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Miljøprojekt

Reducing Uncertainty in LCI

Developing a Data Collection Strategy

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Preface

This report was prepared within the Danish LCA methodology and consensus creation project during the period from 1997 to 2003.

The report is one out of five technical reports to be published by the Danish Environmental Protection Agency and dealing with key issues in LCA. The reports were prepared as background literature for a number of guidelines on LCA, planned to be published by the Danish Environmental Protection Agency during the autumn of 2003. The reports present the scientific discussions and documentation for recommendations offered by the guidelines. The reports and guidelines developed within the project are presented in the overview figure below.

A primary objective of the guidelines has been to provide advice and recommendations on key issues in LCA at a more detailed level than offered by general literature, like the ISO-standards, the EDIP reports, the Nordic LCA project and SETAC publications. The guidelines must be regarded as a supplement to and not a substitution for this general literature.

It is, however, important to note that the guidelines were developed during a consensus process involving in reality all major research institutions and consulting firms engaged in the LCA field in Denmark. The advice given in the guidelines may thus be considered to represent what is generally accepted as best practice today in the field of LCA in Denmark.

The development of the guidelines and the technical reports was initiated and supervised by the Danish EPA Ad Hoc Committee on LCA Methodology Issues 1997-2001. The research institutions and consulting firms engaged in the development and consensus process are:

COWI, Consulting Engineers and Planners (Project Management)
Institute for Product Development, the Technical University of Denmark
dk-TEKNIK ENERGY & ENVIRONMENT
The Danish Technological Institute
Carl Bro
The Danish Building Research Institute
DHI - Water and Environment
Danish Toxicology Institute
Rambøll
ECONET
National Environmental Research Institute

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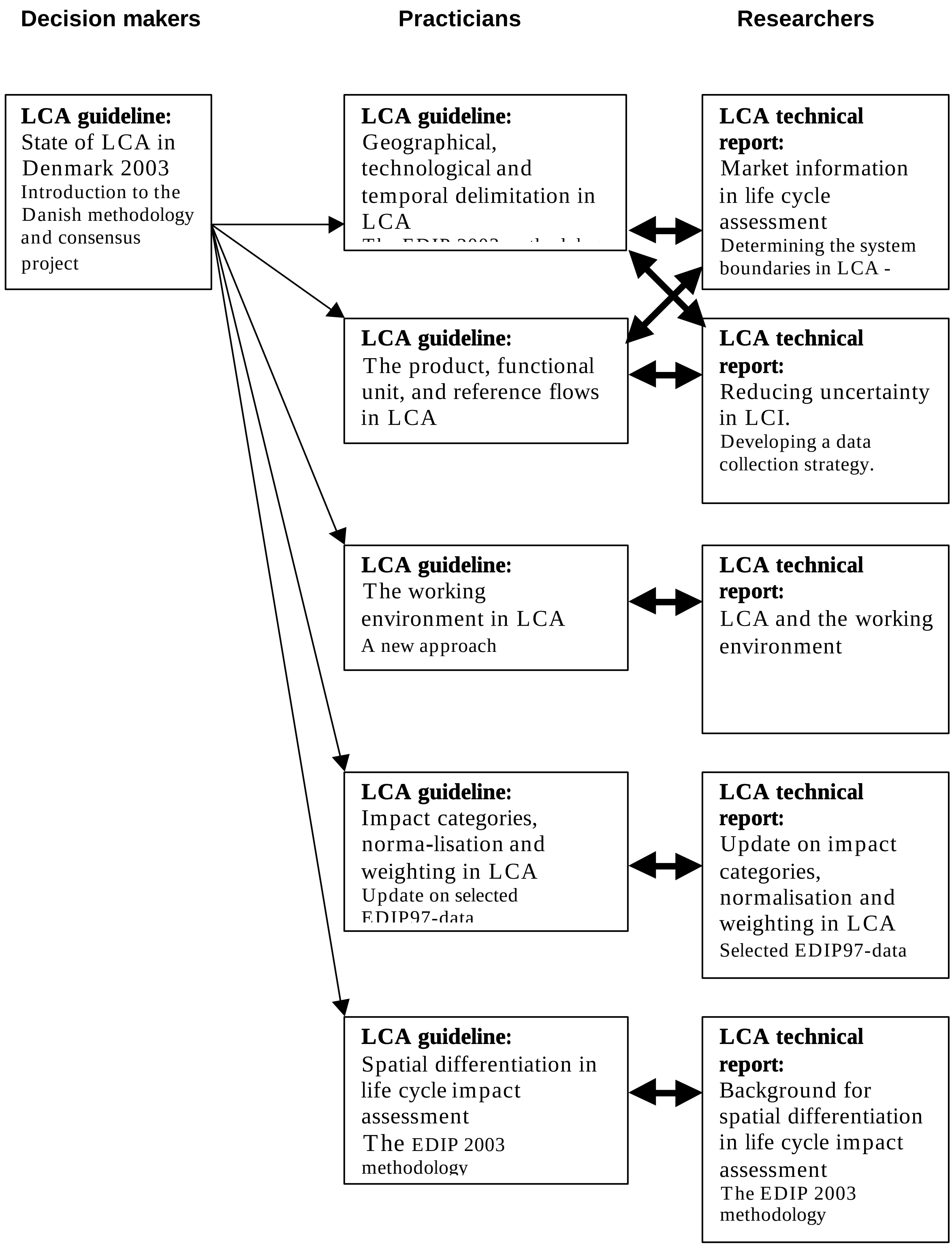
Guidelines and technical reports prepared within the Danish LCA-methodology and consensusproject



1 Introduction

This report has been prepared with the aim of demonstrating how a data collection strategy can be based on understanding the causes of variation in the technological, geographical and temporal aspects of the processes included in a life cycle assessment.

The objective of a data collection strategy is to prioritise the data collection so that the necessary data is obtained in an adequate quality with the least effort. Therefore, a natural target for the data collection strategy is to reduce the overall uncertainty of the life cycle inventory to the level necessary to obtain a result upon which conclusions can be based. Uncertainty, its causes, and ways to reduce it, are therefore natural objects of interest when designing a data collection strategy.

To reduce the overall uncertainty level of the life cycle inventory with the least effort, the largest uncertainties should be reduced first, since these uncertainties will dominate the overall uncertainty. However, some uncertainties may be easily reducible, while others are irreducible. If the result of a life cycle inventory is expected to be inconclusive at the level of the irreducible uncertainties, it does not make sense to seek a reduction of uncertainty at all, i.e. data collection should not be initiated. Chapter 2 deals with procedures to identify and estimate the largest uncertainties in a life cycle inventory. Chapter 3 introduces the distinction between reducible and irreducible uncertainties, and combines the procedures of chapter 2 with procedures to reduce uncertainties, arriving at an overall uncertainty-based data collection strategy, which is summarized in section 3.7. The extensive annex A reports the findings of an investigation into the causes of technological, geographical and temporal variation in life cycle inventory data from a number of industrial sectors. Annex B reports on the statistical terminology applied.

This technical report is based on research performed from 1998 and up to the end of 1999. It therefore does not include sources of information that have become available after this date.

2 Identifying the most important uncertainties

In a life cycle assessment, the overall system studied is the difference between the product systems that substitute each other. Thus, the largest uncertainties are likely to be found in relation to the processes that contribute the most to the differences in environmental exchanges between the product systems. These important processes can be identified and ranked by subjecting the initial system model to an error analysis. The initial system model is based on readily available data and order-of-magnitude estimates. An error analysis identifies and ranks the relative contributions from each process in the model to one or more summary indicators for the environmental impact. A process may be important because it has a large product flow relative to the functional unit (i.e. makes up a large part of the product system) or because its environmental exchanges are large relative to the product flow. The fewer steps between a process and the process in which the reference flow occurs, the more important is an uncertainty on the product flow, since this uncertainty will affect all processes further up- or down-stream.

The uncertainty of a less important process is only relevant if it is so large that a worst-case estimate would shift the process from being less important to become more important, i.e. to contribute to a significant part of the total environmental exchanges.

For a specific process, the sources of uncertainty can be divided in three:

- Uncertain identification of the process as the one to be included in the product system. This may mean that completely different processes are to be included, and is thus a major source of uncertainty.
- Technological mismatch between the desired data and the available data. This may mean that data have to be extrapolated from data representing a different technology, with different environmental exchanges. The resulting uncertainty decreases with decreasing difference between the desired and the available data.
- Uncertainty in the available data as such. This is the least important of the three sources of uncertainty, since it involves only uncertainty within the process in question, and not across different processes.

These three sources of uncertainty are analysed in more detail in the following three sections.

2.1 Uncertainties in identifying the correct processes to include

The procedures for identifying the correct processes to include in the studied product systems are described in the guideline “Geographical, technological and temporal delimitation in LCA” (Weidema 2002a) and the report “Market information in life cycle assessments” (Weidema 2002b). These procedures rely on market data, in which the following uncertainties are of importance: Uncertainty re. the scale of change that may influence the boundary conditions of the market.

Uncertainty re. what intermediate products may substitute each other in different market segments and geographical markets.
Uncertainty re. the temporal and geographical boundaries of the actual market of an intermediate product.
Uncertainty re. what technologies and processes are constrained in their ability to change their volume in response to a change in demand.
Uncertainty re. market trends.
Uncertainty re. the parameters that influence decisions on capacity adjustment, e.g. prices of different technologies and the effect of information on buying behaviour and investment decisions.

These uncertainties are all of major importance, since they may affect which processes are included and excluded from the analysed product systems. The importance increases in proportion to the possible variation in the technologies and processes that may be substituted, i.e.:
Variation in the relevant technologies and processes between different possible markets.
Variation in the relevant technologies and processes within the same market, especially the variation between the least and the most competitive technology/process.
This means that the higher the variation in possible outcomes, the higher is the demand on the quality of the market data.

When relevant, several alternative scenarios should be included to reflect the limits of knowledge.

The mentioned major sources of uncertainty also apply to the handling of multi-functional systems, following the procedure described in Weidema (2001, 2002a, b). Additionally for this procedure, the following minor, technical sources of uncertainty may be considered, when relevant:
Uncertainty of identifying the limiting parameter for a combined production.
Uncertainty of identifying the split-off point and the point of displacement.

2.2 Uncertainty from technological mismatch between desired and available data

The possible mismatch between the desired data and the available data is illustrated in figure 1, where the boxes A, B and C illustrate available data, which are:

A. too specific data from within a desired population,
B. less specific than - but including - the desired data,
C. for a product/material, process type, area/location or time period not including the desired data, and which differs more or less from the desired.

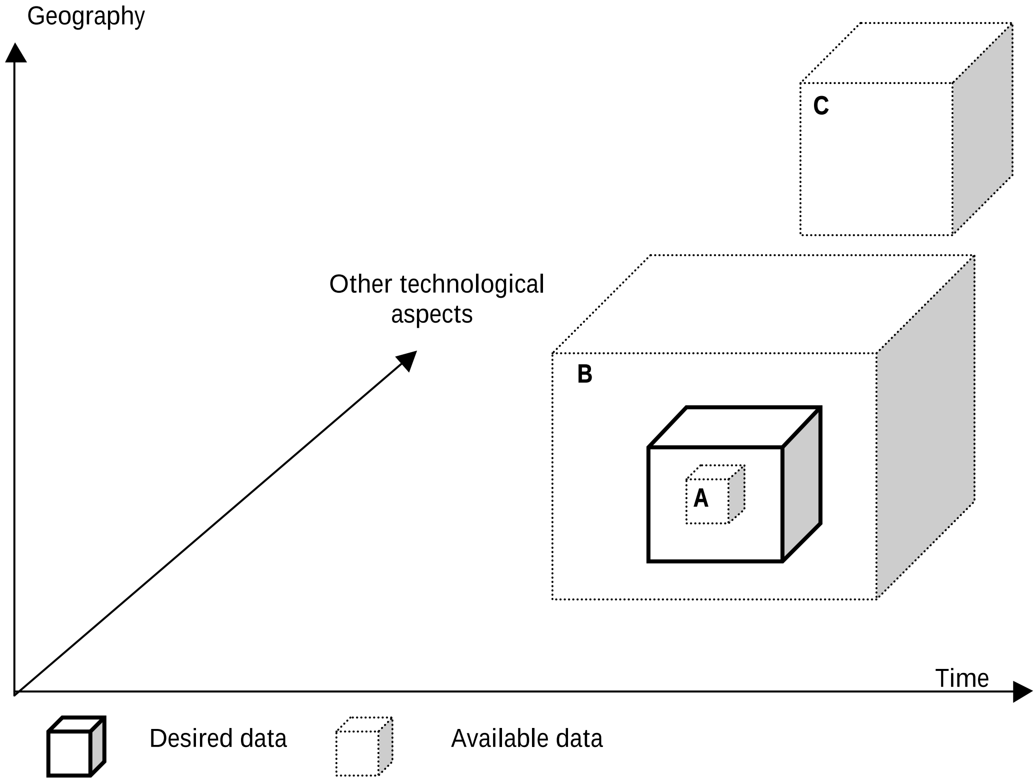


Figure 1. Illustration of different kinds of "technological mismatch" between desired and available data.

The three dimensions of technology in figure 1 are those typically used to establish whether a specific data set is adequate to meet a specific data requirement in a life cycle study (Weidema & Wesnæs 1996, Weidema 1998):
Temporal aspects: Differences depending on the period that the data is assumed to represent or for which data is collected, since technology changes over time.
Geographical aspects: Differences depending on geographical location of the process. This may be caused by differences in natural conditions (as defined by climate, landscape, soil etc.) or administrative conditions (between country-groups, countries, states, counties).
Other technological aspects of the data set, which may be further subdivided into:
Structural aspects: Differences depending on the composition of the products from different processes within the same process class (as defined by CPA-code or more detailed classifications; see Annex A). These are often named 'structural' differences, because they depend on the structure of the product composition within each process class. An example is aggregated data for steel production, which may consist of different amounts of recycled steel, steel that has passed through different amounts of finishing processes, and include a number of specialised steel types. The difference between data may simply be caused by differences in how much recycled steel, how much finishing, and how much of the different specialised steels are present in the different aggregated data.
Differences among individual production plants at a given point in time and within a given geographical region: This is differences depending on e.g. capacity utilisation, age of installed technology at the given point in time, management factors including education, scale of plant, and effectiveness of (emission) control.

To some extent, a hierarchy between the different aspects can established (see Figure 2):
Some (but not all) of the variation at plant level may be explained by structural differences in product outputs, or by differences in administrative or natural conditions.
Some (but not all) of the structural differences in product outputs may be explained by differences in administrative or natural conditions.
Some (but not all) of the variation between administrative regions may be explained from differences in natural conditions.
Furthermore, temporal variation (changes over time) may affect all of the other aspects, but is most important at the plant level and of least importance at the level of natural conditions.

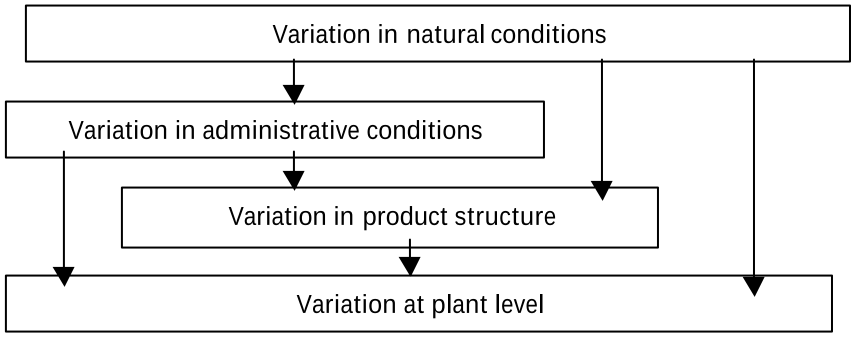


Figure 2. A hierarchy of causes of geographical and technological variation. Please note that variation at a lower level is not solely caused by the variation in the levels above.

This also implies that the total variation at plant level may be divided according to the different causes as shown in table 1. In addition, temporal variation may play a role when the actual temporal position of the process is uncertain or when applying data from different periods.

Table 1 Classification of the causes of geographical and technological variation. Please note that the examples given under each heading are not exhaustive.

Variation between natural regions
Climate
Landscape
Soil type
Density of population
Raw material quality and availability
Variation between administrative regions
Raw material price
Labour costs
Legislation/regulatory differences
Available capital
Variation in process or product structure (structural variation)
Residual variation at plant level
Capacity utilisation
Age of installed technology
Management factors, incl. Education
Scale of plant
Effectiveness of (emission) control

Figure 3 illustrates some of the underlying causes of variation listed in table 1 and how they may be connected more or less to one or more of the 3 dimensions of figure 1.

If we can determine the contribution of each of these underlying causes to the variation in each of the 3 dimensions, we would be in a much better position to estimate the overall variation. If we could furthermore find some small parts of our
3-dimensional space, where an adequate number of measurement points actually is available, we could calibrate our estimates and see how large a residual is not explained by the identified causes (the causes listed in table 1 and figure 3 are not exhaustive).

In Annex A, a first attempt at obtaining such estimates is made on the basis of a theoretical-empirical analysis of underlying causes of uncertainty. The recommendations in the following text are based on the conclusions of this analysis.

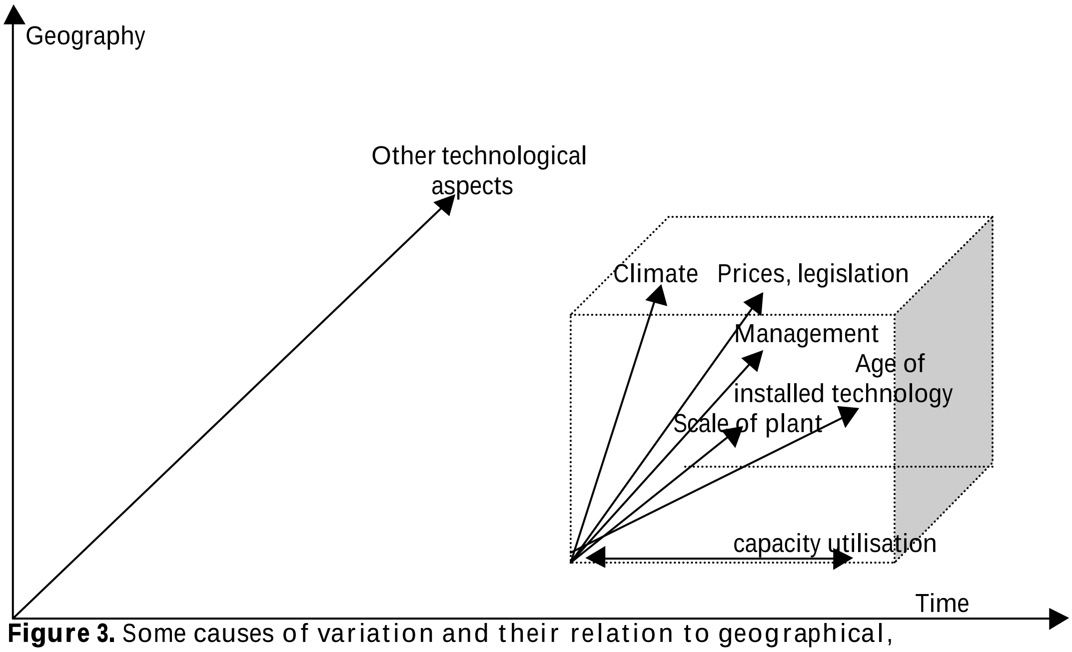


Figure 3. Some causes of variation and their relation to geographical, temporal and other technological aspects.

In general, among the causes of variation mentioned in table 1, the most important one is variation in process or product structure between related processes (structural variation).

Of the geographical causes, practically all sectors are affected by differences in:

- legislation and/or regulation,
- raw material quality and availability,
- availability of investment capital,
- culture, labour costs and educational level.

In addition to these causes, certain sectors (e.g. agriculture, building and transport) are especially susceptible to differences in:

- climate,
- landscape,
- geology, and
- population density.

Differences in legislation/regulation are of largest importance for emissions, while the other causes affect both energy and material consumption and emissions. Nevertheless, emissions are generally affected more than energy and material consumption.

Besides the structural and geographical differences, age of technology appears to be the most important cause for variation at plant level, with management and plant size as other important causes. Capacity utilisation is often of less importance (with transport as an exception). Management is of larger importance for emissions than for material and energy consumption. Emission control equipment and its efficiency is an important cause for variation in emissions.

Besides the above, it is not possible to draw *general* conclusions about the importance of the different causes, because of the large differences between sectors. For one sector, raw material quality may be a dominating cause, while availability of capital may be the most important cause for another. Even within sectors, such differences exist.

However, a general observation can be made concerning the reasons why sectors are different in respect to importance of causes of variation: Issues that are generally important for the activity will also be important as causes for variation. For example, some sectors are more regulated than others, and differences in regulation thus becomes a more important cause of variation. In the opposite end of the spectrum, agriculture and household processes can be mentioned as examples of processes where detailed regulation is difficult to apply and/or enforce. In a similar way, raw materials may play a minor role in some sectors (as shown by the ratio of the production value to the raw material costs), and variation in local raw material availability may thus play a minor role for such sectors. Similar arguments can be made for availability of capital, and labour costs. The obvious importance of natural geography for some sectors (and the consequent minor importance for the remaining sectors) has already been described above. The importance of age of technology depends on the speed of development of the process. For example, in the wood products industry, sawmills are generally slow in development due to lack of capital, while the wood panel industry develops more quickly. The result is a much lower variation in energy consumption (+/-10%[5]) in the latter industry compared to the former (+/-40%).

Thus, using table 1 as a general checklist and asking for each item: "How large a role does this item play for this activity in general?" will allow a quick identification of the most important causes of variation for a specific activity. Once the most important causes are identified, the further uncertainty analysis can focus on quantifying these causes, which will dominate the overall uncertainty of the activity.

If a desired average is not available, but data is available on a smaller part of the population of interest (situation A in figure 1), the desired average may be estimated from this smaller part. If only one single data value is available, and nothing else is known about the population, the best estimate is that the available data represents the mean value and that the uncertainty is of the same size as in other similar populations. Examples of the size of uncertainties of different populations show coefficients of variance ranging from 5% for large populations over 10-30% for specific energy data to the more extreme 60-150% typical for many emissions. Besides population size, the size of the uncertainties depends on the extent to which the variation is controllable (or controlled). The large coefficients of variance obviously reflect technological differences within the population. In a homogenous population, the desired average can be determined as the mean of the sample, but the uncertainty of the estimated average depends on the sample size. The larger the sample, the more likely it is that the sample is a good estimate of the population. If you have only few data, the standard deviation of the average is ½ the range of the sample, but if you have 10 data the standard deviation is 1/3 of the range of the sample. If you have 30 data, the sample is usually regarded as a good approximation of a full, homogenous population. However, the populations studied in life cycle assessments are seldom homogenous, and extrapolations from a sample to a larger population must therefore take into account all the issues described above.

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[5] In this text, we generally use the +/- to describe a range covering 3 times the standard deviation.

If the desired data are not available, but you have average data for the larger population of which the investigated process or population is a part (situation B in figure 1), this average may be used to estimate the desired data. The variation on the average is an expression of the probability distribution for the desired data. The resulting smaller population will have a larger relative uncertainty than the large population of which it is a part. The typical uncertainty on specific processes and small populations can be deduced from the information given above and in section 2.3.

When the desired data are not available, but data are available for another geographical region, extrapolation may be relevant (situation C in figure 1, covering both geographical, temporal and other extrapolations). To judge the error that may be introduced, the following rules of thumb may be applied:

- Extrapolation from one geographical region to another will typically involve some additional variation because of subtle differences in culture, education levels or labour costs. To consider this, the coefficient of variance of the original data should, as a minimum, be increased with 10%.
- Special precautions must be taken when extrapolating:
  - from regions with high availability of investment capital to regions with a low availability,
  - from regions with different population densities,
  - emission data from regions with different legislation/regulation,
  - from regions with different geological conditions e.g. reflecting itself in differences in raw material quality and availability,
  - agricultural data and data on buildings from regions with different climatic conditions,
  - transport data from regions with different landscapes.

In these situations, the specific influence should be investigated in each individual case.

Averaging data over time should not exceed that which is necessary to even out seasonal fluctuations. When using older data to estimate the desired (newer) data, the attention should focus on:

- the possible influence of changes in product mix over time, which may not be obvious from the available data,
- shifts in technology that may cause the old data to be completely obsolete and misleading,
- the speed of development of the sector, which can be used to estimate the necessary correction factors used in the extrapolation.

When it is known that the basic technology remains the same over the period, extrapolation can be based on:

- expressed political targets, e.g. for reduction of specific emissions or reductions in energy use,
- knowledge on efficiency improvements over time.

For further recommendations on forecasting, see Weidema (2002b).

Extrapolation of data from related processes or products is only relevant for activities that are very closely related. This may be the case if the same product is produced with the same technology and under the same conditions at different plants. However, even processes that seem very closely related might in fact be quite different. Even between quite similar activities, extrapolation may still involve additional uncertainty, mainly due to:

- differences in size (as a default, the coefficient of variance should be increased by 10-20%),
- differences with respect to management (for emissions, the coefficient of variance should be increased by minimum 10%, while for energy consumption, the coefficient of variance should be increased by minimum 2%).

2.3 Uncertainty inherent to the available data

The major causes for uncertainty within a specific (available) dataset are similar to those causing uncertainty between different processes, as described in section 2.2, and the dominating cause of uncertainty can be identified in the same way, i.e. by using table 1 as a checklist.

If the available data is an average, its uncertainty can be expressed in terms of the variation of the population in question around its average value. A dataset covering a larger group of processes, a larger geographical area or a larger time span will obviously have a larger absolute uncertainty than a more specific dataset. However, the relative uncertainty will typically be lower, the larger the population. With increasing sample size, the variation increases, while the relative uncertainty decreases, since it is more likely that the sample is a good estimate of the population.

When individual data are not available from which the uncertainty can be calculated, a default coefficient of variance of 5% may be applied for *national* averages. Larger uncertainties should be assumed if the population is small, i.e. if the specific unit process occurs only in a small number within a given country, or if the population is inhomogeneous, i.e. if it includes processes that applies different technologies or have different product mixes.

The smallest uncertainties are generally found for raw material consumption and energy use, and the largest for emissions.

The uncertainty related to emissions tend to fall in four distinct groups:

- Emissions that occur as a result of substances present in fuels or raw materials, e.g. carbon (C) in fossil fuels, which is primarily emitted as CO_2 in known and fixed proportion to the amount of fuel used. For this type of emission, the uncertainty is obviously of the same order as for the fuels and raw materials in which they occur, i.e. below 20% and in the order of 10%.
- Emissions that occur as a result of substances present in fuels or raw materials, but which can be reduced by cleaning of the exhaust gases e.g. sulphur (S) in fossil fuels. For this type of emission uncertainty can be significant depending on the type and efficiency of the cleaning technology used, especially if the data covers geographic areas where regulations regarding emissions are different. If not, the uncertainty will often be of the same order as above.
- Emissions that are created during the production process, and which vary significantly depending on the physical conditions during production, e.g. the amount of CO and NO_x created during combustion of fossil fuels, which depends on temperature, the amount of oxygen present etc. These emissions may vary with a factor of 5-10. The same is the case for emissions that occur from the use of specific chemicals during the production process. In this case, the emissions will usually be highly

dependent on the specific production process, which generally leads to significant uncertainty.

- Emissions that occur as a result of substances present in fuels or raw materials, and which naturally vary significantly, e.g. cadmium, lead, mercury and other metals in coal and crude oil. In extreme cases, this type of emissions may vary with a factor of 1000 or more.

When using averages, both national averages, averages over industrial sectors, and averages over time, it should be remembered that although the uncertainty on the average is low, the underlying processes might still have a large uncertainty. This means that the average with its low uncertainty should only be applied as such, when this is actually the desired data. If used to estimate a smaller part of the population or other data, larger uncertainties will be involved as described in section 2.2.

If the available data is site specific, the inherent uncertainty of a specific data set is typically low. If no information on uncertainty is available, the following default coefficients of variance can be applied:

- for energy consumption: 1%
- for material consumption: 2%
- for emissions: 10%

These defaults reflect general measurement uncertainty. Energy consumption is typically measured continuously, while material consumption is typically registered by weight or volume and may be subject to errors in estimating stocks, concentration, water content etc. Continuous measurements of emissions are seldom, which is the reason for the much larger coefficient of variance suggested. Some emissions may be better monitored and this should be reflected in the applied coefficients. Other emissions (and even auxiliary materials) may be estimated or roughly calculated, which should result in larger coefficients of variance.

Besides measurement uncertainty, site specific data may be subject to uncertainty stemming from implicit or explicit allocation procedures. If the data represents an activity with several products, of which only one is of interest for the life cycle study in question, allocation procedures may be applied to arrive at the data for this product. Such allocation procedures may not always be explicitly reported, since they may be regarded as obvious or implicit, e.g. the allocation of a joint raw material over all produced items by relative weight, the allocation of a surface coating over the relative surface etc. Nevertheless, such procedures may cause considerable uncertainty, especially if the process in question has a variable product mix. When assigning default uncertainties, the possible additional contribution from implicit allocations should be considered specifically.

The above described default measurement uncertainties do *not* apply to data that are interpolated from average data or extrapolated from older data, related activities or geographical regions. Uncertainty on such data was dealt with in section 2.2.

3 The uncertainty-based data collection strategy

3.1 A procedure to identify the most important uncertainties

Usually, the overall uncertainty of a life cycle inventory is dominated by a few major uncertainties. Likewise, the overall uncertainty of a specific process is typically dominated by one source of uncertainty. All other sources of uncertainty are then of minor importance, and may be ignored. A procedure for identifying the most important uncertainties should therefore begin with those sources of uncertainty that can be expected to be the largest, and can be terminated when further uncertainties can be expected not to contribute significantly to the overall uncertainty.

The procedure takes as a starting point the initial system model in which the roughly defined processes are linked by intermediate product flows and rough order-of-magnitude indication of environmental impact is assigned to each process, e.g. using energy or eco-point indicators. The first step in the procedure is then to perform an error analysis of this system model, identifying and ranking the relative impact of these input-parameters on the total environmental output-parameter(s). An error analysis is most easily done by using statistical software, but may also be performed by manual calculation of the environmental impact indicators relating to each process. The same default uncertainty may be assigned to the input-parameters throughout the system model, but it is preferable to use roughly estimated uncertainties based on worst-case considerations, especially if the identification of the process is itself uncertain. The result of the error analysis is a list of the input-parameters in order of decreasing importance, i.e. in decreasing ability to influence the output. Typically, only a limited number of input-parameters - and thus a limited number of processes - will have a strong influence on the output, and only these processes need to be considered in the further analysis.

The second step in the procedure is – for the important processes identified in the first step - to quantify any uncertainty in the identification of the processes to include (see section 2.1). The size of this uncertainty depends on the uncertainty in the market data underlying the identification and the actual variation between the possible processes to be included. This uncertainty is likely to be the dominating uncertainty for a process, except when the process can be unambiguously identified (due to a low uncertainty in the underlying market data) or when the variation between the possible processes is low (i.e. not likely to affect the result of the life cycle study). Only for these exceptions, there is a need to consider the further steps in the procedure.

The third step in the procedure is to quantify the uncertainty due to mismatch between the desired data and the available data (see section 2.2). This uncertainty will dominate any uncertainty *within* the available data. Only for data which are truly the desired data, it will be relevant – as a last step in the procedure - to quantify the uncertainty within the available data (see section 2.3).

3.2 Reducible and irreducible uncertainties

Uncertainties can often be reduced by obtaining data of improved quality. This is the case when the cause of uncertainty is lack of data, a mismatch between the available and the desired data, or inadequate sampling procedures.

However, in some cases, the uncertainty is inherent to the data, and cannot be reduced by further data collection. This is especially the case:

- For forecasted data (both market data and process data), where the uncertainty is a reflection of the fundamental unpredictability of the future.
- When the actual geographical or temporal position of a specific process is unknown (and unknowable) and therefore has to be simulated by the use of an average covering a larger geographical area or time span.
- When the variation at the site specific level has unknown causes or is caused by uncontrollable phenomena, such as climatic variation.

3.3 Determining the minimum uncertainty in a life cycle inventory

Combining the above distinction between reducible and non-reducible uncertainties with the procedures for identifying the largest uncertainties, as outlined in section 3.1, it appears that the minimum uncertainty of a life cycle inventory will most often be determined by the uncertainty involved in forecasting market data. Only when the most important processes can be unambiguously identified or when the variation between the possible processes is low, the minimum uncertainty may be determined by the uncertainty in forecasting process data, or – when forecasting is not relevant – the uncertainty of average data.

When identified, this minimum uncertainty can be used as a boundary below which it is futile to quantify uncertainties further.

If the result of a life cycle inventory is expected to be inconclusive at the level of the irreducible uncertainties, more detailed data collection should not be initiated. Especially for certain toxic emissions, and even for entire impact categories such as occupational health and animal welfare, the irreducible uncertainty of average data (e.g. resulting from the variation in management between individual plants) may be larger than the variation between different technologies or products. In such instances, it is futile to collect specific average data for these items. This should not be used as an argument for leaving out these items, but rather to report the items with their full range of general uncertainty, so that they can be seen in proportion to the other items in the life cycle study. The consequence of this inclusion may then be a requirement for specific certification of all involved production sites with respect to these items.

3.4 The influence of the decision maker

When the result of a life cycle study is implemented, it will typically affect specific processes. Thus, the more specific the life cycle study is able to identify the processes, which will actually be affected, the lower the uncertainty on the result. By placing specific requirements on the individual processes, the decision-maker may to some extent influence which processes are affected. The uncertainties of the life cycle study may be reduced by specifying the requirements that the decision maker is able and/or willing to make.

The degree to which the decision-maker can reduce uncertainty by specifying requirements to the individual processes depends on:

- the freedom of choice (the degree to which the involved uncertainties are reducible),
- the actual influence of the decision maker (ability to place and enforce requirements),
- the actual effects of the choice, i.e. the decision makers ability to control the effects of the specified requirements (even if the decision maker decides to demand that a specific technology is applied by his suppliers, this may not in itself affect the overall production volume of this technology, as pointed out in Weidema 2002a, b).

3.5 A procedure for reducing uncertainty

A procedure for reducing uncertainty in life cycle inventory should focus first on the largest sources of reducible uncertainty. This implies:

1. Focus on the most important processes, as identified by the procedure in section 3.1.
2. Focus on situations where there is simultaneously a large uncertainty in the market data and a large variation in the possible processes to include.
3. Focus on process data that does not match the desired data, especially mismatches concerning issues that are important for the process in question (cf. section 2.2). Typically, it will be more important to obtain better data for a process where the available data has a structural mismatch (a mismatch with regard to product composition) than for a process with a geographical mismatch, which again will be more important than obtaining better data for a process with a mismatch in age of technology, and so on. However, this hierarchy should be modified by taking into account process- and sector-specific differences in what are important causes of variation.

3.6 Reduction of uncertainty by modelling

When the main determining parameters of an uncertainty is known, it can be eliminated or at least reduced to the uncertainty by which the specific parameter values can be determined. The remaining irreducible uncertainty from measurement errors and minor unknown causes is often below +/-10%.

Examples of models:

- Energy consumption for a specific truck size and engine can be related to traffic conditions and speed (urban traffic versus motorway etc).

- Within +/-25%, the energy use of Dutch households is a linear function of the household income.
- The thermal effeciency of combustion processes is largely determined by the flue gas temperature.
- Variation in nitrogen surplus can be linked to the amount of manure applied.

Also for technological choices, it may be possible to make meaningful models, when the causes of the choice of a specific technology are known. For example, fuel choice is to some extent dependent on the specific industrial sector, the size of plant, and the need for specific and easily controlled temperature (Doms 1993).

However, it is not always easy to identify the causes of variation. For example, in a study of electricity use for oil transport by pipeline, a variation of +/-70% could only be reduced to +/-35%, even when taking into account height difference, pipe diameter, and capacity utilisation (Frishknecht 1996).

Uncertainty may be introduced simply because the way different processes are split up and defined (and thereby how each process is delimited) may vary between data collectors.

Also, even when the causes of uncertainty is known and a model is provided, the size of the actual data needed by the model may not be available, so that some model parameters must be estimated, which in itself introduces an uncertainty.

3.7 Summary of the uncertainty-based data collection strategy

Figure 4 summarises the procedure for identifying and reducing the most important uncertainties, as described in the previous sections in this chapter. The entire procedure may be carried through with worst-case estimates, but the actual uncertainty of the result will be better reflected when using best estimates with a reasonable uncertainty.

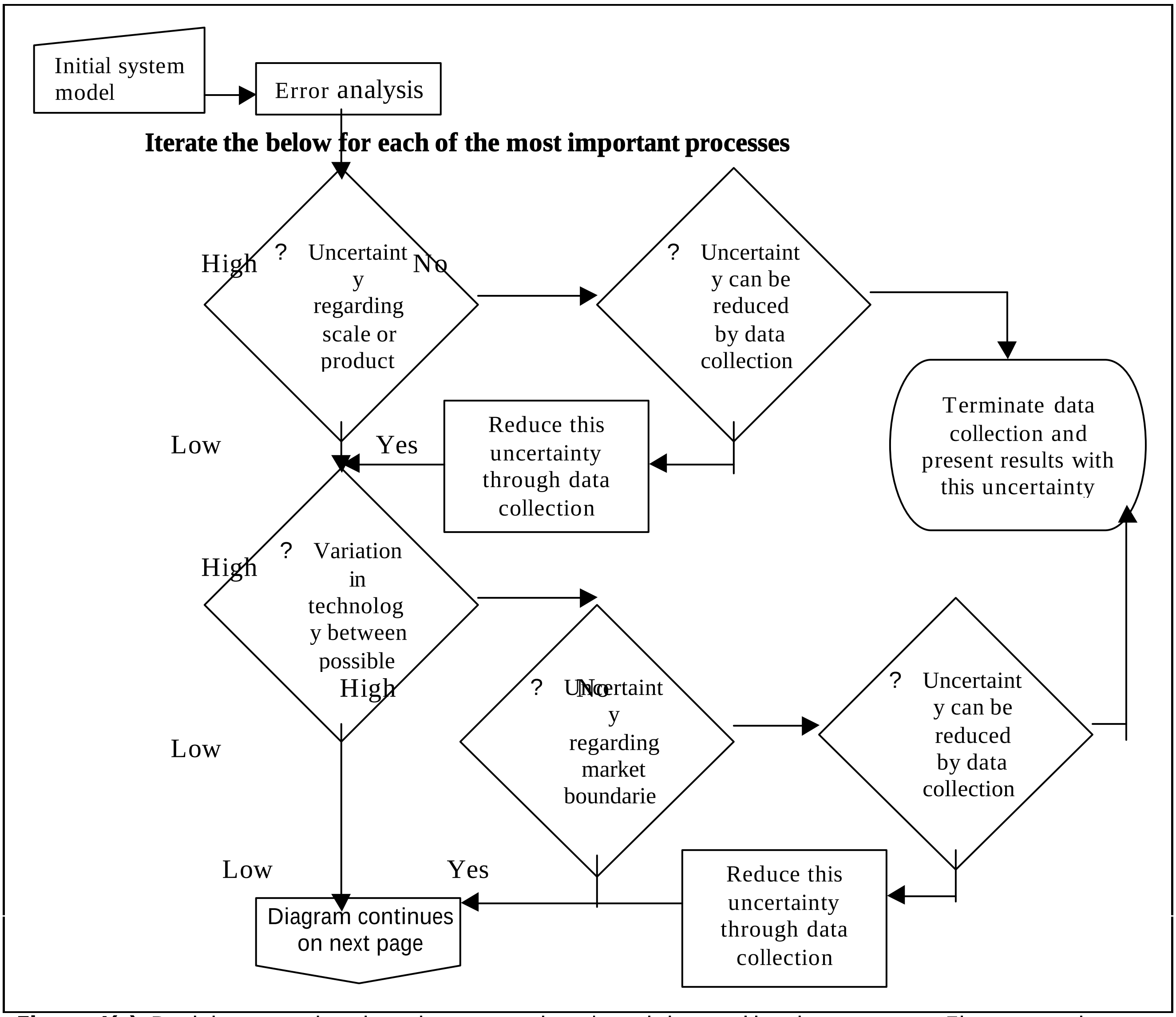

Figure 4(a). Decision tree showing the uncertainty-based data collection strategy. Figure continues on next page.

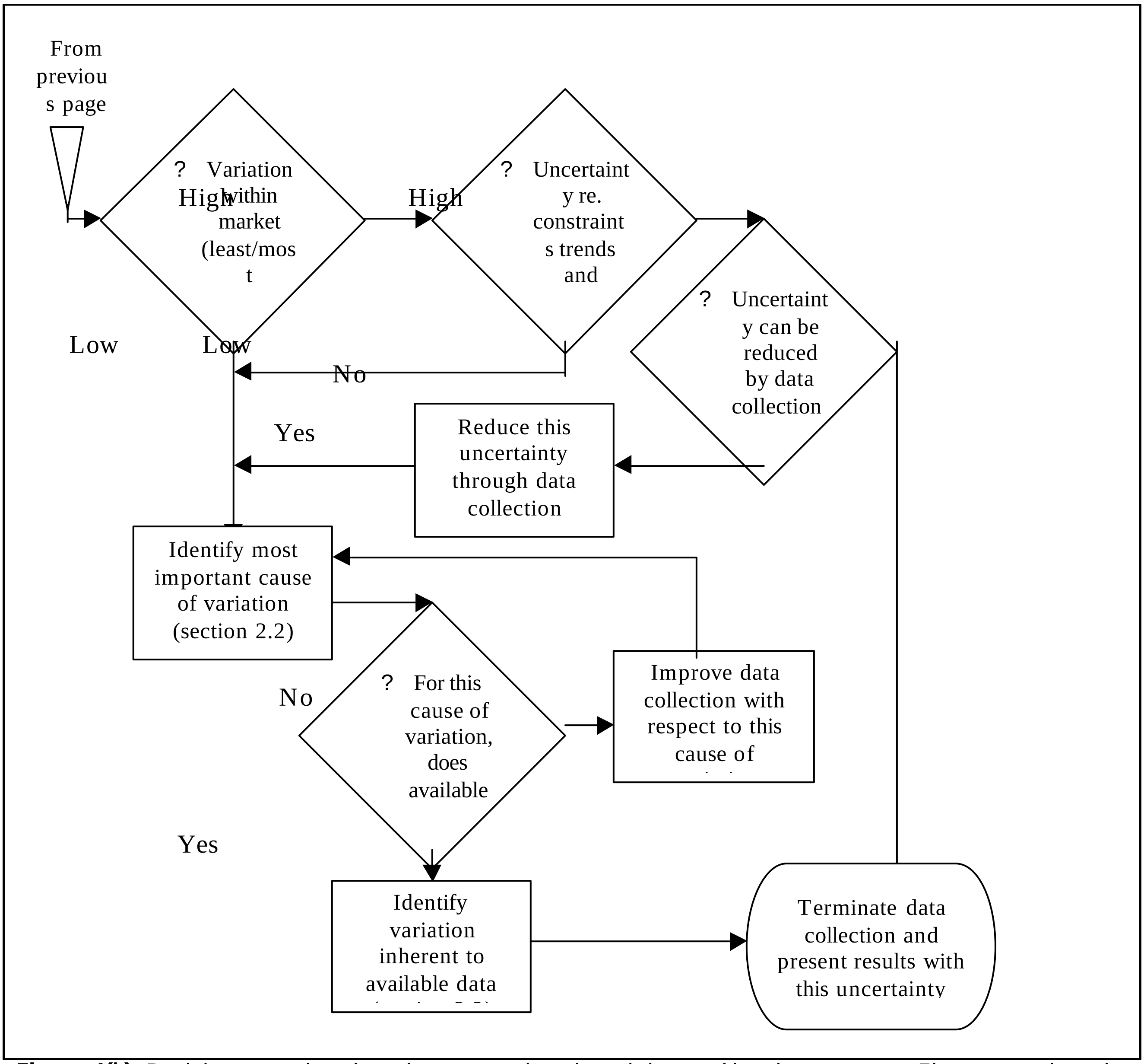

Figure 4(b). Decision tree showing the uncertainty-based data collection strategy. Figure continued from previous page.

3.8 Application-specific circumstances

The dominating source of uncertainty in many life cycle studies is the determination of the relevant electricity production scenarios. This is due to the large variation in efficiency and environmental exchanges from different electricity producing technologies, combined with the dominating role of electricity in the production and use phases of many products.

In life cycle studies with a long time horizon, the dominating uncertainty will be from forecasting, especially with regard to the determination of market constraints and market trends, but also technology development.

Life cycle studies with a short time horizon, the uncertainty will typically be dominated by uncertainty on average data, especially distribution among different technologies at suppliers/customers/waste treatment options (incl. differences in age of technology), but also geographical uncertainty. Life cycle studies with a short time horizon will also be more sensitive to data mismatch and poor data quality, than studies with a longer time horizon.

References

- Ahrens, B. (1998). Beklædnings- og tekstilbranchen i Danmark. Notat. Taastrup: DTI Beklædning og tekstil.
- Alexandratos N. (1995). World agriculture: Towards 2010. Chichester: John Wiley & Sons.
- Aluminum Association, Inc. (1997). Aluminum technology roadmap report. Washington DC: The Aluminum Association.(ATRM-516179).
- Ayres R U, Ayres L W. (1998). Accounting for resources. Vol. 1: Economy-wide applications of mass-balance principles to materials and waste. Cheltenham: Edward Elgar.
- de Beer J, Worrell E, Blok K. (1998). Long-term energy-efficiency improvements in the paper and board industry. Energy 23(1):21-42.
- Berdowski J J M, van der Most P F J, Mulder W, Bloos J P J. Basic oxygen furnace steel plant. Section 040206 in: McInnes (1996).
- Blonk H, Lafleur M, van Zeijts H. (1997). Screening LCA on sugar. Appendix 6 of the report: Towards an environmental information infrastructure for the Dutch food industry – Exploring the environmental information conversion of five food commodities. Amsterdam: IVAM Environmental Research.
- Bouwman A F. (1996). Direct emission of nitrous oxide from agricultural soils. Nutrient Cycling in Agroecosystems 46:53-70.
- BPS. (1998). Håndbog i miljørigtig projektering, Bind 2, Miljødata. Eksempler. Taastrup: BPS-centret, DTI Byggeri. (BPS-publikation 121).
- O´Callaghan P W. (1993). Energy management. London: McGraw-Hill Book Company.
- Cement & Beton (1997). Aalborg Portland, june 1997.
- Dalgaard T. (2000). Farm types - How can they be used to structure, model, and generalise farm data? In: Weidema B P, Meeusen M J G (eds.). Agricultural data for life cycle assessments. Volume 2. The Hague: Agricultural Economics Research Institute LEI.
- Daniëls B W, Moll H C. (1998). The base metal industry: Technological descriptions of processes and production routes; status quo and prospects. Groningen: Rijksuniversiteit Groningen, Interfacultaire Vakgroep Energie en Milieukunde. (IVEM-Onderzoeksrapport no. 92).
- Deslauriers M. (1996). Petroleum products processing. Section 040101 in: McInnes (1996).
- Doms M E. (1993). Inter fuel substitution and energy technology heterogeneity in U.S. Manufacturing. Washington D.C.: Center for Economic Studies. (CES 93-5).
- Eurostat. (1994). Carriage of goods 1991, Road. Luxemburg: Statistical Office of the European Communities.
- Eurostat. (1995). Güterverkehr 1992, Binnenwasserstrassen. Luxemburg: Statistical Office of the European Communities.
- Eurostat. (1997). Energy balance sheets 1994-1995. Luxemburg: Statistical Office of the European Communities.
- Eurostat. (1998a). Carriage of goods 1996, Railways. Luxemburg: Statistical Office of the European Communities.

- Eurostat. (1998b). EU transport in figures. Statistical pocketbook. Luxemburg: Statistical Office of the European Communities.
- Farla J, Blok K. (1998). Cross country comparisons of manufacturing energy efficiency using physical production data: the pulp and paper industry. Utrecht: Department of Science, Technology and Society, Utrecht University.
- Fawer M. (1997). Life cycle inventories for the production of sodium silicates. St Gall: Eidgenössische Materialprüfungs- und Forschungsanstalt. (Bericht Nr. 241).
- Frischknecht R (ed.). (1996). Ökoinventare für Energiesysteme. Zürich: Bundesamt für Energiewirtschaft.
- Gärdenäs S, Malmquist G, Setterwall C, Brännström-Norberg B-M. (1997). LCA elöverföring. Presented to Nordic LCA-seminar in Oslo 1997.10.06-07. Stockholm: Vattenfall AB.
- Gerhartz W. (1986). Ullmann's encyclopedia of industrial chemistry, Volume 12. New York: John Wiley & Sons.
- Gielen D J. (1997). Technology characterisation for ceramic and inorganic materials. Petten: The Netherlands Energy Research Foundation ECN. (ECN-C--97-064).
- Gielen D J, van Dril A W N. (1997). The basic metal industry and its energy use. Petten: The Netherlands Energy Research Foundation ECN. (ECN-C--97-019).
- Gilbreath K, Gupta A, Larson E, Nilsson L. (1995). Background paper on energy efficiency and the pulp and paper industry. ACEEE Summer Study on Energy Efficiency in Industry: Partnerships, productivity and the environment, Grand Island, 1995.08.01-04.
- Halada K. (1998). Database of environment load of 4000 social stocks. http://www.nrim.go.jp:8080/ecomat/ (Last visited: 1998.12.25).
- Halberg N. (1999). Indicators of resource use and environmental impact for use in a decision aid for Danish livestock farmers. Agriculture, Ecosystems And Environment, 76(1):17-30.
- Hanssen O J, Asbjørnsen O A. (1996). Statistical properties of emission data in life cycle assessments. Journal of Cleaner Production 4(3-4):149-157.
- Hekkert M P, Worrell E. (1998). Technology characterisation of natural organic materials, Input data for Western European MARKAL. Utrecht: Department of Science, Technology and Society, Utrecht University. (No. 98002).
- IISI. (1990). Statistics on energy in the steel industry (1990 update). Brussels: International Iron & Steel Industry.
- IISI. (1998). Worldwide LCI database for steel industry products. Brussels: International Iron and Steel Institute.
- McInnes G. (ed.). (1996). Atmospheric emission inventory guidebook. København: European Environment Agency.
- Houghton J T, Meira Filho L G, Lim B, Treanton K, Mamaty I, Bonduki Y, Griggs D J, Callender B A. (eds). (1996). Revised 1996 IPCC guidelines for national greenhouse gas inventories. Vol. 3. Bracknell: UK Meteorological Office.
- Johnson D E, Ward G M. (1996). Estimates of animal methane emissions. Environmental Monitoring and Assessment 42(1-2):133-141.
- Joosten L A J. (1998). Process data description for the production of synthetic organic materials. Utrecht: Department of Science, Technology and Society, Utrecht University. (No. 98028).

- Kirk-Othmer. (1994). Encyclopedia of chemical technology, Volume 12, fourth edition. New York: John Wiley & Sons.
- Kongshaug G. (1998). Energy consumption and greenhouse gas emissions in fertilizer production. International Fertilizer Industry Association Technical Conference, Marrakech, 1998.09.28-1998.10.01.
- Körner A, Müller B, Serra-Verdaguer J, Della Guerra F, Augustin R, Ehrke P. (1998). Establishment of ecological criteria for textile products. Aachen: Deutches Wollforschungs-institut (DWI) / Centro Studi Prato Ingegneria / Teppichforschungsinstitut Aachen.
- Kramer K J, Wiersma G, Gatersleben B C M, Noorman K J, Biesiot W. (1998). Huishoudelijk energiegebruik gemeten: Aard, omvang en veranderingspotentieel. Groningen: Rijksuniversiteit Groningen, Interfacultaire Vakgroep Energie en Milieukunde. (IVEM-Onderzoeksrapport 93).
- Krider D. (2001). The central limit theorem in action. http://www.rand.org/methodology/stat/applets/clt.html. (Last visited: 2001.12.12).
- Laursen S E, Hansen J. (1997). Environmental assessment of textiles. Life cycle screening of textiles containing cotton, wool, viscose, polyester or acrylic fibres. København: Miljø- og Energiministeriet (Miljøprojekt nr. 369).
- Laursen S. (1998). Pers. comm. Danish Technological Institute.
- Leng R A. (1993). Quantitative ruminant nutrition - A green science. Australian Journal of Agricultural Research 44: 363-80.
- Lindeijer E W, Meeusen M J G. (1998). A data conversion tool for environmental life cycle assessments for food. Pp. 149-159 in Ceuterick D: Proceedings of International Conference on Life Cycle Assessment in Agriculture, Agro-Industry and Forestry, Brussels, 1998.12.03-04.
- Lord E. (1992). Modelling of nitrate leaching: Nitrate sensitive areas. Aspects of Applied Biology 30:19-28.
- Martin N, Levine M D, Price L, Worrell E. (1995). Efficient use of energy utilizing high technology: An assessment of energy use in industry and buildings. London: World Energy Council.
- Nielsen P H, Hauschild M. (1998). Product specific emissions from municipal solid waste landfills. Int. J. LCA 3(3):158-186 and 3(4):225-236.
- Nielsen V. (1989). Denmark. Pp. 36-52 in Pick E, Noren O, Nielsen V (eds.). Energy consumption and input-output relations of field operations. Rome: Food and Agriculture Organization of the United Nations. (CNRE Study no. 3; REUR Technical Series 10).
- Nielsen V, Sørensen C G. (1994). Grønne marker. Driftstekniske analyser og modelsimuleringer. Horsens: Forskningscenter Bygholm. (SjF, Beretning, 59). [In Danish with English summary].
- Novem. (1997). Factsheets energy-efficiency: Kunststoffverwerkende Industrie. Utrecht: Novem.
- OECD. (1997). Energy statistics of OECD countries 1994-95. Paris: OECD.
- Pedersen, S H. (1992). Profil af den danske tøjindustri. Herning: Textil- og beklædningsindustrien.
- Petersen E H. (1997). Livscyklusvurdering af bygningsdele. Hørsholm: Statens Byggeforskningsinstitut. (SBI-rapport 272).
- Phylipsen G J M, Worrell E, Blok K. (1995). Parameters affecting energy consumption in the petrochemical industry. In Persson A (ed.):

Proceedings of the 1995 ECEEE Summer Study: Sustainability and the Reinvention of the Government – A Challenge for Energy Efficiency, Latitudes, 1995.06.06-10. Stockholm: The European Council for an Energy Efficient Economy. Also available as Report no. 95049. Utrecht: Department of Science, Technology and Society, Utrecht University.

- Phylipsen G J M, Blok K, Worrell E. (1998). Handbook on international comparisons of energy efficiency in the manufacturing industry. Utrecht: Department of Science, Technology and Society, Utrecht University.
- Pratten N A. (1993). Energieeffizienz in der Europäischen keramischen Industrie. Keramische Zeitschrift 45(2):80-83.
- Pring M, Barbour W, Moody T K. (1996). Preferred and alternative methods for estimating air emissions from boilers. Volume II, Chapter 2 in: EIIP preferred and alternative methods for estimating air emissions. Research Triangle Park: Radian Corporation.
- Rydberg T. (1997). Personal communication. Volvo Technical Developement.
- Samaras Z, Zierock K-H. (1996). Gasoline evaporation from vehicles. Section 070600 in McInnes (1996).
- Schipper L. (1997). Indicators of energy use and efficiency. Paris: OECD/International Energy Agency.
- Siderius H-P, Hedenskog P, Sillanpää, L. (1995). Basic assumptions, test methods and consumer aspects. Background report 1: Washing machines, driers and dishwashers. Group for Efficient Appliances, Working Group - European Energy Network. København: Energistyrelsen.
- Skiba U, Fowler D, Smith K A. (1997). Nitric oxide emissions from agricultural soils in temperate and tropical climates: Sources, controls and mitigation options. Nutrient Cycling in Agroecosystems 48:75-90.
- Statistics Denmark. (1996). Agricultural statistics. København: Statistics Denmark.
- Stevenson C, Coates G. (1997). The central limit theorem and the Quincunx. http://www.users.on.net/zhcchz/java/quincunx/quincunx.1.html and http://www.users.on.net/zhcchz/java/quincunx/quincunx.8.1.html (Last visited 2001.12.12).
- van Tuinen S T, Moll H C. (1992). Metalen in het milieu; Een onderzoek naar de verschillende (milieu)aspekten van metalen. Groningen: Rijksuniversiteit Groningen, Interfacultaire Vakgroep Energie en Milieukunde.
- Vis J C. (1996). Default values for foods manufacturing. Personal communication from J.C. Vis, Unilever to B Weidema, 1996.03.05.
- Webb J, Sylvester-Bradley R, Shepherd M A, Goodlass G. (1997). A review of recent studies to improve fertilizer-N recommendations for cereals. In: Proceedings of the 11th World Fertilizer Congress, Gent, September 1997.
- Webb J, Ellis S, Harrison R, Garwood T W D, Chambers B J. (2000). Nitrogen in arable farming. In: Weidema B P, Meeusen M J G (eds.). Agricultural data for life cycle assessments. Vol 1. The Hague: Agricultural Economics Research Institute (LEI).
- Weidema B P. (1998). Multi-User Test of the Data Quality Matrix for Product Life Cycle Inventory. The International Journal of Life Cycle Assessment 3(5):259-265.
- Weidema B P. (2001). Avoiding co-product allocation in life-cycle assessment. Journal of Industrial Ecology 4(3):11-33.

- Weidema B P. (2002a). Geographical, technological and temporal delimitation in LCA. København: Miljøstyrelsen.
- Weidema B P. (2002b). Market information in life cycle assessments. København: Miljøstyrelsen.
- Weidema B P, Wesnæs M S. (1996). Data quality management for life cycle inventories - an example of using data quality indicators. Journal of Cleaner Production 4(3-4):167-174.
- Wenzel [Christensen] H, Knudsen H H, Hansen J, Hart M, Møller J, Cederholm J, Bendtsen J, Bang O, Andersen I, Kristensen G H, Pedersen BM, Birch H, Henningsen E. (1998). Genbrug af procesvand fra reaktivfarvning af bomuld. København: Miljø- og Energiministeriet. (Miljøprojekt nr. 374).
- World Bank. (1998). EM (energy management) standards.
- Worrell E, Cuelenaere R F A, Blok K, Turkenburg WC. (1994a). Energy consumption by industrial processes in the European Union. Energy 19(11):1113-1129.
- Worrell E, van Heijningen R J J, de Castro J F M, Hazewinkel J H O, de Beer J G, Faaij A P C, Vringer K. (1994b). New gross energy-requirement figures for materials production. Energy 19(6)627-640.
- Worrell E, Smit R, Phylipsen D, Blok K, van der Vleuten F, Jansen J. (1995). International comparison of energy efficiency improvement in the cement industry. Pp.123-134 in Proceedings ACEEE 1995 Summer Study on Energy Efficiency in Industry. Washington D.C.: American Council for an Energy-Efficient Economy.
- Worrell E, Moore C. (1997). Energy efficiency and advanced technologies in the iron and steel industry. Pp. 135-145 in Proceedings ACEEE 1997 Summer Study on Energy Efficiency in Industry. Washington D.C.: American Council for an Energy-Efficient Economy.

Annex A. Analysis of causes and size of variation of the environmental exchanges in some important sectors

The different sections in this annex have been written by different authors and may therefore appear somewhat uneven. The main purpose has been to give a survey of available information that could highlight the causes and scale of variation. We have therefore drawn on many different sources and we have not always followed the information back to the original source. The analysis was performed from 1998 and up to the end of 1999. It therefore does not include sources of information that have become available after this date. All litterature references are included in the reference list of the main report.

We have selected several of the most important trade sectors for closer analysis. The selection has been based on the environmental importance of the sectors, either as important energy consuming sectors (e.g. the steel industry), important emitters of priority emissions (e.g. VOC's from petrochemicals) or as determinants for other sectors (e.g. design decisions in the building sector determines energy consumption and production levels of several important material producing sectors).

Within each trade sector – and depending on the available data – the analysis seeks to:

- show the overall variation (as ranges) when the process is not specified at all,
- explain the different causes of this uncertainty in decreasing order of importance,
- give ranges for how much the uncertainty will be reduced by obtaining more detailed information.

The following sectors were examined:
Annex A1: Agriculture (CPA 01)
Annex A2: Mining and quarrying (CPA 10-14)
Annex A3: Food industry (CPA 15)
Annex A4: Textile industry (CPA 17-18)
Annex A5: Wood and wood products (CPA 20)
Annex A6: Pulp and paper (CPA 21)
Annex A7: Oil refining and petrochemicals (CPA 23.2, 24 and 25)
Annex A8: Chlorine (PRODCOM 24.13.11.11)
Annex A9: Sulphuric acid (PRODCOM 24.13.14.33)
Annex A10: Phosphorous (PRODCOM 24.13.11.60), phosphoric acid
(PRODCOM 24.13.14.55) and phosphorous fertilisers (CPA
Annex A11: 24.15.40)
Annex A12: Soda (PRODCOM 24.13.33.10)
Annex A13: Alkaline silicates (PRODCOM 24.13.52)
Annex A14: Ammonia and nitrogen fertilisers (sub-headings under CPA 24.15)
Annex A15: Glass (CPA 26.1)
Annex A16: Ceramics (CPA 26.2-26.4)
Annex A17: Cement (CPA 26.51)
Annex A18: Lime (CPA 26.52)
Annex A19: Iron and steel (CPA 13.1 and 27.1-27.3)
Annex A20: Aluminium (NACE 13.20.13 and 27.42)
Annex A21: Combustion processes (CPA 40)
Annex A22: Buildings (CPA 45)
Annex A23: Transport (CPA 60-61)
Waste treatment (CPA 90)

Regarding the terminology applied, please see annex B.

A.1 Agriculture (CPA 01)

Agriculture consumes 3-4% of the primary energy consumption in industrialised countries, and is also important from an environmental point of view, because of its large area use and the many diffuse losses of its inputs (notably fertilisers and agrochemicals, but also carbon in the form of CH_4 and CO_2).

Agricultural inputs (both fertilisers, agrochemicals and use of machinery) are mainly related to the cropping area, and not to the product output[6] (yield). This means that a large source of the variation (in inputs and emissions) measured per produced unit is a simple reflection of variations in yield per area.

Thus, the variation in agricultural processes is composed of both variation in yield, variation in inputs for the same (average or expected) yield, and variation in emissions to the environment for the same input.

In the following sections, these three kind of variations are listed together with the main causes of variation. Besides the obvious variation between different crops and animals (section A.1.1), agriculture is more sensitive than industrial

[6] Exceptions to this general rule is the adjustment of fertiliser use to expected yield and differences in energy use for harvesting depending on the actual yield.

processes to differences in natural conditions such as climate, soil conditions, and availability of water resources (section A.1.2). Differences in economic resources, legislation, and management practices also contribute to a large variation between regions (section A.1.3). Even between farms in the same geographical area, with the same crops, the variation can be very large (section A.1.4).

A.1.1 Variation between different crops under the same conditions

Since different crops have different optimum conditions, it is not always meaningful to make general comparisons of the yields of different crops. Because of the inherent variation in yield potential, an extrapolation of expected yields from one crop to another, even under the same conditions and within the same group of crops, e.g. grains, can give uncertainties of +/-50%. For inputs and outputs, similar variations should be expected.

In a Danish study (Nielsen & Sørensen 1994), total fuel use for field operations varied from 30-170 litres per ha with grass seed in the low end and beet crops in the high end. For grain, a variation between 65 and 100 litres per ha was found.

Statistical data allocating fertiliser-N applications to different crops have standard deviations ranging from 0.5% for grain to 6% for vegetables, caused by differences in the sample sizes for different crops (Webb et al. 2000). For animal manure, estimates of application to different crops are uncertain by at least a factor 2.

Nutrient emissions are not directly related to inputs, since it is primarily the nutrient surplus, which is lost to the environment. For example, Lord (1992) report losses in grain crops of 7% of the nitrogen below optimum, but 50% of the surplus N. The same figures for potatoes are 22 and 80% showing the significance of the crop type.

Methane emissions from animals with enteric fermentation range from 3 to 8% of gross energy feed intake, but under most conditions vary only from 5.5 to 6.5% of gross energy feed intake (Johnson et al. 1996). However, gross energy feed intake also varies per unit of product and depends largely on the health and feed status of the animals. In cattle on poor quality forage, a number of essential microbial nutrients may be deficient and under these conditions, reductions in animal methane emissions with a factor 3 (for milk production) to 6 (for meat production) has been obtained by improving the quality and nutrient balance of the animal diets (Leng 1993). This is especially relevant in non-industrialised countries.

A.1.2 Variation due to differences in natural conditions (climate, water availability, and soil)

The same crop will give different yields under different climatic conditions. The main determining climatic factors are solar radiation, temperature and rainfall. Even between regions in a small country like the Netherlands, Blonk et al. (1997) report that solar radiation is responsible for +/-4% differences in yields.

Climatic variation should also reflect itself in annual variation. However, in a study of 20 Danish dairy and pig farms over three years using 10 environmental indicators, Halberg (1999) only found significant yearly variation in one indicator (energy use per kg grain) due to differences in the need for irrigation. Differences in the need for irrigation can be the cause of large variation in energy consumption (+/- 8%; Lindeijer & Meeusen 1998).

Soil type may be an even more important factor in explaining variation, also between productions in the same climatic region. The maximum constraint-free yield in different land classes varies +/-40% (Alexandratos 1995). Blonk et al. (1997) report yield differences of +/- 8% between soils in the Netherlands, and much larger differences in nitrogen consumption patterns and emissions (+/- 30%) as well as in pesticide use +/-18%. Also Webb et al. (1997) found soil type to very important in determining both nitrogen demand (+/-25%) and nitrogen emission. If the soil type is unknown, variation may be up to a factor 2 on average leaching values. Nitrogen leaching for a specific N input and a specific crop depends mainly on soil water holding capacity and (winter) precipitation. When these parameters are used in modelling of nitrogen leaching, the model output values are estimated to be correct within a range of +/-10%.

A.1.3 Geographical variation in economic and legislative conditions and management

Access to adequate amounts of agricultural inputs may be constrained in regions where farmers have less beneficial economic conditions. Legislation may also constrain inputs (especially nitrogen and pesticides) leading to consequent reductions in output. Finally, differences in the educational and advisory services may lead to different management practices in different regions. It is difficult to separate what the part of an observed geographical variation is due to natural conditions and what part is due to economic, regulatory and management differences. A rough estimate is that a variation of +/- 25% should be ascribed to the latter causes.

A.1.4 Variation between farms and variation not treated elsewhere

In Denmark, average yields per area have been found to increase with increasing farm size (Statistics Denmark 1996).

Fuel consumption for a specific field operation is influenced by many factors, e.g. type and structure of the soil, weather conditions, earth moisture, landscape, crops, tractor type (2WD/4WD), tractor size, relation between tractor and implement, driving technique, tractor driver, etc. Nielsen (1989) reports fuel consumption measurements for many specific field operations in Denmark given in litres of fuel per hour or hectare with coefficients of variance generally between 10 and 30%. This is confirmed in Nielsen & Sørensen (1994), where also similar data for harvesting and field spraying are given, with coefficients of variance of 40% and 80%, respectively. It should be noted that the studies were performed on fairly flat terrain and uniform soils. Thus, variation would probably have been larger if a larger variation of climate, soil and landscape types had been included. For harvesting of grass, Nielsen & Sørensen (1994) found fuel consumption to vary from 6.0 to 10.6 l/t of dry matter depending on the harvesting technique.

In spite of the large variation on fuel consumption, averages for an entire country calculated by models using the above values showed very good correspondence (within a few percent) to total fuel consumption for the agricultural sector.

Nitrogen surplus was found by Dalgaard (2000) to vary less than +/-10% between cattle farms, but more than +/-30% between pig farms and between farms without animals. On animal farms, the variation was closely correlated to the amount of animal manure applied. Dalgaard also found that variation between management practices (organic/conventional) was an important explanatory factor.

For fertiliser use, large differences in efficiency can be observed. Worrell et al. (1994b) estimated improvement possibilities, reducing the present use of 220 kg N/ha in the Netherlands to 128 kg/ha, mainly by larger adherence to fertilisation recommendations and improvements in maintenance of fertiliser spreading equipment. However, such large amounts of fertilisers are not used in general. With a European average of 67 kg N/ha only a 10-25% improvement in efficiency can be expected, unless more widespread use of biological N-fixation is introduced (Gielen 1997).

Ammonia losses depend mainly on the type of fertiliser applied and the way it is applied, and to a lesser extent on soil type (soil pH for mineral-N, infiltration rate for manure-N), meteorological conditions, and time of application in the cropping cycle. Estimates of ammonia emissions typically lie in the range of 10-40 kg per ha with an estimated uncertainty of +/-30% for manure-N and +/-50% for fertiliser-N (Webb et al. 2000).

Current emission factors for N_2O are ranging from 0.25 - 2.25% of N inputs (Bouwman 1996). The magnitude of N_2O emissions depends on the form of fertiliser applied, the crop type, soil temperature and soil moisture content. However, it has not yet been possible to derive different emission factors for different fertilisers, crop or soil types.

NO emissions depend mainly on the mineral N concentration in the soil and Skiba et al. (1997) estimate emissions ranging from 0.003 to 11% of applied fertiliser-N, with a median of 0.3%.

A.1.5 Conclusion

The variation in the yield is generally smaller, the more that is known about the crop type, the climate, and the soil. The variation in the data for inputs and emissions can only be significantly reduced when more detailed knowledge is available on the individual farm practices, notably fuel use, fertiliser type, and manure handling. This makes it difficult to provide a general guideline for reducing uncertainties in agricultural data for life cycle assessments.

A.2 Mining and quarrying (CPA 10-14)

For mining of raw materials, there is a parallel to agricultural products, in that the inputs and emissions are not linearly related to the yield. Thus, the yield and ore grade plays an important role in the variation of inputs and emissions per produced unit.

Different minerals are mined at different concentrations (with overburden and gangue weighing from 0.1 to 3000 times the mineral or metal content) and from ores of different composition and degrees of contamination (giving different types of waste) and using different benefication methods and chemicals. Energy consumption data from van Tuinen & Moll (1992, cited in Daniëls & Moll 1998) range from 10 MJ/kg for boron, chromium and manganese to 1200-1800 MJ/kg for cobalt, silver, thallium, yttrium, and zirconium, with outliers of 3.5 MJ/kg for arsene and 6 GJ/kg for beryllium and 70 GJ/kg for gold. Thus, it is seldom meaningful to extrapolate from one mineral or metal to another, and even for the same mineral or metal, the use of average values may be questionable.

The same mineral or metal may also be mined from different ore grades. For example, bauxite is presently mined in concentrations from 25 to 60%, copper in grades between 0.3 and 2%, and potassium in grades from 9 to 30% K_2O-equivalents. As a result, energy consumption may vary +/- 50% between mines and the use of grinding materials and flotation chemicals vary by a factor 2 to 5 (Daniëls & Moll 1998).

Also, the same mineral or metal may be mined from open or closed (underground) mining, using different amounts of explosives, causing different amounts of overburden, and different reclamation methods (propping up or levelling and replanting), and using different benefication methods (e.g. KCl is separated from the ore by either recrystallisation or flotation, the latter being less energy demanding, but not always applicable depending on the ore type).

Sulphur dioxide is a common by-product from mining, and may in some cases be emitted (mainly in non-industrialised countries), in other cases recovered with efficiencies ranging from 96 to 99.8%. Similarly, particulate removal may vary from 20 to 99%, mainly depending on local regulatory demands and the age of technology.

Carbon-gasses (CO_2 and CH_4) are released from some mining operations. For potassium mining, Gielen (1997) cite a variation from 30-100 m^3 gas per Mg K_2O-equivalents. The composition of the gas (i.e. the distribution between CO_2 and CH_4, which is very important for its climate forcing potential) may also vary. From coal mining, Frischknecht (1996) cites OECD for a range of methane emissions from 10-20 cubic metres per Mg extracted coal ore. Up to 90% of these emissions could be recovered by adequate measures, but in practice less than 30% is recovered.

For oil and gas drilling, Frischknecht (1996) reports a diesel consumption per metre between 25 and 200 litres for onshore drilling and between 250 and 1250 litres for offshore drilling. The drilling depth varies from 1000 to 5000 metres.

Natural gas is found together with oil in quantities ranging from 100 to 600 m3 per 1000 kg oil and 0.05-1% of this is vented and 10-20% flared in the field, while 40-85% is utilised as net natural gas production (Frischknecht 1996). For pure gas fields, the flaring is only 0.2-0.3% of the produced quantity. The variation is geographically dependent and may therefore be substantially reduced with knowledge of the geographical location of the oil field.

A.3 Food industry (CPA 15)

Vis (1996) investigated datasets from 80 plants under the Unilever food industry and found coefficients of variance of 50% for energy consumption and 220% for COD and other emissions. Even in sub-sets (e.g. for margarine factories only) similar variation in data was found. Vis suggests that the cause of variation is mainly due to differences in management, since the technology is assumed to be fairly even within this one company.

A.4 Textile industry (CPA 17-18)

This sector has a relatively high water consumption and consumption of chemicals compared to the size of the sector (measured in turnover or employees), while the energy demand is relatively low.

Synthetic fibres and cotton fibres constitute about equal percentages and the majority (app. 90%) of the total world production ($42 \cdot 10^9$ kg fibres) in 1994. The consumption of textiles (production + import - export) in Western Europe constitute app.15% and the highest consumption is observed in Asia (excl. China/Taiwan), corresponding to app. 50% of the total consumption of textiles (Körner et al. 1998).

The main exporting countries (fabric and apparel) in 1992 were Hong Kong, China, Italy and Germany (Körner et al. 1998). For products on the Danish market the main exporting countries are China, Portugal, Italy and Hong Kong (Pedersen 1992). Imported textiles constitute app. 64% of the Danish market in 1997. It is not possible to obtain statistics on the distribution on different fibre types, but Denmark is known as a cotton and polyester country (Laursen 1998). More than 50% of the dyeing in Denmark is cotton dyeing (Wenzel et al. 1998).

The variation in energy and material consumption as well as in emissions is related to:

- The raw material (natural fibres or man-made fibres)
- Processes/product type/production technology
- Maintenance in the use phase

A.4.1 Variation in the raw material phase

The fibres (raw materials) used in the textile industry have very different origin. The fibres may be divided into three main types:

- Natural fibres (e.g. cotton, wool)
- Artificial fibres (e.g. viscose)
- Synthetic fibres (e.g. polyester, polyamide)

Natural fibres, e.g. cotton and wool, have their origin in the agricultural sector, the manufacture of viscose is part of the pulp and paper sector, whereas the manufacture of the synthetic fibres is a part of the petrochemical sector.

Therefore, very different processes are involved in the manufacture of textile fibres. The consumption of energy and materials as well as the nature of emissions to the environment varies accordingly. When comparing e.g. the energy consumption among the fibre types a range of 8 MJ/kg (wool) to 158 MJ/kg (acrylic) of energy is required in the production of raw material (Laursen & Hansen 1997). Thus, a very important factor in reducing the uncertainty on textile data is knowledge of the fibre type (raw material) of the studied object.

Examples of the variability and nature of consumption and emission from each of the 3 sectors is summarised below in tables A4.1-4

Table A4.1. **Cotton.**

	pr. kg cotton fibres
Water consumption	7,000 -29,000 l
Energy consumption	48,65 MJ
Consumption of fertilisers	0-560 g
Consumption of pesticides	0.007-1.45 g

Ref. Laursen & Hansen (1997).

Table A4.2. **Wool.**

	pr. kg wool fibres
Water consumption	130-170 l
Energy consumption	8 MJ
Consumption of pesticides	0.1-2.5 ml
Consumption of detergents and soda	6.5-50 g
Emissions of BOD	460 g
Emissions of grease	450 g

Ref. Laursen & Hansen (1997).

Table A4.3. **Viscose.**

	pr. kg viscose fibres
Water consumption	640 l
Energy consumption	71MJ
Consumption of C_2S	310 g
Emissions of C_2S	20-30 g
Emissions of COD	276 g

Ref. Laursen & Hansen (1997).

Table A4.4. **Polyester.**

	pr. kg polyester fibres
Energy consumption	109MJ
Consumption of chemicals (e.g. TiO_2)	0.2-20g
Emissions of e.g. COD	7,4 g

Ref. Laursen & Hansen (1997).

The above tables demonstrate the importance of knowledge of the fibre type. Within each of the 3 types (natural, artificial and synthetic), specific uncertainties can be identified and the variation may be attributed to very different causes as discussed in chapter 2 of the main report.

The dominant causes of variation for natural fibres lies within differences between natural regions: Climate, soil type and raw material quality and secondly on differences between administrative regions, predominantly labour costs.

For the man-made fibres, geographic variation is primarily related to differences in administrative regions: regulatory differences (environmental taxes, threshold on emissions), processes and differences between plants: age of technology, effectiveness of control.

A.4.2 Textile production

The use of technology in textile sector is relatively low, except for manufacture of technical fibres. The sector is not technology leading and the basic technologies are the same world-wide. However, several different processes are involved in the production phase of textiles. They may roughly be divided into:

- Dry processes: Yarn manufacture, knitting and weaving (fabric), making up, incl. sewing. cutting, drying, dry finish
- Wet treatment: Pre-treatment, dyeing or printing and wet finishing.

Energy consumption (electric and thermal) and water consumption in the different processes are summarised below in table A4.5.

Table A4.5. **Energy and water consumption in textile processing (from Körner et al. 1998)**

Process	Electric consumption [MJ/kg]	Thermal consumption [MJ/kg]	Water consumption [l/kg]
Dry processes			
Yarn	0.6-6.0	0.02-3.60	0.14-3.2
Fabric (knitting, weaving)	2.4-12.5	1.6-15.6	1.0-1.4
Wet processes			
Dyeing	0.5-6.0	6.1-23.0	14-95
Finishing[1]	1.1-6.8	15.0-28.8	27.6-75.3
Total consumption in production	4.6-31.3	22.7-71.0	43.5-176.1
Care and maintenance[2]	24.8		510

[1] It is not possible to distinguish between wet or dry finishing
[2] Based on 30 wash cycles

The overall variation in energy consumption (electric and thermal) when the process is not specified at all may, as seen from the table, be app. 28 to 102 MJ/kg (0.6 to 22 MJ/kg for the dry processes, 6.5-30 MJ/kg for wet processes).

For the dry processes, it is not essential to distinguish between different fibre types because the fibres may undergo essentially the same processes, depending on the requirements/purpose of the end use of the textile. The variation in dry processes is primarily explained by the specific process technology involved in the production (e.g. knitting or weaving).

For wet treatment, on the other hand, variation depends on both the specific processes involved, e.g. batch or continuous, and the fibre type with associated production lay out. Thus, knowledge of the specific processes and production layout is essential to diminish uncertainty.

Other less important causes for variation are:

- Type of technology (process), incl. auxiliary chemicals, dyes etc.
- Age of technology,
- Management (operational optimisation) and education.

Geographic variation in consumption and emissions for comparable technologies (processes) and products are mainly related to legislation/environmental costs and labour costs. Pollution prevention measurements and cleaner technologies are generally applied as a result of regulatory demands and a higher degree of automation if the labour costs are high.

Cutting introduces a remnant (spill-percentage) of fabric/textile from 6-25% (Laursen & Hansen 1997). The amount of remnant is strongly related to the complexity of the product e.g. bed linen vs. trousers and shirts. As a consequence, the geographic variation is considered to be low.

Labour costs has a significant influence on the degree of automation in the making up of textiles. Variation in energy consumption for making up may thus vary geographically caused by different labour costs.

To reduce uncertainty related to the production of textiles, it is necessary to have a detailed insight in the layout and specific technologies involved in the production process.

A.4.3 The use phase: care and maintenance

During the use of textiles the most important variation in energy consumption is caused by consumer behaviour i.e. preferences for laundry/cleaning (wash vs. dry cleaning, machine wash vs. hand wash). Consumer behaviour may be explained by:

- Customs and culture,
- Price of technology,
- Availability of water and energy supply.

The energy consumption of an appliance (washing machine, dryer) is determined by product features (programmes available), consumer behaviour (frequency of wash) and situational aspects (inlet temperatures, used detergent etc.). In a study by Siderius et al. (1995), the specific energy consumption between different efficiency classes of washing machines on a European level varies between 0.159 to 0.560 kWh/kg (60°C cycle), while the country specific averages have been calculated as 0.26 kWh/kg and it is stated that are in the range of ± 10%.

In the use phase the availability of resources such as energy and water as well as the cost resources may vary between natural and administrative regions. Also, customs and culture may cause a substantial variation, due to differences in preferences for cleaning methods (laundry vs. cleaning; machine vs. wash by hand).

A.4.4 Temporal differences

According to Wenzel et al. (1998), the technological development within the textile sector is related to competition on the market. The most important parameters for development of cleaner technology is as a consequence related to:

- Price of resources (materials, water, energy)
- Environmental taxes (legislation)
- Time consumption (labour costs)
- Specialisation/capacity utilisation
- Demands on fast delivery (Just in time)

The development of cleaner technology includes both technological development and development of dyes with enhanced performance. The factors mentioned may also be driving forces for implementation of cleaner technology/new technology in the textile industry.

Due to an increase in international agreements on environmental issues regarding e.g. emissions it is predicted that legislative demands and regulatory instruments slowly will be harmonised on a global level. Therefore, a push towards development and implementation of cleaner technologies in the textile sector may be expected on a global scale. Variation in consumption and emission of energy, water and chemicals may in consequence diminish, when comparing the individual technologies. However, the variation between different processes is likely to remain.

Concerning labour costs, there is a trend towards an increase in the degree of outsourcing (specialisation) and production in countries where the labour costs are low. Ahrens (1998) states that for Danish companies there is an ongoing process towards (in order of present importance):

- Outward Processing Traffic (OPT). Poland and the Baltic countries (sewing and packaging)
- Cut, Make, Trim (CMT). Eastern and Central Europe (whole production, except fabric, design, quality etc.)
- Sourcing out from own design (SOD): The Fareast and Turkey (whole production, fabric etc, except design and quality)

Labour costs often determines the geographic location of production (c.f. Ahrens 1998) and the technology choice in the textile sector. Labour costs are closely related to the standard of living and the GNP (gross national product). The development in standard of living in less developed countries may be expected, but the time scale of these changes can not be established at present. Variations caused by differences in labour costs may, therefore, be expected to persist over long time.

A.5 Wood and wood products (CPA 20) (Based on Hekkert & Worrell 1998)

The main energy consuming process in wood products manufacture is drying. Besides the difference between hardwood and softwood, where the energy requirement for drying is approximately the double for hardwoods, factors influencing the variation are mainly the initial water content and the degree of heat recovery. Modern drying plants with heat pumps and variable speed can have an energy use of 60% compared to older equipment. The most common drying technique is using ventilation with hot air. This is rather energy in-efficient, but the more energy-efficient closed systems are based on electricity and their primary energy consumption is therefore typically in the same range as the open systems based on thermal energy. Other techniques, both the very low-intensive outdoor drying and the high-intensive techniques, such as vacuum or infrared drying, are little used either because of quality problems or high energy requirements.

The sawmill industry in Europe is characterised by many small mills with limited ability to install new technology.

Durability may differ between tree species and depending on wood preservation technologies. Wood preservation have important toxicological aspects and it is therefore an important information whether (and how) the wood has been preserved. Durability (and suitability for different purposes) may also be increased by modern wood modification techniques, such as high-pressure steam compression.

For wood based panels, figures for the energy consumption from different authors agree within less than 10%. Wood based panels include different amounts of glue (from 2% for plywood to 6-9% for particle boards) and the gross energy requirement of the glues differ from 70 to 140 MJ/kg. The average is probably in the very low end of the stated intervals.

A.6 Pulp and paper (CPA 21)

With 4% of the industrial energy consumption, the pulp and paper industry is the fourth largest energy consuming industry. De Beer et al. (1998) report ranges of energy consumption of 2.3-8.6 MJ heat and 0.36-1.0 kWh electricity per kg paper. The variation mainly depends on differences in energy efficiency of the mills rather than on differences between paper types, although obviously some paper types require more processing than others. The drying process consumes about 90% of the heat, while the electricity is mainly used for pumping and ventilation. If ozone is used for bleaching, this is often produced on-site, resulting in a 5-10% increase in electricity consumption (Gilbreath et al. 1995 cited in Phylipsen et al. 1998).

Worrell et al. (1994b) and Farla & Blok (1998 cited in Phylipsen et al. 1998) show that national averages of energy efficiency in 1988 was less than 25% above best practice in most European countries and Japan, while Sweden was 50% above and for Australia, Denmark, Greece, the U.K., and the USA, the energy consumption was approximately 100% above best practice. For Denmark, Greece, and the U.K., this can probably be ascribed to small mills with low capacity utilisation, while for Sweden, Australia and the USA the cause is less obvious. It may be related to the local availability of cheap energy sources.

Hanssen & Asbjørnsen (1996) analysed emission data from 27 sulphate pulp mills in Sweden and found differences between the mills with coefficients of variance between 34% (for NOx) over 50-60% (for BOD, COD and Tot-P) to approximately 100% (for SO_2, AOX and Tot-N). The emissions were generally reduced over the studied 8-year period, but the variation between mills was not reduced significantly. The coefficients of variance within one plant from year to year were much lower, generally 20-50%. Only for AOX, which is specifically related to chlorine bleaching, which is a technology being phased out during the investigated period, the within-plant variation was still high. The authors conclude that differences in management is a more important cause of differences between plants than differences in technology.

Contrary to expectations, Hanssen & Asbjørnsen (1996) found integrated mills (producing both pulp and paper) to have less emissions per kg pulp than stand-alone mills. Hekkert & Worrell (1998) suggest that when the pulp is produced at a different location than the paper, an additional energy consumption for pulp drying of approximately 25% should be needed at the pulp mill, while de Beer et al. (1998) claim that there is no significant differences in specific energy consumption between integrated and non-integrated mills.

A.7 Oil refining and petrochemicals (CPA 23.2, 24 and 25)

The chemical industry accounts for 10% of the primary energy consumption in Europe (half of which is consumed in the petrochemical industry) and a major part of the VOC emissions.

A.7.1 Oil refining

The energy requirement of a refinery depends largely on the complexity of its product mix. Simple distillation and thermal cracking will take 2-4% of the feedstock input, while a refinery producing more complex products may require up to 10% of the feedstock input. Thus, a comparison of gross refinery data is not meaningful.

The crude distillation unit is the largest energy consumer of a refinery. Its energy consumption may be influenced by the crude oil type with as much as 25% corresponding to 4-8% of the total primary energy consumption of the refinery operations. Since no data are available on the crude oil types used, nor on the specific energy consumption of specific processes within the refineries, this uncertainty cannot be further reduced.

An allocation of the overall energy consumption of a specific refinery to the individual processes is discussed in Worrell et al. (1994b) and Frischknecht (1996) resulting in allocation factors based on weight from 0.5 for the heavy fractions (bitumen and diesel) to 2 for the lighter fractions (gasoline and naphta).

The age of the refinery and its technology is of importance. Especially, the degree of heat recovery and co-generation is important. A variation of +/-50% can be deduced from the data reported in Frischknecht (1996). Variation in national averages in the EU was below +/-10% with the exception of Ireland, which had an average 50% above the EU average (Phylipsen et al. 1998).

Part of the reported variation (up to 30%) in statistical data may be due to different interpretations of the data on crude oil input and product mix (Phylipsen et al 1998).

The VOC emissions vary between 0,25 and 2 kg/Mg refinery-output (based on Deslauriers (1996) and Frischknecht (1996). These emissions should also be allocated among the individual processes and products of the refinery. For this purpose, it may be useful to note the following information from Deslauriers (1996):

- 26-75% of the VOC-emissions come from storage and loading,
- 25-53% is caused by evaporation from valves, process-equipment etc. Out of this, 67% comes from valves and 11% from pumps. The evaporation is higher for gas and light oil fractions than for the heavier fractions (factor 3-100 for valves and factor 2-5 for pumps),
- 5% is actual process-emissions from cracking,
- A maximum of 22% comes from treatment of wastewater (mainly from process-wastewater).

This information may be combined with the fact that evaporation is larger for the lighter fractions, which in general are also more processed, giving allocation factors from 0.3 to 1.2 for the different fractions.

A.7.2 Steamcracking

The energy consumption of the steamcracking depends on the feedstock. Measured per product output (olefines, aromates and fuels) the energy consumption increases from 6MJ/kg for the heavier to 12 MJ/kg for the lighter feedstocks. Furthermore, the temperature of the process has an influence on the energy consumption. Since the product mix also changes with the feedstock and temperature, and energy consumption is typically reported in relation to the main output (ethylene) only, it is difficult to compare energy consumption data for processes operating with different feedstocks and temperatures.

Differences in feedstock and temperature are for a large part geographically dependant (e.g. naphta is the main feedstock in Europe, while ethane is the main feedstock in the USA). However, these differences only explained 1-2 MJ/kg of an observed 4-5 MJ/kg difference between West Germany and the East European countries (Phylipsen et al. 1995). The remaining 3-4 MJ/kg may be explained by a lower degree of process integration and waste heat recovery, but up to 2MJ/kg could also be caused partly by lack of retrofitting and a higher share of small plants in the East European countries.

For the same feedstock and temperature, Phylipsen et al. (1995) estimate the causes of variation as follows:

- Older plants could have 20-30% higher specific energy consumption than new plants, but they are typically retrofitted so that the difference is kept below 10%.
- Differences in energy consumption as a result of differences in plant size are most important (up to 10%) between very small and small plants, while it is less than 5% between large and very large plants.
- Differences in plant design is of minor importance (+/- 1%) under western technology, but can be more important when comparing e.g. with Russian technology (-10%).
- Differences in maintenance and operation is estimated to account for 5% variation in energy consumption.
- Reduction in capacity utilisation from 100% to 75% will increase the specific energy consumption with 3-5%. Average capacity utilisation typically vary between 80 and 90%.

A.7.3 Polymerisation

For the polymerisation of olefins several processes are available. The energy requirement depends on the polymer (from 1.5 to 7 MJ primary energy per kg and polymerisation of PET and PUR even being exothermic) and to lesser extent (+/- 15%) on the process (Joosten 1998). For PVC the differences between processes are reported to be much larger, but also connected to quality differences.

A.7.4 Plastics processing

Energy consumption for plastics processing may vary from the low energy consuming processes like extrusion (1.4-1.9 MJ electricity per kg plastic) over injection moulding (3.2-7.2 MJ electricity per kg plastic; smaller items being more energy intensive) to thermoforming (13 MJ electricity per kg plastic). (Joosten 1998 based on Novem 1997)

A.8 Chlorine (PRODCOM 24.13.11.11)

Chlorine is produced together with sodium hydroxide and hydrogen by electrolysis of sodium chloride. Three different technologies are used (mercury, diaphragm and membrane processes) which differ widely in energy consumption and environmental exchanges. Thus, average data are not representative of any of the specific processes and it is not meaningful to express the variation between the technologies as an uncertainty. The membrane process, which has the lowest energy requirement (9.2-9.8 MJ/kg Cl_2 against the 11.8 MJ/kg for the mercury process and 12.5 MJ/kg for the diaphragm process at 50% NaOH concentration) and lowest environmental impact, is presently replacing the older technologies (Joosten 1998). Variation between country averages of specific energy consumption may also be explained by differences in the degree of penetration of these technologies (Phylipsen et al. 1998). The variation of the energy requirement of the membrane process is mainly due to differences in current densities and cathode overvoltage, where technological improvements are still made (Joosten 1998).

A.9 Sulphuric acid (PRODCOM 24.13.14.33)

Sulphuric acid is produced from elemental sulphur with a net export of steam of between 0 and 6 MJ/kg H_2SO_4. The variation is mainly due to differences in the age of the plant (Kongshaug 1998).

A.10 Phosphorous, phosphoric acid, and phosphorous fertilisers (CPA 24)

Phosphorous is produced from phosphorus carbonate ore with concentrations from 30 to 40% P_2O_5-equivalents of phosphorous. The ore is sintered at 1000 °C, mixed with a SiO_2 source (gravel) and coal and melted in an electric oven resulting in the process:

$$2\ Ca_3(PO_4)_2 + 6\ SiO_2 + 10\ C \rightarrow 6\ CaSiO_3 + 10\ CO + P_4$$

This process is very energy consuming (approximately 85 MJ/kg P). Part of the energy used in this process (up to 25 MJ/kg P) can be recovered when P_4 is oxidised to P_2O_5 (Kongshaug 1998).

High-purity phosphoric acid (H_3PO_4) can be produced from P_2O_5, but the normal production route is the wet process:

$$Ca_3(PO_4)_2 + 3\ H_2SO_4 \rightarrow 3\ CaSO_4 + 2\ H_3PO_4$$

Different wet-process routes exist, where the least energy consuming leave more contaminants in the gypsum, which is emitted or deposited (radioactive contaminants make the gypsum unusable for other purposes).

A.11 Soda (PRODCOM 24.13.33.10)

Soda (Na_2CO_3) can be produced from NaCl by the Solvay process resulting in low density (light) Solvay soda or from NaOH resulting in high density (heavy) soda. The latter process is significantly less energy consuming (3 MJ/kg versus 9 MJ/kg for the Solvay process). Also, the Solvay process requires as a raw material the energy intensive quicklime (see section A.17) to form $CaCl_2$.

A.12 Alkaline silicates (PRODCOM 24.13.52)

Fawer (1997) report ranges for energy and raw material consumption for 5 different production routes for sodium silicate at 13 plants covering 93% of the European production of alkaline silicate. For energy consumption, the ranges vary from 40% (for mixing and melting) to 135% (for spray drying) of the average values. The ranges tend to be skew (e.g. -13%/+27%, -42%/+93%), although the number of plants is too small to make general conclusions. Fawer suggests that the causes of the uncertainty are differences in capacity utilisation and age of technology. Raw material use is ranging from 0-1.5% of the average for most processes, up to +5% for metasilicate. The averages are all very close to the theoretical minimum.

A.13 Ammonia and nitrogen fertilisers (sub-headings under CPA 24.15)

Nitrogen fertiliser production is responsible for 1.2% of the global primary energy demand. Worldwide, ammonia is produced by the same general technology, the Haber-Bosch process, and 80% of the production uses the same feedstock route, namely steam reforming of natural gas. In Europe, 90% of the ammonia is produced from natural gas. The remaining production uses partial oxidation, a route requiring 40-50% more energy but being more flexible with regard to feedstocks. Typically, oil residues and coal are used. (Phylipsen et al. 1998)

Since the technology is homogenous, the differences between energy consumption and emissions of individual plants can only be attributed to differences in efficiency between plants, which again can mainly be explained by differences in the age of the plants. The differences are quite large. In 1994, the best practice plant in Europe, using the integrated AMV-process, had an energy consumption of 28 GJ/t NH_3, while the European average was 35 GJ/t NH_3 and national averages varied from 29 in Spain to 43 in Greece (Worrell et al. 1994b). Obviously, this reflects an even larger variation at plant level.

The average energy requirement for production of urea from ammonia in Europe is estimated to 9 MJ/kg N with modern plants at 7.2 MJ/kg N (Kongshaug 1998).

The conversion of ammonia into nitric acid is an exothermic process, for which the amount of heat recovered show a large variation (5-11 MJ/kg N according to Kongshaug 1998). Emissions of N_2O from the process can be substantial. Abatement technology has been developed, and should be able to reduce the emission with 70-85% (Kongshaug 1998). Thus, in present day practice, it is likely to find plants with anywhere between 15 and 100% of the original emissions (0.03 kg N_2O or 9 kg CO_2-equivalents per kg nitric acid).

A.14 Glass (CPA 26.1)

Many types of glass with different mechanical and optical properties are made. However, unless exceptional chemical durability and heat resistance is required, soda-lime glass is used, i.e. for containers, flat glass, pressed and blown ware, and lighting products, accounting for nearly 90% of all glass produced world-wide.

The most important raw materials (measured by weight) are sand, soda ash, limestone/dolomite and cullet (waste glass). In addition to these materials, small amounts of other raw materials as well as various colorants may be used.

Soda-lime glass articles are manufactured by melting the raw materials at 1300-1500 °C and forming into the articles. This is nearly always followed by annealing of the glass products, i.e. reheating to a temperature sufficiently high to relive any stress, followed by slow cooling. Some products additionally require secondary or finishing operations, in the form of cutting, grinding, polishing, heat treatment, sintering, chemical treatment, or surface coating.

The energy efficiency of the melting process varies due to differences in technology and size (Gielen 1997). Continuous melting, which is the most common, is much more energy efficient (3-8 MJ/kg melt) than pot melting (from 17 MJ/kg for large pots up to 100 MJ/kg for small pots). The larger the tanks, the lower the specific energy requirement. This is likely to be the main cause of the variations between glass works cited in Gielen (1997) from a study covering Germany, Austria and Switzerland showing a variation of fossil fuel fired glass works from 3.4 to 7.9 MJ/kg for both container glass (mean 4.8 MJ/kg) and flat glass (mean 5.7 MJ/kg), while the mean for the electric melts was 4.2 MJ/kg.

Tanks where electrical energy is applied directly to the molten glass are more energy efficient than the more common gas-fired regenerative furnaces, which have an efficiency about 30%. All-electric melting units have significant environmental advantages, because they heat the melt from the bottom, which not only results in high energy efficiency but also in low volatilisation. For example, in a fluoride-containing batch as much as 40% volatilisation might occur with gas firing compared to 2% with electric (Gerhartz 1986).

Oxygen, when substituted for air, reduces the fuel requirement by 30% (Kirk-Othmer 1994). This option is especially relevant for small furnaces.

Regenerative burners, which are used in all modern plants, also increase energy efficiency.

Another important factor which influences energy use is the amount of cullet used in the production process. Up to 70% of the raw materials may be substituted by cullet (broken and crushed glass from imperfect articles, trim, and other waste glass from the production process as well as recycled glass). The use of cullet not only reduces the use of raw materials (1 kg of cullet will substitute 1.2 kg of raw materials), but also the amount of energy, since the cullet does not require energy for chemical reactions, which leads to a reduction in energy demand of up to 0.8 MJ/kg for a melt with 70% cullet (Gerhartz 1986). The saved raw material also gives an energy saving, especially for soda, which has a specific energy requirement of approximately 10 MJ/kg.

Finally the energy use per unit finished product depends on the amount of glass which is wasted during cutting of the glass into products of the required size. The amount of waste differs significantly for different products, and may for some products be as high as 70% (Kirk-Othmer 1994).

The amounts of liquid effluents and solid waste from glass production are limited. The most significant emissions related to the production of glass are the airborne emissions, which mainly occur during the melting of glass. Most airborne emissions are due to the fuels used. However, during melting significant amounts of CO_2 are released from the raw materials (not when melting cullet). Substituting raw materials with cullet therefore significantly reduces CO_2 emissions (using 70% cullet will reduce CO_2 emissions by apx. 140 kg per Mg melted glass).

Other factors, which may significantly influence emissions, are cleaning of flue gases, e.g. removal of dust. Pollution prevention measurements and cleaner technologies are generally applied as a result of regulatory demands.

A.15 Ceramics (CPA 26.2-26.4)

Different qualities of ceramics (with different strength and water absorption rates) have different energy requirements due to different burning temperatures and residence times in the kilns/ovens. For example, Gielen (1997) cite the average energy requirement for Dutch bricks to vary from 0.7 MJ/kg (for inside cladding) over 2.9 MJ/kg (for the standard outside cladding brick) to 3.3 MJ/kg (for pavement bricks). Energy requirement for unglazed tiles is approximately 6 MJ/kg, for table stoneware 10 MJ/kg, for sanitary stoneware 30 MJ/kg and for china 70 MJ/kg (Pratten 1993).

Modern tunnel brick kilns have an energy consumption 20% lower than the older designs, and further reductions seems feasible. Large kilns also use less energy per produced unit than smaller kilns.

Weight of bricks may vary depending on their degree of perforation (up to 60% perforation is possible) with a corresponding variation in energy requirement. Gielen (1997) estimate that some of this saving is offset by an increased mortar requirement resulting in a corresponding increased consumption of 0.1 kg cement per kg saved brick.

A.16 Cement (CPA 26.51)

The cement industry is responsible for 1-2% of the global primary energy consumption and more than 2% of the CO_2 emissions (Worrell et al. 1995).

The term cement is used to designate many different kinds of finely grounded, non-metallic, inorganic materials that are used as hydraulic binders or adhesives. Portland cement is the most widely used cement for construction concrete. All Portland cements are produced with the same basic technologies world-wide. The mineral raw materials (clay and Calcium carbonate) are mixed and ground to a fine powder (dry processing) or a slurry (wet or semi-dry processing). For semi-dry processing the raw materials are wet ground, and then dried before sintering. The ground raw material mixture is slowly heated in a cement kiln to the sintering temperature of 1450 °C, to produce clinker (65% CaO). In Europe, clinker is predominantly burnt in rotary kilns. Cement is then produced by finely grinding either clinker alone (Portland cement) or clinker with other materials, which are capable of hydraulically hardening, e.g. pozzolana, glassy blast-furnace slag, and coal fly ash from power-plants (modified Portland cement). Gypsum or anhydrite may be added in small amounts (~5%) as fillers. These substances are inert or have weakly expressed hydraulic, latent hydraulic, or pozzolanic properties.

Coal is the most widely used fuel, with oil as a second. For the production of grey cement an increasing amount of other combustible materials are used, such as waste tyres, waste oils and contaminated waste wood, since the contaminants of e.g. heavy metals are sealed in the clinker, and the high temperature and pH prevents the formation of toxic flue gases. Production of white cement, however, requires a fuel that burns without slag and ashes, which would otherwise colour the cement.

Energy requirements for the production of clinker vary significantly depending on the processing method. Wet processing requires up to twice the amount of energy required for dry processing (with semi-dry processing somewhere in between). In general, the dry processing is used in all modern plants. However, the natural water content of the raw materials determine which production method is used, and energy use may therefore vary significantly between different geographical regions. Aalborg Portland - the only Danish producer of cement - produces almost all cement used in Denmark. Aalborg Portland uses both wet and semi-dry processing. The dry method is not used because of the natural high water content of the raw materials.

Another factor that may influence energy use is the degree of utilisation of waste heat from the cement oven.

The production of clinker being the main energy consuming process in cement manufacture, the overall energy requirement for cement vary significantly depending on the amount of clinker used in the cement. Cement may e.g. contain up to 40% fly ash, or up to 85% blast-furnace slag. Consequently, energy use for the production of Portland fly-ash cement and Portland slag cement may be respectively up to 40% and 85% lower than for cement made from clinker alone. A further advantage of reducing the amount of clinker in the cement is that it also leads to an equivalent reduction in the CO_2 release from the calcination process ($CaCO_3 \rightarrow CaO + CO_2$).

Gross energy requirements for Danish produced cement, measured as higher heating value, varies from 5.8 to 9.7 MJ/kg depending on the type of cement (BPS 1998). This is caused both by differences in processing type and the amount of clinker pr. Mg cement. The current average in the EU is 3.7 MJ/kg (Worrell et al. (1994a) with a current minimum of 3.1 MJ/kg (theoretical minimum 1.8 MJ/kg).

The types and amount of waste products which may be used as raw material (e.g. fly ash, slag, gypsum from desulfuring of power-plant exhaust gases) or fuel (e.g. waste oil) depend on the types of waste materials available in the region where the cement plant is located, and may therefore vary significantly between geographical regions (Worrell et al. 1995). Some Danish cement types contain up to 15% flyash and gypsum from desulfuring of power-plant exhaust gases (Cement & Beton 1997), while blast-furnace slag is not used in Danish cement. In countries with a low potential of waste materials (like Ireland and in Latin America), a barrier for the increased use of waste materials is the lack of standards for blended cements. Also traditions and building codes for strength testing may limit the development of the market for blended cements. In the USA, some of the potentially available waste materials may currently be treated in a way that makes them less suited for blended cements (Worrell et al. 1995).

Including the effects of the different amount of clinker, the national average energy requirements for cement vary from 2.1 MJ/kg in The Netherlands (27% clincker) to 7.3 MJ/kg in Russia (72% clincker) with a potential for energy savings ranging between 0 and 57% of current consumption.

The amounts of liquid effluents and solid waste from cement production are limited. The most significant emissions related to the production of cement are the airborne emissions, which mainly occur during the burning of clinker. Most airborne emissions are due to the fuels used, but for dust and CO_2 (due to the calcination process) the raw materials are a significant source also.

Other factors, which may significantly influence emissions, are cleaning of flue gases, e.g. desulfuring of exhaust gases, and removal of dust. Pollution prevention measurements and cleaner technologies are generally applied as a result of regulatory demands.

The summary effects of the above, and including the effect of different fuels (coal, oil and combustible waste materials), is a variation of gross emissions for Danish cement of (BPS 1998):
0,9-1,5 t CO_2 per t cement
0,8-3,3 kg SO_2 per t cement
3,3-7,2 kg NO_x per t cement

A.17 Lime (CPA 26.52)

Quicklime (CaO) is produced by heating calciumcarbonate ($CaCO_3$) under the release of CO_2. The released CO_2 is often fixed again when the product is subjected to oxidation. Only when incorporated into glass, in steel conversion (where a glass-like slag is formed) and in flue-gas desulphurisation (producing gypsum), this CO_2 fixation does not occur.

Gielen (1997) cite energy requirements of lime kilns in 1986 varying from 3.7 MJ/kg CaO to 6.9 MJ/kg CaO. Today, the upper limit is probably 5 MJ/kg, with an average at 4 MJ/kg.

A.18 Iron and steel (CPA 13.1 and 27.1-27.3)

Steel production requires about 5% of the world's primary energy demand (Martin et al.1995).

Three technologies are used for steel production (IISI 1990 cited in Phylipsen et al. 1998):

- the old (however, in 1990 still used for 17% of the world production, mainly in East Europe) and energy intensive open hearth furnace (OHF) or Siemens-Martin route, based on pig iron or scrap,
- the most common (57% of the world production in 1990) and most energy efficient basic oxygen furnace (BOF) route, based on pig iron to which only a minor part of scrap can be added (depending on the heat released from the oxidation of the carbon in the pig iron),
- the electric arc furnace (EAF) route, based on scrap (24% of the world production in 1990) or direct reduced (DR) iron ore, which is still a minor route (2% of the world production in 1990) but increasing in Latin America and Asia, despite this route being more energy intensive than the BOF route.

Within each of these routes, differences in specific energy consumption are caused by:
- differences in raw material, i.e. iron ore or scrap, in that iron ore reduction requires 7 MJ energy per kg iron,
- differences in product mix (slabs, hot or cold rolled products), which amounts to maximum 5 MJ/kg,
- process efficiency.

Differences in process efficiency between plants are large. The energy input to the blast furnace varied from 12.3 MJ/kg in Japan to 15.3 MJ/kg in the USA in 1994 (Worrell & Moore 1997). In Europe, national averages adjusted for the product mix and a uniform 10% scrap content, showed a variation in specific energy consumption of the BOF process (i.e. not the entire route) up to 8 MJ/kg higher than the best practice, which was 14 MJ/kg slab (Worrell et al. 1994b). Global average data for the entire route (from cradle to factory gate) for hot rolled coil from 26 steel mills (IISI 1998) showed a range of 12 MJ/kg between the lowest and highest primary energy consumption, with a coefficient of variance of 12%. Similar data for the EAF route from 11 sites showed a range of 12 MJ/kg and a coefficient of variance of 40%. This corresponds with the theoretical relation between the range and the coefficient of variance (for sample size 30, the theoretical coefficient of variance is ¼ of the range and for sample size 10, the theoretical coefficient of variance is 1/3 of the range).

Explanatory factors for the differences are (Phylipsen et al. 1998):
- the degree of combined heat and power production,
- material efficiency,
- integration of mills,
- the use of energy-efficient technologies such as:
  - thin slab casting, which may save 50% or 1-1.2 MJ/kg of the hot rolling energy requirement (Gielen & van Dril 1997),
  - continuos operating EAFs with preheating of the scrap save around 15% of the electricity compared to batch-wise operation furnaces (Daniëls & Moll 1998),
  - direct coal injection in the BOFs, which is also very significant for the air emissions, since coking - together with ore preparation - is the most polluting process in the primary steel production. Differences between coking processes are also large. The Jewell-Thompson coke oven reduces emissions compared to conventional ovens with 5% for CO and NOx, 25% for SOx, 50% for total suspended matter, 70% for particles below 10μm, 80% for VOC (Daniëls & Moll 1998).

IISI (1998) report average data on resource use and emissions for the entire route (from cradle to factory gate) for several steel products, e.g. for hot rolled coil from 26 steel mills following the BOF route. The reported coefficients of variance are:
9% for raw material consumption (iron ore),
15% for CO_2,
28% for sulphides to water and 37% for NO_x
65%-75% for ammonia to water and SO_2 to air,
90-100% for water emissions (e.g. fluoride, cyanide, nickel ions and indicators as Tot-N and COD),
around 150% for phenol and zinc ions to water.

The similar data for 11 steel mills following the EAF route show the same variation in material inputs (CV 9% for scrap, 35% for limestone) and many of the emissions, but larger variations for some of the energy related emissions (CO_2, NO_x). This can mainly be explained by the smaller sample size and by differences in the electricity scenarios for the 11 mills (since the energy supply of the EAF route is mainly in the form of electricity) .

Berdowski et al. (1996) report order of magnitude differences and more in BOF emissions of heavy metals to air based on different literature sources. This is in line with the above measured uncertainties for metal ions to water.

It should be noted that different speciality steels, coated steels, and alloys may have very different data for energy consumption and emissions, depending on the specific processes and metals involved. For example, both tin-free steel and tinplated coil has an extra energy consumption of 9 MJ/kg compared to hot rolled coil (IISI 1998). Examples with respect to alloys and speciality steels can be found in a Japanese database (Halada 1998) showing especially large energy use for Nickel benefication and large NOx emissions from mining of Nb, Mo, V and W alloying elements.

A.19 Aluminium (NACE 13.20.13 and 27.42)

Primary aluminium production is electricity-intensive. Variation in electricity consumption is reported from 13 to 17 kWh/kg with 15 kWh/kg as the US average (Aluminum Association, Inc. 1997, Gielen & van Dril 1997). Production cells normally have current efficiencies ranging from 85 to 95%. The lowest electricity consumption is still the double of the thermodynamic minimum, but only improvements of 5-10% is foreseen as a result of larger cells, continuous anodes, and improved bath composition (Gielen & van Dril 1997).

A.20 Combustion processes (CPA 40)

Combustion is central to any energy consuming process and is causing a major part of the total global emissions to the environment.

The thermal efficiency of the combustion is largely determined by the technology and operating conditions determining the flue gas temperature. Thermodynamic calculations for high quality hard coal, oil, and natural gas, shows the thermal efficiency to vary from approximately 96% at a flue gas temperature of 400 °K (123 °C) over 87-88% at 600 °K (323 °C) to approximately 79% at 800 °K (523 °C). NO_x reducing technology and the use of excessive oxygen may decrease the efficiency by a few percent (O´Callaghan 1993). The loss of heat from stoke depends on technology (primarily isolation) and is approx. 3-5% for normal operation. If the stoke is not used continuously, the loss of heat rise remarkably (O´Callaghan 1993).

For electricity generation, conversion efficiencies depend on fuel type. Natural gas in combined cycle can give efficiencies of 60% while coal and oil typically have efficiencies of 40-50%. Since technology development is ongoing, the age of the plant is of large importance. Phylipsen et al. (1988) cite a study of OECD statistics for the year 1990 showing actual average regional conversion efficiencies ranging from 22 to 44% with a global average of 34%. Variation between countries and individual plants are even larger.

Some emissions depend on fuel type. This is true for CO_2 emissions and metals emissions, which depend on the origin of the fuel. Also SO_2, VOC, and particle emissions depend on type of fuel, but may be reduced by different combustion or cleaning technology. NO_x depends entirely on combustion and cleaning technology.

For coal combustion, different boiler emission control technologies may remove 5-80% of NO_x emissions, 30-95% of SO_x emissions, and 97-99% of coal particulate emissions. From oil combustion, control technologies may remove 0-90% of NO_x emissions and 70-90% of SO_x emissions. For natural gas combustion, different boiler emission control technologies may remove 50-80% of NO_x emissions. (Pring et al. 1996)

Because of this large variation in emission control, the regulatory emission limits may often be the best estimate for actual emissions of these substances, in the absence of direct measurements. Examples of regulations on emissions of SO_2, NO_x and particles in Western Europe are shown in table A20.4.

Table A20.1 below provides emission ranges from different types of fuels. The low value of some of the ranges implies emission control by technical precautions (except for SO_2 of gas oil and for waste). Even lower values may occur depending on the efficiency of control technology, as given above.

Table A20.1. Emissions in g per MJ fuel combusted – i.e. input energy

Fuel type	Reference	CO_2	SO_2	NO_X	Particles
Gas oil	Frieschknecht 1996	74	0,025[2]-0,06	0,025-0,06	0,0001
	McInnes 1996	73-74	0,025[2]-0,45	0,055-0,5 (1,5)[1]	-
Fuel oil	Frieschknecht 1996	78-79	0,04-1,2	0,16	0,012-0,05
	McInnes 1996	76-78	0,015-1,7	0,075-0,5 (1,9)[1]	-
Natural gas	Frieschknecht 1996	56-59	0,0005	0,015-0,05	0,0001
	McInnes 1996	55-61	0	0,03-0,36 (1,2)[1]	-
Coal	Frieschknecht 1996	(80)[1] 91-95	0,1-0,5	0,05-0,2	0,05-0,2
	McInnes 1996	93-99	0,025-4	0,05-0,6	
Renewable, wood	Frieschknecht 1996	100-125	0	0,02-0,17	0,007-0,36
	McInnes 1996	-	<0,04	0,003-0,3 (1)[1]	-
Renewable, waste	Frieschknecht 1996	110-140	-	-	-
	McInnes 1996	-	-	0,14-0,28	-

[1] Deviant value

[2] Calculated from EU regulation 1996, max. 0,05% S in gasoil

It follows from the above that very important factors in reducing uncertainty on combustion data is knowledge of the fuel choice and the combustion and control technology.

The fuel choice is to some extent dependent on the specific industrial sector, the size of plant, and the need for specific and easily controlled temperature. When fuel choice is not obtainable directly from the involved enterprises, an estimate of the choice may be based on statistical data giving average distributions per sector, see table A20.2. These distributions may vary between countries with price and availability of the individual fuels.

Table A20.2. Distribution of fuels consumed in industry, 1994 (Eurostat 1997, OECD 1997).

Region	Fuels	Iron & steel		Chemicals		Mineral materials		Machinery etc.		Food & tobacco		Pulp & paper	
		ktoe	%	ktoe	%	Ktoe	%	Ktoe	%	ktoe	%	ktoe	%
OECD (1995)	*Hard coal*	*12312*	*19*	*10190*	*79*	*29015*	*94*	*2570*	*81*	*5452*	*88*	*6417*	*96*
	Coke	*51695*	*81*	*498*	*4*	*927*	*3*	*525*	*16*	*259*	*4*	*96*	*1*
	Lignite	*28*	*0*	*2130*	*17*	*1038*	*3*	*93*	*3*	*499*	*8*	*162*	*2*
	Solids	64035	49	12818	11	30980	39	3188	9	6210	13	6675	10
	Gasoil	*2198*	*22*	*3521*	*21*	*4598*	*30*	*4470*	*44*	*5415*	*41*	*1861*	*14*
	Fueloil	*6080*	*60*	*12414*	*74*	*8919*	*58*	*2187*	*21*	*7251*	*54*	*10292*	*77*
	LPG	*1817*	*18*	*819*	*5*	*1885*	*12*	*3600*	*35*	*697*	*5*	*1153*	*9*
	Petro, all	10443	8	21590	18	21280	27	10980	29	13397	28	13666	20
	Nat.gas	54845	42	86095	71	25729	33	23290	62	24585	52	26054	38
	Renewable	71	0	944	1	575	1	20	0	3339	7	22007	32
	Sum	129394	100	121447	100	78564	100	37478	100	47531	100	68402	100
EU 15	*Hard coal*	*6029*	*25*	*2389*	*73*	*6338*	*82*	*363*	*50*	*903*	*72*	*1155*	*85*
	Coke	*17704*	*75*	*216*	*7*	*371*	*5*	*261*	*36*	*178*	*14*	*29*	*2*
	Lignite	*15*	*0*	*660*	*20*	*985*	*13*	*97*	*13*	*168*	*13*	*169*	*12*
	Solids	23748	53	3265	11	7694	28	721	6	1249	8	1353	8
	Gasoil	*422*	*11*	*611*	*10*	*923*	*17*	*4514*	*64*	*1444*	*25*	*284*	*10*
	Fueloil	*3232*	*83*	*5080*	*83*	*3859*	*70*	*2113*	*30*	*4002*	*68*	*2500*	*84*
	LPG	*235*	*6*	*409*	*7*	*704*	*13*	*449*	*6*	*403*	*7*	*177*	*6*
	Petro, all	3893	9	9133	30	8520	31	3735	29	5854	36	3019	18
	Nat.gas	16759	38	17651	58	10666	39	8468	65	8835	54	6641	40
	Renewable	4	0	490	2	447	2	5	0	447	3	5586	34
	Sum	44404	100	30539	100	27327	100	12929	100	16385	100	16599	100

Note on Natural gas: The figures include derived gas which is approx. 50% for iron & steel and maximum a few percent for other sectors

When geographical location is known, local statistics may be obtained on the average fuel choice per industrial sector, see table A20.3 for an example.

Table A20.3. Country specific distributions of fuels consumed in industry, 1994 (Eurostat 1997, OECD 1997) .

Country	**Fuels**	Iron & steel		Chemicals		Mineral materials		Machinery etc.		Food & tobacco		Pulp & paper	
		Ktoe	%	Ktoe	%	ktoe	%	Ktoe	%	ktoe	%	ktoe	%
Germany	*Hard coal*	*1516*	*24*	*1054*	*62*	*1183*	*51*	*43*	*24*	*156*	*42*	391	*73*
	Coke	*4696*	*75*	*36*	*2*	*197*	*9*	*46*	*25*	*66*	*18*	29	*5*
	Lignite	*15*	*0*	*618*	*36*	*929*	*40*	*93*	*51*	*151*	*40*	116	*22*
	Solids	6227	49	1708	20	2309	36	182	4	373	11	536	24
	Gasoil	*117*	*8*	*250*	*27*	*353*	*29*	*905*	*78*	*730*	*57*	*146*	*30*
	Fueloil	*1323*	*91*	*685*	*73*	*671*	*55*	*55*	*5*	*455*	*35*	*271*	*55*
	LPG	*19*	*1*	*2*	*0*	*207*	*17*	*206*	*18*	*97*	*8*	*73*	*15*
	Petro, all	1460	12	955	11	1439	22	1167	27	1283	38	547	24
	Nat.gas	4931	39	5822	69	2656	41	3038	69	1696	51	1125	50
	Renew Able	0	0	0	0	0	0	0	0	0	0	60	3
	Sum	12618	100	8485	100	6404	100	4387	100	3352	100	2268	100
Denmark	*Hard coal*	*0*	-	*0*	-	*202*	*91*	*0*	-	*75*	*95*	1	*100*
	Coke	*0*	-	*0*	-	*21*	*9*	*0*	-	*4*	*5*	0	*0*
	Lignite	*0*	-	*0*	-	*0*	*0*	*0*	-	*0*	*0*	0	*0*
	Solids	0	0	0	0	223	40	0	0	79	15	1	2
	Gasoil	*8*	*100*	*10*	*24*	*44*	*26*	*45*	*73*	*87*	*41*	*6*	*25*
	Fueloil	*0*	*0*	*29*	*71*	*123*	*74*	*11*	*18*	*108*	*51*	*12*	*50*
	LPG	*0*	*0*	*2*	*5*	*0*	*0*	*6*	*10*	*16*	*8*	*6*	*25*
	Petro, all	9	21	45	58	232	42	66	55	213	41	25	42
	Nat.gas	34	79	33	42	98	18	53	44	223	43	32	54
	Renew Able	0	0	0	0	1	0	2	2	0	0	1	2
	Sum	43	100	78	100	554	100	121	100	515	100	59	100
Sweden	*Hard coal*	*335*	*36*	*1*	*14*	*167*	*92*	*0*	*0*	*15*	*83*	44	*86*
	Coke	*586*	*64*	*4*	*57*	*15*	*8*	*15*	*100*	*3*	*17*	0	*0*
	Lignite	*0*	*0*	*2*	*29*	*0*	*0*	*0*	*0*	*0*	*0*	7	*14*
	Solids	921	54	7	3	182	51	15	5	18	6	51	1
	Gasoil	*27*	*9*	*40*	*31*	*23*	*13*	*119*	*48*	*38*	*21*	*25*	*5*
	Fueloil	*130*	*43*	*82*	*64*	*66*	*39*	*83*	*33*	*101*	*56*	*432*	*87*
	LPG	*146*	*48*	*6*	*5*	*82*	*48*	*48*	*19*	*41*	*23*	*41*	*8*
	Petro, all	304	18	129	64	172	48	250	88	181	59	499	13
	Nat.gas	470	28	50	25	6	2	19	7	108	35	39	1
	Renewa ble	0	0	15	7	0	0	0	0	0	0	3305	85
	Sum	1695	100	201	100	360	100	284	100	307	100	3894	100

Note on Natural gas: The figures include derived gas which is approx. 50% for iron & steel and maximum a few percent for other sectors

Geographical location may also allow a more specific determination of regulatory requirements. Examples of regulations in different countries are provided in table A20.4.

Table A20.4. Examples of emission regulation on combustion processes (World Bank 1998).

Country/ Region	Plant and fuel type	Capacity MWh	As to	Regulation
EU	Combustion plants, new by 1990	>50	NO_x	max. 650 mg/m^3*
	Combustion plants, new by 1990 Coal, <10% volatiles	>50	NO_x	max. 1300 mg/m^3*
	Combustion plants, existing	>50	NO_x	total NOx must not increase more than 94% from 1980 to 1993/98
	Combustion plants, new by 1990	<100	SO_2	max. 2000 mg/m^3*
	Combustion plants, new by 1990	>500	SO_2	max. 400 mg/m^3*
	Combustion plants, new by 1990 Indigenous high/variable sulphur coal	>500	SO_2	min. 90% S removal
	All point sources by 1990	>500	particles	max. 18 g/GJ fuel input
Germany	New conventional boilers	10-50	NO_x	max. 400 mg/m^3*
	New and existing boilers	>300	NO_x	max. 200 mg/m^3*
	Existing and new plants Hard coal and lignite	<1	S	max. coal S content 1%
	Existing utility and industrial plants	>300	SO_2	max. 400 mg/m^3*
	Point sources, coal and lignite	>50	particles	max. 18 g/GJ fuel input
USA	Industrial plants by 1986 FBC (fluidised bed), coal	>29	NOx	max. 740 mg/m^3*
	Industrial plants by 1986	>29	SO_2	max. 740 mg/m^3* and min. 50% S removal
	All point sources		particles	max. 50 mg/m^3*

* normal cubic metres, i.e. at 0°C, 101.3 kPa, dry flue gas at 6% excess O_2, except for USA

Geographical location may also allow a more specific determination of fuel prices, which may affect the fuel choice. Coal and biomass of low quality – i.e. high moisture, ash and maybe sulphur content - may be preferred due to low price with resulting decrease of combustion efficiency and increase in CO_2, particle, and possibly SO_2 emissions, c.f. the intervals in table A20.1. Low price fuel oil may have a high sulphur content resulting in increased SO_2 emission. Low price natural gas may have a high content of e.g. N_2 resulting in decreased combustion efficiency and increased CO_2 emission.

Further to geographical information, the uncertainty on combustion data may be reduced by obtaining information on boiler technology (the ranges in table A20.1 reflects different technologies) and specific fuel composition.

Capacity utilisations within normal ranges (25-100%) has little influence on conversion efficiency, but low degree of utilisation leads to decreased efficiency. At 5% utilisation, the conversion efficiency may drop from e.g. 75% to 50% (O´Callaghan 1993).

Poor maintenance may lead to a 10% decrease in efficiency, while emissions, especially concerning particles and VOC may increase considerably.

IPCC emission factors for N_2O have ranges for coal from 0 to 10 kg/TJ energy input with 1.4 kg/TJ as the recommended value (Houghton et al. 1996). For oil, the recommended emission factor is 0.6 kg/TJ, with a range from 0 to 2.8 kg. The range is smallest for natural gas (0 to 1.1 kilograms), with 0.1 kilogram as the suggested factor.

A.21 Building (CPA 45)

The construction sector is an important materials consumer. It represents approximately one tenth of the Gross Domestic Product in Europe and about the same fraction of the total CO_2 emissions. Most of these, however, do not relate to the construction phase itself, but to the building materials, some of which have been described separately (e.g. wood and wood products, glass, ceramics (bricks), cement, iron and steel, aluminium). Furthermore, heating and cooling of buildings cause approximately one third of the total primary energy consumption in Western Europe.

As more new buildings are built than old buildings demolished, buildings materials are increasingly stored in the existing building mass.

Differences in constructions can be significant. Gielen (1997) suggest that material use may be reduced with 40-50% by optimisation of current practices. Circular shapes of structural building elements can also save 50-80% of the material use. However, due to lacking availability of special building element shapes, conservative building standards, lacking knowledge regarding advanced calculation methods, and traditional consumer preferences may limit actual variation to 10%. Design and safety criteria may vary considerably between countries. For hollow steel sections, Gielen (1997) give an example where Japanese design criteria for regtangular sections result in a materials consumption 12% below that of the EU, while for bending loads on circular sections, EU and Japan require a factor 2.7 more material used than in the USA. A survey of concrete standards show an even larger variation for the same application (e.g. 15-40 mm for the minimum cover to reinforcement, minimum 200-380 kg cement per cubic metre, and a strength requirement varying from 25 to 40 N/mm^2). Similar examples can probably be found for other design, durability and safety criteria.

The use of improved quality materials may also reduce materials consumption significantly. Gielen (1997) estimate potential CO_2 savings of 20% by the use of engineered wood products, 10-20% by the use of high strength steel, 15-20% by the use of high strength concrete and 10-15% by the use of hollow bricks.

The energy use for heating and cooling depends on use characteristics, insulation, ventilation and thermal mass of the building. Each of these factors may vary considerably both within countries and between countries and average values will often be irrelevant for life cycle assessments.

A.22 Transport (CPA 60-61)

In the OECD countries, transport of goods account for 10-12% of final energy use, out of which 9-17% is for maritime transit between countries (Schipper 1997).

The energy consumption for the transport of a specific good of a specific weight depends on two variables:

- the transport distance, and
- the energy intensity per Mgkm.

Emissions are to a large extent linearly related to fuel use, although some important exceptions are mentioned in the last part of the section on energy intensity.

A.22.1 Transport distance

In the following, only transport within EU and border crossing to EU's nearest markets is considered, unless otherwise specified. The calculations are based on information and figures in (Eurostat 1994, 1995, 1998a, 1998b) unless otherwise specified. The distance is calculated by dividing the work of transport (Mgkm) with the weight of transported goods (Mg). Since the information of transport work is not always available for international transport of goods, a long transport distance may be indicated by a high share of tonnage transported internationally.

The average transport distance per Mg of goods within EU is 150 km (Eurostat 1998b). 90% of the goods are transported within one country, of which 60% are transported 0-49 km and 22% are transported 50-149 km (Eurostat 1998b). The average distance for national transport within the EU countries is roughly 80 km. The remaining 10% of the goods are transported internationally of which the average distance for inter-EU transport is roughly 500 km. Transports involving flight and ocean-going shipping are not included in the 10%. The tonnage of ocean-going shipping is roughly half the amount of the tonnage for inter-EU transport.

The average distance of the transport is influenced by:

- The nature of the transported good. Products, which are only produced in certain locations or where price differences are large between different producing countries, have larger transport distances. Examples are fruits and vegetables (approx. 140 km national transport and 10-12% internationally transported), iron ore (approx. 130 km national transport and 50% internationally transported) and semi-manufactured metal products (approx. 150 km national transport and 25% internationally transported).
- The price of the transported good. Highly processed and expensive products such as machines, apparatus, textile- and leatherwear are transported roughly 150 km nationally which is in the high end of transportation distance for all products. The share of these products transported internationally is 10-15 %, which is above average. Examples of national transportation distances for cheaper products are minerals (approx. 30 km), building materials (approx. 60 km) and manufactures of metals (approx. 90 km). The share of goods internationally transported is

3-4 % for minerals and building materials and below 10% for manufactures of metals.

- Population density. Low population density - as in Finland, Sweden and the United States - may lead to longer transport distances, but this however cannot be clearly verified from the Eurostat statistics.

A.22.2 Energy intensity

The energy intensity of domestic transport of goods by water, rail, and road ranges from 0.2 to 5 MJ/Mgkm, national averages of OECD countries varying from 1 to 3.5 MJ/Mgkm (Schipper 1997).

The most important cause of variation in energy intensity per Mgkm is modal choice, in that ships have ranges from 0.05 to 1.2 MJ/Mgkm depending on size, rail ranging from 0.3 to 0.7 MJ/Mgkm and trucks vary from 0.7 to 5 MJ/Mgkm. Differences in modal mix between countries may explain up to one third (0.8 MJ/Mgkm) of the difference between national averages (Schipper 1997). Modal choice is influenced by:

- Local infrastructure (destinations on coasts and along waterways favour water transport, lack of rails may favour road transport, congested roads or mountains may favour water and rail).
- The price of the transported good (in general, products with a low price per weight unit are transported by ship, while expensive products are transported by truck).
- Demands for quick deliveries (e.g. of perishable products, uncommon spare parts, just-in-time production) lead to a relative preference for road transport, and often in smaller trucks, or air transport.
- The transport distance. Long transports leads to a preference for water and rail over road transport. 35% of all transport work (Mgkm) in the EU is international (the share of international transport work is higher than the share (10%) of international goods transport (i.e. measured in Mg) since international transport involves longer distances). For inland waterways and sea traffic the international share is 70%, for rail 45%, and for road 20 %.
- The nature of the transported goods, insofar as bulk goods are more often transported by ship or rail. According to Eurostat (1998b), the average modal split of transport work (Mgkm) of all products between road, rail and inland waterways is 77/15/8 (pipelines and sea transport not included). An example of above average for road is machinery/manufactured articles. Examples of above average for rail are the bulk products coal, ore, and semi-manufactured metal products. Above average for inland waterways, we find the same products as for rail but also petrol products. The rule must be seen as secondary to other influences, since bulk products like agricultural products and minerals (short distances), are preferably transported nationally by truck. Internationally, minerals are preferably transported by rail or ship.

Second most important cause of variation in energy intensity per Mgkm is the size and utilisation of the vehicle, which explains most of the variation in fuel intensity of both ships and trucks. For example, a 14t diesel truck has double the fuel consumption of a 52t truck of the same age and utilising a truck 40-50% instead of 100% also double the fuel consumption (Rydberg 1997). Due to the weight ratio of vehicle to load, the difference is most pronounced for small trucks, but it is still important for larger trucks. The capacity utilisation for trucks typically vary between 40% and 70%.
For trucks, vehicle size is influenced by:

- The transport distance (long transports leads to a preference for larger trucks).
- The nature of the transported goods (bulk versus parcels).

- Demands for quick deliveries, lead to a relative preference for smaller trucks.
- Local infrastructure (low bridges, narrow roads, roads, bridges with weight limits and congested locations may give a preference for smaller trucks).
- The price of the transported good (expensive goods are more often transported in smaller trucks).
- Regulation (truck weight limits are low in Japan, but high in Scandinavia, Australia and the United States).

Capacity utilisation of the vehicle is influenced by:

- Demands for quick deliveries (e.g. of perishable products, uncommon spare parts, just-in-time production), which may lead to lower capacity utilisation.
- The density of the transported good, as lightweight goods causes vehicles to be loaded at less than full weight capacity. The weight capacity of trucks is typically utilised fully at a product density of 250-300 kg/m^3 (including transport packaging). For lighter products, the fuel consumption can be calculated by assuming a linear relationship of fuel consumption (MJ/km) between full loaded (by weight capacity) and empty truck (Rydberg 1997) and then divide the calculated fuel consumption with the transported load. Subtracting the fuel consumption (MJ/Mgkm) by full load gives the additional fuel consumption for lighter loads.
- The price of the transported good (expensive products justify more often deliveries with lower loads).

Third most important cause of variation in energy intensity per Mgkm is traffic conditions and type of engine/fuel, being the second most important explanation for variation in fuel intensity of trucks. This also leads to differences in emissions other than those linearly related to fuel consumption, see below. Traffic conditions are influenced by:

- Congestion, depending on population density, infrastructure development, etc. Urban traffic on average – i.e. as an average of urban center and urban periphery - accounts for an additional fuel consumption of 25% for large trucks and 50% for small trucks compared to driving on a motorway (Samaras & Zierock 1996). By 40-50% load utilisation, the additional fuel consumption corresponds to 0.2 MJ/Mgkm for large trucks and 1 MJ/Mgkm for small trucks (Rydberg 1997). The reason why the fuel consumption of large trucks are less sensitive to urban traffic than the fuel consumption of small trucks is that large trucks do not operate as much in the center part of towns as small trucks. The emissions of CO, VOC and particles are much larger under urban conditions, while NOx emissions may be slightly lower than for motorway traffic.
- Regulation, i.e. mainly speed limits. At motorway speed, the fuel consumption theoretically relates to the square of the speed. In theory, the reduction of speed from e.g. 90 to 80 km/h will reduce the fuel consumption approx. 20%. In practice the reduction is smaller due to uneven road and traffic conditions.

The type of engine/fuel is first of all a question of diesel versus gasoline. Due to better efficiency, diesel engines use 30-40% less fuel than gasoline engines for the same performance (Samaras & Zierock 1996). For trucks under 6 tonnes, diesel is common in most of Europe, while e.g. Sweden, Norway, US, and Japan have higher shares of gasoline use. The emission characteristics of gasoline and diesel engines are very different and also depends on technology and regulations, see below. In general, diesel engines produce more NOx and particles than gasoline engines but less CO and VOC. For both gasoline and diesel, the fuel composition may vary due to local availability or regulation, e.g. low octane gasoline or poor quality diesel (high sulphur) in e.g. Eastern Europe, which may lead to slightly increased fuel consumption and large differences in emissions. High sulphur diesel results - besides increased SO_2 emissions - also in increased particle emission. For trucks manufactured according to EU standards after 1993 a large part of these particles are however captured by filters.

Less important causes of variation are:

- Age of the fleet. Elder trucks have larger fuel consumption, partly due to engine degradation and partly due to elder technology, e.g. turbo/non turbo and air resistance of vehicle. For diesel engines, EU standards adopted in 1993 and in 1997 regulates particles, CO, VOC and NOx. A truck manufactured after 1997 emits approx. 85% less particles, 60% less CO and 50% less VOC and NOx compared to a truck from 1993. For gasoline trucks equiped with catalyst the emission of CO, VOC and NOx is reduced by order of 90% compared to non catalyst trucks. The situation is similar in US and Japan.
- Driving habits and education of drivers.
- Efficiency in emission control.
- Maintenance of machinery.

For these causes, variation between countries are not expected to be large, but variation between trucking enterprises within one country may be of importance. In general, the variation due to these causes can be assumed smaller than for the causes discussed above, i.e. less than +/- 10%.

A.22.3 Pipelines

Gas transport by pipeline involve two major environmental problems, namely the leakage and the energy use for transmission. Modern PE pipes have an order of magnitude lower leakage than old steel pipes (Frischknecht 1996). In percentage of the transported gas, leakage has been estimated between 1 and 2% depending on the age of the net and average distribution distances (Ayres & Ayres 1998). For the same reasons, turbo-compressor power for transmission varies from 1% of the transported gas for European conditions (Frischknecht 1996) to the double for the USA (Ayres & Ayres 1998).

Frishknecht (1996) reports specific electricity consumption for oil transport by pipeline from 3 to 16 Wh/Mgkm, mainly depending on the height difference but also on pipe diameter and capacity utilisation. However, even when taking these items into account a residual variation of +/-35% was found.

A.22.4 Electricity transmission

The main loss in electricity transmission is caused by voltage conversion. Gärdenäs et al. (1997) and Frischknecht (1996) report 9-14% losses for household electricity (less than 1 kV), 2-6% loss for industrial users around 10 kV and 1-3% loss for industrial users around 100 kV.

A.23 Waste treatment (CPA 90)

The distribution of the different waste treatment options (incineration with and without heat recovery, landfilling with and without gas and/or leachate collection, etc.) must be estimated from statistical information and literature data, which is often incomplete. Within each waste treatment option, the emission data are typically based on models. The uncertainties on these models vary for different waste treatment options and for different materials.

For landfills, the largest uncertainties are due to (Nielsen & Hauschild 1998):

- Lack of knowledge on the decomposition and transport within the landfill (most important for specific organic chemicals, metals, chlorine, sulphur and nitrogen).
- Lack of knowledge on extent and efficiency of gas collection (estimated to +/- 60%).
- Lack of knowledge of the extent and efficiency of leachate collection and treatment (+/- 100%).

For incineration, the largest uncertainties are on:

- Extent of heat recovery and efficiency of conversion in the municipal waste incinerators,
- Extent and efficiency of flue gas cleaning,
- Material specific properties, such as the composition and contamination of materials and the completeness of combustion.

A.24 Household energy use

The energy use of households has been found to vary +/-25% around an average, which is determined as a linear function of the household income (Kramer et al. 1998). The elasticity of the relation was calculated to 0.8.

Annex B. Terminology on uncertainty and statistical properties

Many different concepts are used to describe uncertainty. This annex describes the terms used in this document. When applicable, statistical terms are defined in accordance with ISO 3534.

Uncertainty is the general term we use to cover any distribution of data caused by either random variation or bias. Uncertainty expresses the general problem that an observed value can never be exactly reproduced, but when an adequate number of observations have been made, certain characteristic features of their distribution can be described, such as mean and standard deviation.

Variation is the general term used for the random element of uncertainty. This is what is typically described in statistical terms as variance, spread, standard deviation etc., see definitions below. It is the randomness of the observations, which allows a statistical treatment, since this describes the probability distribution of the observations.

Bias is the skewness introduced into a distribution as a result of systematic (as opposed to random) errors in the observations, e.g. when the observations are made on a specific sub-set of a non-homogenous population.

Population is the total number of items under consideration, from which only a sample is typically observed.

Probability distribution is the function giving the probability that an observation will take a given value. The function is typically described in mathematical and/or graphical form, see also under normal distribution and lognormal distribution.

The *mean* or average value is the sum of the observed values divided by the number of observations.

The *median* (ε) is the value for which 50% of the distribution is smaller and 50% of the distribution is larger, also known as the 50% fractile.

The *mode* is the value that has the largest probability within the distribution.

The *error* of an observation is the deviation of the observed value from the mean value, i.e the value of the observation minus the mean value.

Variance is a description of variation defined as the sum of the squares of the errors divided by the number of observation less 1.

The *standard deviation* (σ) is the positive square root of the variance.

The *coefficient of variance (CV)* is the standard deviation divided by the mean value.

The *normal distribution* is a specific probability distribution also known as Gaussian or bell-shaped often found in real life populations. The reason for this is its specific mathematical properties, namely that 1) any sum of normal distributions is itself a normal distribution, and 2) when enough non-normal distributed variables are added, the result is approximately normal distributed. This is called the "central limit theorem" (Stevenson & Coates 1997 and Krider 2001 give wonderful illustrations of this theorem). The convergence to the normal distribution is surprisingly fast. For example, the distribution of the sum of ten uniformly distributed random variables is already indistinguishable by eye from an exact normal distribution. Since many real life phenomena are caused by a large number of independent random effects, the central limit theorem explains why we so often find real life data to be approximately normally distributed. The normal distribution is a symmetrical distribution (as opposed to a skewed distribution, see the lognormal distribution), which implies that the mean, the median and the mode all appears at the same place (at the centre or top of the curve, see the figure). An interesting feature of the normal distribution is that 68% of the data lies within one standard deviation either side of the mean, 95% of the data lies with two standard deviations of the mean, and 99.7% of the data lies within three standard deviations of the mean. Thus, it is easy to compare confidence intervals and standard deviations.

A two-sided *confidence interval* is the central part of a distribution that lies between two values chosen so that it is certain that the interval includes a required percentage of the total population. For example, in a 95% confidence interval, you can be 100% confident that it includes 95% of the population, i.e. it excludes 2.5% of the population in both ends.

The *lognormal distribution* is a specific probability distribution where the natural logarithm of the observed values follow a normal distribution. The lognormal distribution is also common in real life populations. One reason for this is that many real life effects are multiplicative rather than additive, and in parallel to the central limit theorem for additive effects (see under the normal distribution), it can be shown that multiplicative effects will result in a lognormal distribution. Another reason is that real life populations typically cannot attain values below zero, and with a high variation this will result in a skewed distribution with a longer tail towards the higher values. The lognormal distribution is such a skewed distribution, although certainly not the only one. Because of its easy transformation into the normal distribution, it is often – and also in our analysis here - used out of convenience, as an approximation for other more complicated, skewed distributions. As for the normal distribution, the confidence intervals is related to the standard deviation, but for the lognormal distribution, this relation is multiplicative: 68% of the data lies in the interval ε/σ to $\varepsilon\sigma$, 95% of the data lies in the interval ε/σ^2 to $\varepsilon\sigma^2$, and 99.7% of the data lies in the interval ε/σ^3 to $\varepsilon\sigma^3$.

The *range* is the difference between the largest and the smallest observed value. Empirical data are often given as a range, expressed e.g. by a minimum and a maximum value. The range will increase with an increasing number of observations, since it becomes more likely that the range will cover the full population. For the normal distribution, the range is approximately 3, 4, and 5 times the standard deviation when the sample size is 10, 30, and 100, respectively. This relation can be used to calculate the standard deviation when the range is given. Life cycle data often result from a small number of observations, so it is reasonable to use the factor 3 when the number of observations is unknown.

Plus/minus (+/-) is a popular way of expressing uncertainty. However, it is not always clear what is the intended meaning, especially when a skewed distribution is described. In this text, we use the +/- to describe a range, generally with the above assumption that we thereby cover 3 times the standard deviation.

Factor (e.g. “factor 2”, “factor 5” or “factor 10”; the latter being identical to “an *order of magnitude*”) is another popular way of expressing uncertainty. Compared to “plus/minus”, the factor may indicate a skewness. Consider for example 20+/-50%, which is equal to the interval 10-30, while a “factor 2” on 20 denotes the interval 10-40, i.e. a skewness resembling that of a lognormal distribution. An order of magnitude on 20 denotes the interval 2-200, which is very difficult to describe by a “plus/minus” notation. However, the concepts of factor and order of magnitude are used ambiguously. When used without indication of mean value, they may describe the size of a range, in which case an order of magnitude may denote e.g. the interval 2-20 or 20-200. In this text, we use the concepts in the former sense, i.e. as a factor on the mean value.