcome the obstacles to disclosing Life cycle data. Some possible strategies are given below:

- Technical answers when appropriate (e.g. how to overcome data confidentiality issues, for instance by averaging);
- Communication of success stories, including experienced benefits and how dangers were avoided;
- The role of industry associations for promoting exchange of LCA data and avoiding competition issues;
- The role of authorities for promoting exchange of LCA data;
- The role of environmentalists for promoting exchange of LCA data.

First of all companies and industry organisations that have published LCA data or performed LCAs but refrained from publication should be interviewed. Personal interviews are preferable over standardised questionnaires, since some of the questions strongly depend on the individual situation, and the interviewer needs a deep insight into the mechanism of LCA. An additional inquiry should get the missing information from regulators and environmentalists. In a second round, the findings should be discussed with all stakeholders (industry, LCA practitioners, regulators and environmentalists) to develop a strategy for the promotion of disclosing LCA data.

It should be noticed, that presently an EU sponsored project titled "The use of Life-Cycle Assessment in business decision making processes and its implications for environmental policy" is being carried out. This project is not aimed on exchange of LCA data, however, it has many points in common with the above outlined research proposal. It has therefore been suggested to the project co-ordinator, Frieder Rubrik, when ever possible to address the above mentioned research questions and report results from his research which could help to a better understanding of how the barriers for data exchange can be eliminated.
1.3 Expected benefits

The lack of public available LCA data is often hampering LCAs, resulting in LCA with data gaps or the use of data with a high uncertainty. An increased availability of public LCA data would furthermore lead to lower LCA costs and increase its credibility.

2. Generation of LCI-datasets

The existing databases show some similar approaches in the organisation of the generation of LCI-data. The following steps can be distinguished in the process:

1. internal or external driving force to set up a database (see above the chapter 1 on barriers for data exchange),
2. development of a questionnaire,
3. data collection from individual sites by an independent person or organisation to guarantee confidentiality,
4. checking of data,
5. data processing,
6. reporting.

The steps that need improvement and/or better understanding are discussed in this chapter.

2.1. Data collection

2.1.1. State of the art

During the process the data collection the generator has to decide on the following questions:

- how to organise the data collection,
- which data are necessary to guarantee the required quality of the database,
which boundaries (cradle to gate, cradle to grave, gate to gate etc.),
which level of detail,
which allocation rules,
which sites/companies to include in the data collection,
how to obtain maximum response,
how to obtain the correct information,
how to check if response to the questionnaire is correct/consistent,
which data processing is necessary: data that are needed are spread over different departments of the company / production sites and often need recalculation, regrouping,
how to deal with data gaps: not all data are available (no measurements),
how to deal with lack of sufficient response to the questionnaire,
primary data only or in combination with data from other sources,
how to obtain transparency vs. confidentiality,
what and in which way should the data be reported.

At present there are neither guidelines nor publications available for data collection. The SETAC code of practice implicitly gives advice as the requirements of the final results are specified. No amendments to this can be expected following the work in the Working Groups on Inventory Analysis and Case Studies. Data generators have dealt with these questions in many ways leading to databases with a large variety of system boundaries, level of detail etc. This often leads to problems of compatibility when datasets from different data generators are used together. It also complicates the possibility of comparing datasets of the same product from different generators.

In the end the usefulness of the data is largely determined by the data collection. When data are not collected in a suitable way, the possibilities of application of the resulting database are limited. For
example:

- Database is already out-dated when it is published: due to problems with the correct response to the questionnaire the database is published years later than the data collection was done.
- Important data can not be included in the database, because they were not included in the data collection.

Data collection is a time consuming and costly affair and it is important that the quality is guaranteed by helping the generator make the right choices.

2.1.2 Research needs

In order to improve the speed, quality and ease of collecting data as well as the credibility of databases, it is necessary to define a guideline for the data collection as well as tools to be used directly in the process.

Concerning the questions stated above many answers and compromises can and have been found. To establish a framework for data collection, the following questions need to be answered:

- can a "best practice" be found from existing data collections,
- how can efforts in time and costs be minimised,
- how can the quality of the basic data be optimised (linked to import/export),
- can a general checking procedure be found (linked to expert systems),
- what future needs will there be for data collection,
- how to promote application of a "best practice".

Information should be collected from data collectors (Associations, Institutes), data collected (individual sites, companies) and LCA practitioners through personal interviews. Since there are technical,
LCA, management and communication aspects to data collection the investigation should be done by a team that has knowledge in these areas.

2.1.3. Expected benefits

Data collection is the fundament of the database. It is also the most time and cost consuming part of the process of LCI data generation. To facilitate the setting up of databases high priority should be given to establish guidelines to minimise time and effort and to guarantee that the whole effort delivers the required quality.

2.2 Identification of appropriate data averages - purposes/sectors

2.2.1 State-of-the-art

LCA`s are being carried out with different purposes:

- for instance, for one company, in order to get information and to change the production on the basis of the result;
- or, for many companies in one sector, in order to get information for designers for the choice of a specific product or material.

For these different purposes different types of data are needed, i.e. foreground and background data. For the purposes where average or representative data are needed the averaging method is decided by each LCA performer and is therefore calculated in different ways. However, often data from different sources (different production sites & same processes, different production sites & different processes, different companies, different countries) are averaged by taking into account all the data related to the amount of the production of the company. Most of the time these average data are given without stating the variance, i.e. standard deviation, maximum/minimum values, variation of the characteristics and the quality etc.

2.2.2. Research needs 2.2.2.1 Development of a standardised methodology of producing average data.

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This topic can be divided into two different levels:

a. *calculating average data*

There is a need for a methodology of calculating average data out of data coming from different sources: from different sites, different technologies, different companies... The final average data has to take into account the amount of the production of each site, the "age" (old/modern) and representativeness of the technology, the quality of each data collected. The methodology will describe how to handle these factors within the calculation.

b. *producing pieces of information about the variability of the original data*

Each average data is the result of choices and approximations made out of original data. Therefore it is important to provide, together with the resulting average data, pieces of information concerning the type of calculations carried out, and concerning the variability of the original data. This is essential to ensure the quality of the average data, and to ensure that this type of data can be used in an appropriate way.

So the methodology shall also recognise a standardised way of describing:

- The variability of the hypothesis linked with the original data collected for the calculation of the average. This is to handle the fact that the original data that one wants to aggregate may refer to different configurations: for example one site uses natural gas as a fuel, another brown coal, another oil, and another all sorts of combinations of fuels.
- The variability of the values of the original data collected for the calculation of the average. This variability assessment can be composed of the standard deviation, and/or the minimum/maximum values, and/or adequate indicators developed within the research programme.
• The variability of the characteristics and quality of the original data collected for the calculation of the average. The characteristics of a data set consist in for example the type of technology concerned and its representativeness, the geography and the time of the data, the limits of the system, the energy or transport or waste models used, the quality of the measurements (data coming from the bibliography or from an industrial site, regular measures or punctual measures)...

Adequate and standardised indicators should be developed to describe the variability of the range of original data collected within each of these characteristics.

Of course this topic is strongly linked with the chapter 6.3, "Use of data quality indicators", although it brings up a specificity: the quality of an average data depends not only on the quality of the original data, but also on the variability of this quality. There is a need for adequate and standardised quality indicators specific for the handling of average data. It would mean that the research topic "Use of Data quality indicators" should take into account the previous requirements.

2.2.2.2. Databases and softwares compatibility with average data

Databases and softwares should be able to handle both original data and average data. This means that they also should be able to handle, together with average data values, the variability indicators mentioned in the previous chapter. There is therefore a need for guidelines (aimed at databases and softwares) describing:

• for databases: the way of including an average data (together with its variability factors) into a database,
• for softwares: the way of handling average data variability indicators within LCA inventory calculations involving average data, or involving both original and average data.
2.2.2.3 Guidelines about the use of average data

There is a need of harmonising the use of average data among the LCA community. Therefore there is a need for guidelines describing the requirements related to the use of average data, adapted to the purpose of the project:

- for an internal, for instance, by describing the conditions required if used as foreground data,
- for an external use (for example to be included in a database, or to be published, or to be shared with industrial or institutional partners).

2.2.3 Expected benefits

The described research needs are important in order to improve the representativeness and reliability of LCA data and to make comparison of data sets meaningful. Furthermore, the research needs are important in order to make it clear when to use background and when to use foreground data. If for instance there are large variations and average data makes the basis for choice of a specific product or material, this choice might be wrong if the product or material is delivered from the company with the maximum environmental impacts.

2.3 Required level of detail

2.3.1 State of the art

The publicly available databases are not published with the same level of detail:

- concerning the representation of unit processes, they can be highly vertically averaged or the system can be broken down to the process
- concerning the cut-off rules, some publications take into account

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very small amounts of material flows when others do not
describe the inflows and outflows at the same level of detail.

2.3.2 Research need

The problems posed by this situation are the following:

- discrepancy in level of detail between different data sources used
  in the same study,
- as a result of the further point, a certain inequality in the
  treatment of materials and processes as well as some losses of
  credibility, since the length of input / output lists are very
  different from one database to one another,
- and a reduced data usability, due to a low level of detail in the
  system description, hampers the identification of sources with
  potential environmental impact

These problems become increasingly obvious because LCA is more
and more used in public debates. They arise also because the users of
databases (industrialists, authorities) are increasingly demanding; for
instance the development of modelling capabilities requires more
broken down systems. This problem is not easy to solve, because the
vertical averaging, for instance, is one of the available techniques
which allows the protection of data confidentiality.

The research proposed should therefore cover, at least, the two
following areas:

1. to survey the needs of the users of the databases, in order to put
   their needs as a central criteria for the data providers,
2. to compare systematically the different possible techniques
   which can help to combine the protection of industrial secrecy
   and the accuracy of modelling.

The outcome of the research would be guidelines defining a
minimum acceptable level of detail in data publication and system
modelling. Such a research should imply all parties (authorities, citizens, industries and experts) in order to find out an acceptable compromise.

2.3.3 Expected benefits

A better harmonisation in the level of detail should play in favour of more detailed and transparent databases. These databases would therefore more frequently be used and in more studies. It is also expected that the credibility of LCA will be improved.

3. The import of data into Life Cycle Assessment databases

LCA is a data intensive activity as it not only attempts to cover the complete life cycle of product systems but also tries to integrate data from different sources or types in a comparable way. Life Cycle Assessment experts are required to access, and harmonise, data from a wide variety of sources, including companies, industry groups and Government agencies, to ensure the reliability of data used and to reduce the amount of resources expended in undertaking LCA studies.

3.1 Relationship with other management tools, both as data providers to LC databases and as recipients of LC data

3.1.1 State of the art

There are many instances where companies have to measure, check and store data relating to their process operations. These can be for internal purposes such as process control, energy management and internal site accounting procedures or for external purposes which could include regulatory compliance and reporting to IPC.
requirements, environmental auditing or risk assessment. The purposes of the data collection as well as the methodology and rules applied during collection can differ considerably from LCI. There are, however, also likely to be many overlaps and duplications.

A need therefore exists to maximise the interchange of useful data between the various management systems requiring them and to reduce, as far as possible, any overlapping, useless efforts and separate / redundant storage systems and maintenance or updating procedures.

3.1.2 Research needs

Research teams comprising 'practical' experts from LCA, other environmental tools, industry, regulatory authorities and database design should be formed to systematically assess:

- the types of data gathered (and why),
- the rules followed for their collection, checking and maintenance,
- the nomenclature used,
- the differences in semantics and structures of the relevant databases.

Draft guidelines could be tested via application to a number of case studies. The consequences on costs and data quality and reliability should be evaluated and quantified. The outcome of the research could be guidelines applicable to a wide range of data gathering requirements and needs.

3.1.3 Expected benefits

- Improved availability of data, not only for use in LCA studies but also provided by LCA studies for other purposes, for example in standardisation (BS 7750, ISO 14000)
- Reduced cost of data collection.
- Closer integration of industry management tools.
• Improved dialogue between experts representing different environmental reporting fields in industry.

3.2. Guidelines for the integration of data into databases

3.2.1 State of the art

All LCA studies require environmental data on a range of product systems and services which are outside of the direct control of the organisation for whom the study is being performed. There is a general need, therefore, for publicly available data (and databases) on all types of processes and product systems.

A number of large LCA projects have been undertaken with the intention of publishing LCI data for specific industry sectors, including APME, FEFCO and ECOSOL. These projects are generally very expensive and time consuming and cannot therefore be performed often or widely over all industrial and economical sectors. There are still, therefore, many significant data gaps for which data may exist in other database systems.

3.2.2 Research needs

Producing data exclusively for LCA use is expensive. Finding ways to use data in LCA, which originally has been produced for other purposes may effectively decrease the costs for LCA-data and make LCA studies more complete.

Different databases not originally intended for LCA use may be useful, and may sometimes be incorporated into, or interpreted as LCA-data. In some cases a combination of data from different databases could result in data sets covering the LCA needs.

Research in this area should aim at finding criteria for categorising LCA-related databases depending on their contents, their semantics and their data structure, in relation to LCA data demands, semantics
and structures. The databases should be categorised according to how relevant the data structure and data are to LCA and to how easily specific databases can be combined to meet LCA requirements.

The work could be performed as a survey of potentially relevant and useful databases including:

- Governmental environmental statistics
- Transport statistics and economical statistics databases
- Corporate databases - logistics, raw materials, process throughputs etc.

Questions to answer during such a survey could be:

- Could data in this database be used to derive amounts of emission, resource use, products and waste from specific processes?
- Could this database be combined with one or more other databases to answer these questions?
- What is the cost for performing such derivations, in relation to the cost for exclusive retrieval of LCA data?
- What is the practical quality of the data (practical value in a decision situation), in relation to the practical quality of exclusively retrieved LCA data.

For instance, a governmental statistics database on air emissions is based on the questions of the forms sent from the government. If the questions asked give emission amounts as answers, the database may contain useful LCA data. Still though, the semantics of these emission data may not be the same as in LCA: LCA requires that the emissions reported are related to production, while the emissions reported may be given as a yearly total. In addition the data may not be structured in such a way that it can easily be retrieved for immediate LCA use.

The outcome of the research will be guidelines for how to evaluate a
database in accordance with LCA data demands. The result of the evaluation should lead to a practically applicable decision on how to relate to a specific database instance. Three possible approaches would be:

1. The content, the semantics, and the structure are sufficiently compatible with LCA data requirements that the database can be used directly as an LCA database. It may be possible that there still will be a need for some data treatment before the data can be used. Guidelines or methods for estimating the costs associated with this treatment should be identified during the research.

2. The database structure is unsuitable for LCA needs, but the actual data content of the database can be used in LCA. The research should find methods for identifying efforts needed for accessing this original data, as well as methods for estimating the efforts and costs associated with formatting this data into LCA data.

3. Neither the database structure nor the data content are suitable for LCA. But there may be reasons to expect that the data sources from their previous relation to an other database owner have collected LCA data while gathering information for the forms for the other database. The sources should then be identified, and the LCA-information could be collected directly from the sources. A method for estimating efforts, secrecy problems and cost should be found during the research, as well as methods for estimating the cost to transform the retrieved data into LCA databases.

In general it should be expected that these three levels of database categorisation and application from an LCA perspective will be used in combination, especially when there will be a need to retrieve data from more than one database.

3.2.3 Expected benefits

Gathering LCA data is expensive and time consuming with specific
information often difficult to retrieve, largely because of difficulties with identifying the sources, the use and re-development of ad hoc methods for formatting the data, lack of understanding of what extra information is needed in addition to what is already being retrieved, as well as concerns over confidentiality of data.

An assessment of the actual data-situation in relation to LCA data and databases could be extremely useful at all levels of LCA application. The advantages can be listed as follows:

- Potential availability of additional data for lower costs to increase the application and use of LCA.
- Analysing the data structures and semantics of different environmental information channels and databases could help to improve especially LCA data communication but also environmental communication in general (What is being communicated? How? Could it be more efficient? More effective?).
- If done carefully, this research could decrease the number of different environmental information channels and improve clarity in environmental matters.
- The costs associated with gathering LCA data exclusively for LCA use could be considerably decreased, if the data is also gathered for some other purposes at the same time.
- By focusing on methods for cost estimation, the economical control of the LCA data retrieval will be improved.

### 3.3 Qualitative data in Life Cycle Assessment: their integration in and compatibility with quantitative databases

#### 3.3.1 State of the art

Qualitative data have hitherto not been included in the data format used in most LCA's. The main reason for this is that qualitative data cannot generally be handled along with quantitative data when trying
to establish a limited number of environmental impact indicators, suitable for comparisons between products and product systems.

The increasing need for simplified but yet reliable LCA's as well as for implementing the life cycle approach in environmental management may however be met by including qualitative information, either as a surrogate for quantitative information or as a set of complimentary/additional data.

3.3.2 Research needs

The research need for this topic is closely correlated to the needs identified for both Applications of LCA (for instance, a designer needs information on the technical properties of material or of a part, information which are usually not reported neither used in Life Cycle Assessment and Impact Assessment (since not all impacts on the environment are quantifiable). The overall aim is to develop a general methodology for implementation of qualitative data in LCA. This development can best be achieved by performing an investigation in relevant fields.

At present, the use of qualitative data can be envisioned for a number of environmental issues which are not currently included in LCA because of lacks in the LCA methodology or because of data gaps, e.g.:

- Recyclability of mixed plastics waste, either in the form of products containing a number of plastics materials, or in the form of unsorted waste from production facilities and households. No methodology exists at the moment, but many data are believed to be available. The issue may especially be of great importance in product development.
- Hazard identification of chemicals and substances for which only limited information on toxicology and ecotoxicology is present. This aspect may be of importance when dealing with regulatory
issues and for the development of screening indicators for identifying 'hot spots' in the life cycle.

- Landscape degradation, where both methodology and data availability is still in its infancy.

The methodology for implementation of qualitative data in LCA is suggested to be a step-wise procedure:

- identification of areas where the need of information is not met by state of the art LCA-methodology,
- identification of areas where qualitative information can enhance the credibility of the quantitative information,
- analysis of whether relevant qualitative data are available, either from other research areas or from other environmental tools,
- specification of a suitable data format to be used in LCA databases and other environmental management tools,
- transformation of available data into the specified format,
- development of guidelines for the integration and use of qualitative information in LCA-methodology.

3.3.3 Expected benefits

The integration of qualitative data is believed to significantly enhance the reliability and usefulness of LCA, especially for internal decision-making but also generally. As much of the qualitative information is of a general nature (i.e. it does not apply to specific products only), the research results can be made available to all interested parties without disclosing confidential information. The integration of qualitative data in quantitative databases may significantly increase the usefulness of these in some, but not all, applications. An example of this is EcoDesign and other LCA-related product development programmes. The wish for simple answers to complex questions will not be fulfilled in doing so, but the decision support will be significantly improved, also for external communication of LCA results.
The priority for this research topic is high in the context of implementing the life cycle approach by performing screening and streamlining LCA\textsuperscript{s}, whereas the relevance in the context of quantitative LCA\textsuperscript{s} for comparative assertions is of less importance.

4. The integration of process and system modelling into the Life Cycle Assessment softwares

4.1 Process modelling

4.1.1 State of the art

The purpose of process modelling is to formalise relationships between input and output on unit process level based on additional information about how parameters influence the process and (obviously) information about the relationships so that the process might act dynamic (that is: the relation between input and output depends on one or more independent parameters).

Process modelling State of the art of process modelling in LCA Three types of process modelling can be identified in current LCA studies:

- black box models of processes. This is the mostly used type in LCA because this is the easiest way of process modelling (fewest data and information needed). All inputs and outputs are changed in the same way if a parameter is changed (double input A leads to double output of all emission streams, i. e. there is a very easy linear way of modelling) (Reference: all public databases)
- models of processes with linear functional relations. In this concept linear relations (functions) between each input and output as well as between the different inputs are defined (double input A leads to different linear reactions of each output and the linked other input streams). This concept is due to the necessary effort not very common in performed LCA but exists e. g. for

• models of processes with non-linear and linear functional relations. In this concept linear or non-linear relations (functions) between each input and output as well as between the different inputs are defined (double input A leads to different non-linear reactions of each output and the linked other input streams). This concept is the rarest in performed LCA but exists e.g. for some special LCAs using sensitivity analysis [Note 2: E.g. Schmidt, W.-P., Fleischer, G.: High recycling rates = high reduction of environmental burdens? In: R'97 Congress Proceedings, 4-7, February 1997 in Geneva.].

In several software tools all kind of process modelling can be done.

4.1.2 Research needs

Process modelling could be integrated in order to allow more flexibility in the LCA simulations and scenarios, and to go more closer to physical industrial processes. The problem to solve is the (enormous) effort in linear and especially non-linear process linear. Data collection and data bases are much more complicate than in the case of black box models. In consequence the research need is:

• to identify in what kind of LCA study which kind of process modelling is necessary (time efficiency in performing an LCA).
• to identify what data is necessary for what kind of process modelling in general (i. e. consequences in data bases) and what kind of support can be given (i. e. in an expert system, in data bases etc.).

The method of investigation could be the following:

• performing different LCAs (in different branches, using
sensitivity analysis etc.) by using different kind of process modelling. By comparing the results and their deviation. Developing a mathematical model of possible cases of LCAs for general recommendations what kind of process modelling is connected with a sufficient level of confidence / reliability

- deducing different types of possible process models (out of a survey of existing LCAs, rules in engineering science etc.) and identify for each type the necessary kind of data. By generalising specific examples of (non)-linear and black box process models general recommendations can be deduced.

This research could allow to take into account how changing circumstances might influence the way the process acts; for instance:

- the modelling of non linearity.
- how changing recycling circumstances change the in-output efficiency.

Process modelling might help in generating new information. For instance with the automatic calculation of CO2 emission due to the carbon content of the input. It should be studied when it is necessary to include process modelling, (either linear or non linear), and when it is not. This means:

- when does it influence the results substantially/ significantly,
- what types of process modelling exist,
- specification of goal and technique dependent process modelling,
- how to define the BAT in process modelling, as integrated in Life Cycle Assessment methodology.

4.1.3 Expected benefits

Linear and non-linear process modelling enhances data collection and treatment (data availability: filling data gaps, performing sensitivity analysis for uncertain data or for regarding future developments etc.) due to e. g. stochiometry, enthalpy, understanding the process etc.
Data quality and reliability increase by a good process model data base (data check because of linear or non-linear process modelling). Due to the aim of the research project time efficiency will increase (modelling only when necessary), i.e. big reductions of costs for performing an LCA are possible. As far as it is unknown what kind of process modelling is necessary for what kind of LCA study it is not clear whether LCA can give a valuable decision support, i.e. this project proposal aims at making LCA ready for a good decision support.

4.2 System modelling

4.2.2 State of the art

System modelling could be defined as making relationships between processes (including feedback loops and marginal scenarios), based on additional information about how parameters influence the whole system and (obviously) information about the relationships so that the system might act dynamic; that is: the relation between processes depends on one or more independent parameters.

The following examples can illustrate the necessity of better system modelling:

- for feedback loops: electricity is needed for the generation of electricity,
- for marginal scenarios: What happen to the average if we need an additional plant for the production?

Often feedback loops can be treated, but mostly the information concerning parameters that influence the whole system are not included. The problem of marginal scenarios is rarely treated yet and there is lack of experience exchange in that field.

4.2.2 Research needs
It is unknown if the simplifications in system modelling seriously influence the results. A secondary problem is that the simple way of LCA restricts the application area and the usefulness of the instrument. One could think of better insight in the causes of environmental load, more opportunities for generating improvement options. In other words: a more sophisticated use of LCA will give better possibilities for analysis.

The following items should be included in the research program:

- how to define the links between processes properly so that the system can be solved correctly,
- how to react if the links are not properly defined,
- which correct solution methods exist and how do they influence the results of representative case studies.

A more accurate system modelling implies the gathering and treatment of many additional information on the physical characteristics of the links within the system studied. The first research need is the answer on the question how large the influences on the final results can be, if more sophisticated relations are used. Therefore it is necessary to find out which kinds of information could be used when building the system. The second research need is to find out if and where the necessary information is available. One could for instance think of existing environmental management or quality management systems and structures. Thirdly, the structure of storing the information into a database should be investigated. Information has to be linked to the currently used information in LCA. Finally, methods are necessary that can solve systems with highly sophisticated information and that can treat unbalanced systems by estimating optimised results.

The method of investigation should cover the following points:

- find out what information could be added to the currently used in
LCA,
- find out if it gives benefits to the method,
- find out if it provides a better basis of sharing data between different environmental tools,
- find out in what way it changes the LCA procedure (it may improve the results, it also may facilitate the data gathering process),
- find out if it improves the reliability of the Life Cycle Assessment studies.

4.2.3 Expected benefits

For the applicability of LCA for (long-term) scenarios applied to new technologies, relations between environmental policies and economics, choices of investments etc. a correct system modelling is necessary. The improvement of system modelling in Life Cycle Assessment current practice should have several positive effects:

- It may stimulate the data availability when implementing other existing databases into Life Cycle Assessment.
- It should improve the reliability of the data used in Life Cycle Assessment studies.
- It should improve the reliability of the Life Cycle Assessment results.
- It might increase the efficiency of LCA since more sophisticated results might give better opportunities for different ways of analysis, detecting more opportunities for environmental improvement.

5. Quality Validation

This chapter deals with the different aspects of quality regarding
database and software. Three topics had been found as being very significant. They are targeting the databases and their data itself, the software calculating the results and then a combined point, which includes database quality aspects as well as the processing of quality aspects within the software.

5.1 Quality Monitoring in the Maintenance of Existing Databases and the Development of New Databases

5.1.1. State of the Art

Life cycle inventories for complex process trees often contain thousands of data modules with 10'000 or more numeric values that are collected from a variety of sources (measurement protocols, company records, interviews with experts, literature, etc.) and, for instance, they are usually entered into an LCA database system manually.

A better quality in the maintenance of the databases implies an efficient monitoring of the whole chain of operation, from data acquisition to data treatment. Inevitably, errors can occur in the various steps of this data processing:

a) Inappropriate or incomplete measurement techniques / strategies.
b) Faulty instruments and measurement errors at data generation.
c) Data transmission / transcription errors at data collection.
d) Data loss due to inappropriate system boundaries ("forgotten data").
e) Data loss due to too lenient cut-off criteria.
f) Omission of processes with difficult data acquisition.
g) Faulty data entry into the LCA system: Typing errors in numeric values, choosing wrong measuring units or reference amounts (1 kg instead of 1000 kg), etc.
h) Incomplete data entry into the LCA system: Omission of some inputs, emissions, or multiple outputs (from long lists of such items).
i) False, missing, or inappropriate links from measured (foreground)
processes to their literature-based background equivalents (wrong energy model etc.).

j) Referential integrity violations (references to non-existent input processes, synonyms/ambiguities in emissions/burdens, incommensurable units)
k) Calculation mistakes due to faulty programs.
l) False characterisation and valuation, due to ambiguities and choice of measured parameters.
m) Incorrect transcription of inventory data into summaries / final interpretations.

Probably, this list is not exhaustive, and more error types may exist, so far unrecognised. Error detection is not straightforward, due to the complexity and size of LC inventories, thus false or implausible values are ubiquitous. Probably, most LCA practitioners have observed errors during their work, even in frequently used literature or well-renowned databases. Some quality-conscious data suppliers keep checking their data beyond the publication date and issue errata reports or updates with corrections frequently.

Of course, there is already a set of established techniques for error detection (this list only serves as an example and is not exhaustive):

A Error types a)-c) should be avoided by classical GLP/GMP techniques.

B Error types d)-f) can be detected with peer review processes already common in LCA work.

C For error types g)-i), there is a whole spectrum of measures (listed according to required effort and time, in descending order):

1. Double entry of complete inventories by independent researchers allows a target-oriented subsequent audit of differences (hardly affordable in usual LCA work).
2. Selective internal peer review / proof reading, preferably by independent persons, can identify all sorts of errors, but needs considerable time and knowledge. Returning the data printouts to the original data generator for checking is often beneficial.

3. Lists of all processes occurring in a process tree (computer-generated) allow summary plausibility checks. Examples: European electricity models occurring in an all-American study, or "Potato growing" in an all-chemical LCA might indicate erroneous entries and need to be checked. Even the absence of certain processes can sometimes be used as an error indicator.

4. "Hot spot" lists also show all input processes in a tree, and additionally indicate their contribution (of selected burdens to the total result of the study). "Big contributors" can then be examined in detail, especially if the results look counter-intuitive. False low contributions are much harder to detect.

5. "One step usage" lists for selected input processes show all parent processes that use the input under study. If similar or synonymous inputs are run in parallel and compared (e.g.: different electricity models, grades or trade names of substances), inconsistent use can be detected. Also, such lists give an impression of orders of magnitude for the inputs investigated - sometimes this is a way to detect "factor-of-1000" errors.

6. "Typical" emissions lists, showing all processes with a given output, help to discover synonyms and/or inconsistent usage of outputs, as well as unexpected occurrence of emissions or exceptional orders of magnitude, which possibly indicate data entry errors.

7. "Terminal processes" lists, showing all processes at the end points of a process tree (with their respective overall input), indicate "loose ends" (omitted connections), and also help to establish uniform cut-off criteria.

8. Comparisons between reasonably "similar" goods (the same good from different suppliers or data sources, e.g. US vs. European current models; chemically related substances, e.g. polyethylene /
polypropylene; etc.) may hint to conspicuous differences, which are then investigated for their correctness.

D Error j) is easy to detect with appropriate precautions in the database system, preferably already at data entry time. Both j) and k) are the subject of research item 5.2 in this chapter.

E Errors l) and m) can be detected in peer review, due to the limited amount of data involved.

5.1.2. Research Needs

Experience shows that substantial errors occur frequently in LCA work, and many attempts were already undertaken to detect and correct errors. However, error checking is often done in a random, intuitive way, and the wealth of experience gained in other scientific disciplines about error finding strategies and data quality improvement is hardly used.

To find a more systematic approach to improve data quality, the following questions should be answered:

- Are there further error types - beyond the list of a)-l) shown above - that deserve consideration?
- Can we document the remedies listed in A - E above, especially the LCI-system-related entries C1- C8, in a way that makes them useful and applicable for all LCA practitioners?
- Are there further error detection/correction measures already in use that can be documented in the same way?

What can we learn from other, more mature disciplines that encounter similar problems, such as:

- Engineering: here quality controls are vital, and long-established.
- (Eco-)toxicology, pre-clinical studies, and environmental analytics: all observe GLP and follow sophisticated data quality
management and auditing schemes.

- Chemical (mostly pharmaceutical) production: all operations are ruled by GMP, and manufacturers mandatorily collect industrial process data that are very similar to LCI data.
- Financial accounting, especially product cost calculation: here, precision requirements in accounting standards are proverbial, financial auditing is a well established discipline, and the techniques used for costing (including the crucial system boundary, averaging, and multi-product allocation problems) are very similar to LC inventory calculations, and may in fact serve as an example.

Research in the field of error detection and data quality in LCI should lead to a compendium of proposed quality control measures, formulated as guidelines or standard operating procedures, and ranked by their efficiency, applicability, feasibility, and economic effort needed (cf. chapter 2.1, Data generation). Out of this collection, minimal requirement sets for various study types, as well as minimal quality standards for LCA computer systems and databases could then be derived.

This investigation is closely linked to any research objectives dealing with peer review. In a wider sense, it is related to all topics of the Goal/Scope Definition and Inventory Analysis working group, since all information discussed there are subject to errors as explained above, and should eventually be scrutinised.

The methods used in this research are dual:

1. In a comprehensive in-depth field study of present LCA methods, the greatest possible number of practitioners should be asked (by interview or questionnaire) for common error types and their methods for detection and correction.
2. In a multi-disciplinary approach, other sciences and techniques (the ones stated above plus others) that cope with comparable
amounts of data need to be analysed for possible analogies, and their error-detection strategies should be adapted to LCA work, if possible. This is mostly a study of existing literature in the appropriate fields. Also, established mathematical theories (e.g. on error propagation, probabilities, and spot check randomised sampling) should be assessed for their usefulness.

5.1.3. Expected benefits

If LCA shall serve as a decision-making tool for industry and government, appropriate quality standards are absolutely indispensable to establish credibility. Such standards are necessary for all steps of LCA, but due to the immense volume of information, they are hardest to achieve in LCI.

LCA as a science should not repeat the mistakes made in toxicology some 20 years ago: Toxicology was originally developed as a rather free, intuitive discipline, then became widely used as a decisive tool (in drug and chemical registration). Almost inevitably, inappropriate and even fraudulent studies appeared and temporarily affected the reputation of toxicology, whereupon state authorities decided to (over-)regulate it with a dense network of guidelines and quality assurance requirements. Experimental toxicology has since lost much of its appeal as an innovative science due to this rigid "cage" of very formal legalistic prescriptions, which could have probably been avoided by a timely, rational, and reasonable consideration of quality issues by the scientists themselves.

Reliability of databases and calculational software is only meaningful, if the underlying primary (LCI) data are reliable. If the data quality of the original inputs is questionable and cannot be assessed, the use data bases and also peer review become futile.

Data availability and exchange of data and results are presently impeded by the non-transparency of the data sets (deliberately
introduced by data providers to protect their business secrets). Inspection and certification of such data according to established standards by an independent auditor (as in financial accounting, bound by a similar professional secrecy obligation) will resolve many of the confidentiality problems.

Finally, thousands of person hours were spent by many practitioners to independently detect and eliminate errors in commercial or literature data sets. In most cases, these efforts were not published, and thus did not lead to a general improvement of data quality. Rather, every newcomer in the LCA field would eventually duplicate the checking and waste more time and money, further increasing the cost of LCA studies.

5.2 Validation of softwares

5.2.1. State of the art:

LCA-software has the purpose of enabling a LCA-method and facilitating LCA-work. There are general methods for qualitatively validating software, some actually applied to LCA-software (beta testing, ordinary debugging, following recommended coding principles etc.). Methods not generally applied to LCA-software are round robin testing and quality assurance according to quality management systems (ISO 9000 etc.)

The software differ from each other by the interface and the options they provide, such as allocation function, impact analysis, sensitivity analysis. Some software contains data and default values, which software automatically use for calculating inventories while some software are entirely based on users inputs, some combine these two options.

5.2.2. Research needs:

What has to be done?
1. Check the congruency between LCA-method and the according LCA-software tool.
2. Check the similarity of the inventory results while using different software with the same input data.

How?

1. Develop a method for congruency checking, which should cover the LCA-methodology. This could be made by studying general software quality assurance methods, and mapping these methods into the application LCA-software.
2. Develop a hypothetical test case, which contains all the special features of LCA (closed loop, allocation etc.). This test case will be calculated with each software. The case should be complex enough to reveal the possible bugs of the software but also simple enough to be verified by hand calculations.

5.2.3 Expected benefits

To help ensure reliability and meaningfulness of the output from the software.

5.3 The Use of data quality indicators

5.3.1. State of the Art

*Data quality indicators* (DQI) are symbolised or alphanumerically codes to describe several quality related characteristics of data or data sets conducting life cycle inventories. The results of LCI’s often hide the complexity of the data or data set used for the calculation from many different sources. Therefore it is often almost impossible to assess the *quality* of the results. Using DQI within an LCI is a step towards transparency of the results as well as the used data or data set.

There are several approaches and suggestions to use DQI in current
LCI projects. Within these indicator systems the following characteristics and information had already been described in the literature as being relevant for DQI’s:

- data collection method/ data generation method,
- data type),
- age of data,
- data uncertainty,
- statistical representativeness,
- completeness of flows/processes,
- and geographical and technological correlation.

The current approaches on defining DQI’s differ in the number of characteristics included as well as in the aggregation level of the used data quality symbol or code. These ranges from one-dimensional symbols to three or more dimensional alphanumerically codes. There are also different scales used within the same characteristics in current LCI work.

Nevertheless most of the LCI work in the field of databases and models is done without considering DQI. Therefore a lot of information on the significance of results got lost during generation and calculation. DQI are not sufficiently discussed within the national and international process of standardisation of LCI.

5.3.2. Research Needs

The analysis of the state of the art shows the need for further research to establish a common system of DQI within the LCI-work. The following aspects has to be taken into account:

- Which characteristics are necessary for the sufficient description of data or data set used in databases and models from the DQI point of view (examples of used characteristics are listed in the chapter above).
- Which level of aggregation (sub-aggregation) should be used?
Which implications does this have for the scales used to describe single characteristics.

- The DQI from different data within process chains used in databases and software must be indicators, in order to keep all necessary information about the data quality of the result and especially give an assessment of the reliability of the result.
- The DQI has to be easy to understand and apply for data generators, especially regarding that they are not experts in the LCA-field.
- The description of and assessment of the data quality characteristics needs to be so accurate and explicit that their application by different data generators does not lead to different DQIs. The DQI has to be applicable for the import of data from databases which are originally not designed for usage in the LCI area.
- The DQI-system should be able to deal with data quality gaps, which means that data or data set without sufficient information about a characteristics on data quality can nevertheless be handled.

The DQI system should allow an easy identification of data which significantly contribute to a poor LCI/LCA results.

5.3.3. Expected benefits

DQI should also be considered in the impact assessment and interpretation group as well as in the goal and scope definition and inventory analysis group. The discussion about DQI is linked to Chapter 5.1 (Monitoring and maintenance of Databases) and Chapter 3.3 (Qualitative data).

With the introduction of DQI as a standard in the LCA work, the credibility of LCA will increase because:

- a step towards more transparency of the result and the database
will be achieved,
- the reliability on results is much more provable and can be documented,
- it enables to investigate LCA results for their weak points (from data base point of view),
- it will be easier to identify data or data sets, which are most responsible for the uncertainty of the LCI results.

The conduction of LCA projects will be promoted too, because the data exchange on a high information level will be much easier.

6. Expert systems for LCA

LCA is an approach that has been developing rapidly over the last years. There are, however, a relatively small number of LCA experts (numbering in the hundreds rather than thousands). Life Cycle Assessment has the real potential to become more widely adopted as a decision making tool by Governments, Industry and others who do not want to themselves become experts in LCA. To facilitate this spread of use the opinions and judgements of experts should be made available to assist in the decision making process.

Computer-based "Expert Systems" provide the means to store and interrogate the expert's views and to provide an output in a summary fashion for the non-expert to include as an input in decision making. The main components of expert systems are:

- Knowledge base - accumulated knowledge from experts
- System to search knowledge base to arrive at conclusions to problems
- System to solve unstructured and/or difficult problems
- System to present results, inferences and conclusions and to show how these were derived.
What the decision-makers need is a software system offering the experts knowledge to the user.

**6.1 State of the art**

Expert systems have been developed for many fields of application including, for example, medicine, financial planning, engineering, design and project scheduling. They are still, however, in relatively early stages of development. A considerable amount of research effort is being undertaken in the field. In case of empirical or diffuse knowledge expert systems are a very good approach, for example

- if input data is
  - subjective data
  - incomplete
  - partly incorrect
  - inconsistent
  - measurement of the data is too expensive, time extensive or dangerous
- if knowledge is
  - fragmentary
  - empirical
  - uncertain, vague
  - inhomogeneous
  - dated
- if conclusions are
  - hypothetical
  - not monotone
  - approximative
  - multi causal

No specific expert system for LCA is available yet. However, there are many such developments in related fields. Some specific examples include - Industrial Energy Efficiency, Pesticide Fate Modelling, Minimising Industrial Hazardous Waste etc.
6.2 Research needs

LCA is a very broad discipline requiring input on a range of issues from processing, waste treatment, emission fate and effects, modelling of impacts that it will be a large task to complete a specific expert system for LCA. The research should be in two phases Prior to undertaking any research to try to develop a specific expert system for LCA the following should be undertaken:

1) Assess feasibility of developing an expert system for LCA:

   • Define goal of the research programme - what is the ultimate aim of the exercise.
   • Study developments of expert systems in related environmental disciplines and assess their relevance and applicability to LCA.
   • Assess if it is possible or feasible to construct an expert system specifically for LCA.
   • Define the sub-sets of LCA Methodology for which an expert system can easily be developed - for example:
     A) Goal and scope dependent LCA (which data is necessary?),
     B) Selection of relevant system boundary conditions for all parts of LCA,
     C) Identification of data gaps,
     E) Cut-off criteria considering mass, energy or ecological relevance, prognosis and scenarios.
     F) Allocation rules

2) Begin researching the development of the expert system

   • Systematic analysis of all published LCA case studies - methodologies, rules applied etc.
   • How to acquire and store the knowledge of LCA experts which is unpublished in studies
   • How to link the LCA expert system with the many other relevant expert systems
It is difficult to make experts knowledge explicit. For that reason in the first approach might be a systematic analysis of the case studies published in Europe. These case studies contain a lot of information about the handling of specific LCA problems. The organisation LCANET covers the main part of the LCA community in Europe. To transfer their knowledge into rules of a knowledge-base, some workshops like the LCANET workshops for research needs are useful.

6.3 Expected benefits

The benefit of expert systems is seen in the implementation of experts knowledge, the combination of various specialists and the possibility to formalise information more objectively. Most important for the field of application LCA is the multiplication of knowledge on how to handle problems in a simple way.

Other potential benefits are:

- more reliable and reproducible LCA results,
- easier use of LCA by non-experts in decision making,
- wider application of LCA methodology,
- closer links between LCA and other, relevant environmental management systems.

Annex 1: Contributors to the theme report

This theme report is a compilation and edition of written contributions brought by the below listed experts. Their contribution summarises the discussions held during the three days meeting (6-8 November 1996) of the LCANET workshop, Leuwenhorst, The
The Leeuwenhorst workshop was prepared by a group of experts: Laurent Grisel (Ecobilan), Philip McKeown (Unilever), Raul Carlson (Chalmers), Tiina Pajula (KCL), Thorsten Volz (IKP). All of them are warmly thanked for their contribution. This report is issued due to their effort. Laurent Grisel, acting as chairman of the different meetings and as editor of the present report, is fully responsible of any mistake and misunderstanding.

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