LCA Case Studies

Life Cycle Assessment of Bread Produced on Different Scales

[1]Karin Andersson, Thomas Ohlsson

SIK, The Swedish Institute for Food and Biotechnology, P.O. Box 5401, SE-402 29 Göteborg, Sweden
[1]Current address: CIT Ekologik, Chalmers Teknikpark, SE-412 88 Göteborg, Sweden

Corresponding author: Karin Andersson; e-mail: karin.andersson@cit.chalmers.se

Abstract

A case study of white bread has been carried out with the purpose of comparing different scales of production and their potential environmental effects. The scales compared are: home baking, a local bakery and two industrial bakeries with distribution areas of different sizes. Data from the three bakeries and their suppliers have been collected. The systems investigated include agricultural production, milling, baking, packaging, transportation, consumption and waste management. Energy use and emissions have been quantified and the potential contributions to global warming, acidification, eutrophication and photo-oxidant formation have been assessed.

The large industrial bakery uses more primary energy and contributes more to global warming, acidification and eutrophication than the other three systems. The home baking system shows a relatively high energy requirement; otherwise, the differences between home baking, the local bakery and the small industrial bakery are too small to be significant.

Keywords: Bread, production scales, LCA; LCA case study, bread, production scales; production scales, bread, LCA

1 Introduction

As a basis for decision-making, when moving towards more sustainable systems for production and consumption of foods, studies using the systems analysis approach for different types of staple foods are needed. The LCA methodology is a useful tool for such studies.

In the 1970s and the early 1980s, the use of energy in food production systems was widely studied. For bread, the whole production system, or a part of it, has been studied, among others, by LEACH (1976), AVLANI AND CHANCELLOR (1977), BEECH (1980), LAUKKANEN (1984), and CHRISTENSEN AND SINGH (1984). Recently, two life cycle studies of bread have been carried out. LÖRCHER et al. (1994) have made a detailed site-specific product LCA which includes a comparison of conventional and organic cultivation. Both quantitative and qualitative results are included in the impact assessment. WEIDEMA et al. (1995) have carried out a life cycle screening of rye bread with emphasis on establishing the energy and material flows. The cultivation of wheat has also been studied separately; both energy analyses (TAYLOR et al., 1993 and SONESSON, 1993) and LCA studies have been carried out (WEGENER SLEESWIJK et al., 1992, BÜCHEL, 1993 and AUDSLEY et al., 1997).

There are many difficulties in conducting LCA studies of foods (ANDERSSON et al., 1998). Food production systems are often large and complex. The agricultural production makes special demands on the LCA methodology. No public data bases exist, either for common inputs to agriculture or for common food ingredients. A representative model is difficult to obtain, especially with regard to the agricultural production and the consumer phase.

For many products, the scale of production is an important systems-related aspect. In Sweden there is much discussion of whether or not baking at home and in local bakeries causes less environmental impact than the baking in industrial bakeries and the subsequent distribution of bread. Although home baking has been quite common, the trend is decreasing.

The aim of the bread study carried out was to compare different scales of production and their potential environmental effects. The systems investigated include: production of inputs to agriculture; cultivation of wheat; milling; baking; packaging systems for bread ingredients and bread; transportation; the consumer phase; and waste management. The production of capital goods has been left outside the system boundaries. The study has been carried out with the assistance of three bakeries and their suppliers of ingredients and packaging materials. Therefore, it has been possible to obtain a large amount of site-specific inventory data. The study concentrates on energy use and emissions related to energy use. Use of land and water have been taken into consideration for cultivation and food processing, respectively. The impact assessment conducted includes the following environmental effects: global warming, acidification, eutrophication and photo-oxidant formation.

The comparison of the packaging materials used by the different systems has already been published as a Master of Science thesis (ARNKVIST, 1997). This article is a summary of the comprehensive report of the case study (in print).

2 Objective

2.1 Goal Definition

The case study is part of a research project funded by the Swedish Waste Research Council. The main goal was to compare the potential environmental effects of producing white bread on different scales. The scales compared are the following.

- Industrial Bakery 1 with Sweden as the distribution area is referred to as Industry 1 or the large industrial bakery. (The total annual production is approximately 30,800 tonnes and the capacity of the specific production line with a tunnel oven is 1,694 kg of bread per h).
- Industrial Bakery 2 with a region as the distribution area is referred to as Industry 2 or the small industrial bakery. (The total annual production is approximately 12,800 tonnes and the capacity of the specific production line with a tunnel oven is 1,008 kg of bread per h).
- The local bakery has an annual economic turnover of 3.6 million SEK (470,000 US$) and uses a rack oven. The total annual production is not known.
- Home baking was for three loaves of bread (approximately 2 kg) baked at a time.

Another goal was to identify hot spots, that is parts of the systems investigated which are important for the total environmental impact.

2.2 The type of bread studied

The product studied is white loaf bread baked in pans (the industrial bakeries use lids on the pans). The recipes differ somewhat between the four baking scales, with regard to the choice and amounts of ingredients. The following ingredients are used per kg of home baked bread: 683 g wheat flour, 344 g water, 44 g margarine, 36 g yeast, 7.2 g sugar, and 6.3 g salt. The confidentiality of the commercial bread recipes prevents giving them here, however they are quite similar to the one for home baking.

3 Methodology

3.1 The systems investigated

For each scale, a model system was constructed (→ *Fig. 1 - 4*). A more thorough description of all the model systems, the assumptions made and the data used, can be found in the comprehensive report (in print) and in the report on the packaging systems (ARNKVIST, 1997). Each of the model systems was divided into sub-systems. For the food processing and packaging sub-systems, alternative scenarios were analysed. **Table 1** shows a summary of the sub-systems, the processes they include and the scenarios investigated. In the households, either oil or electricity is used to heat the hot water; therefore two scenarios were used for home baking in the sub-system food processing. As regards the packaging sub-system, the waste management is based on the Swedish situation, which means 42 percent landfilling and 58 percent waste incineration. Since waste incineration results in both waste reduction and heat production, the contributions from a heat production system were subtracted from the waste incineration step. Since two alternative heat production systems were used in this study, there are two scenarios for the packaging sub-system. The aim was to study the differences when waste incineration competes with a "dirty" fuel such as oil (scenario A) or a "clean" fuel such as biofuel (scenario B).

3.2 The functional unit

The functional unit is defined as 1 kg of bread (ready for consumption at home). Representative information for product losses in the consumer phase is missing. We prepared an inquiry which was answered by 41 persons. This very limited survey indicated that there are considerable losses. In some extreme cases, the figure of 25 percent was mentioned. We have chosen to omit the consumer phase losses at this stage; they can be included afterwards by use of the scenario technique.

3.3 The data collection and the inventory analysis

Site-specific data have been collected from mills, bakeries and suppliers of bread ingredients and packaging materials. For home baking, we used our own measurements and compared them with test results for ovens (KONSUMENTVERKET, 1996). Literature data, statistics, estimates and assumptions have been used as a complement. The type of flour used in the different systems varies with regard to the mixture of spring and winter wheat. The mills are supplied by different regions (→ *Figures 1 - 4*). The inventory analyses of the cultivation of spring and winter wheat are based on:

- a modified version of the energy analysis carried out by SONESSON (1993);
- statistics for standard yields in the specific regions (SLU, 1996);
- estimates of the amounts of fertilisers applied (made by the Rural Economic and Agricultural Societies in the specific regions);
- estimates of the nitrogen leakage in the specific regions (JOHNSSON AND HOFFMANN, 1996).

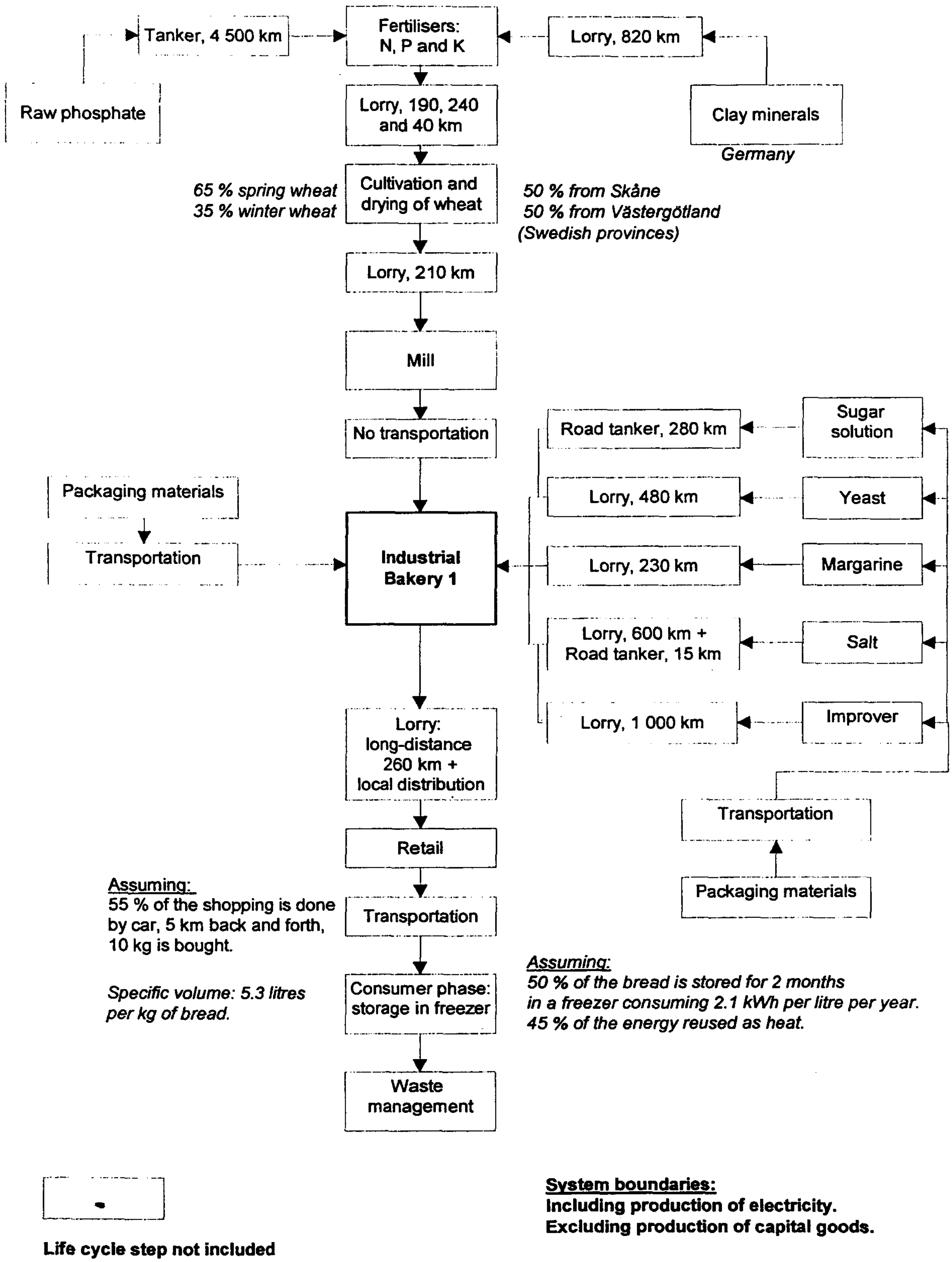

Fig. 1: The life cycle of bread from Industrial Bakery 1

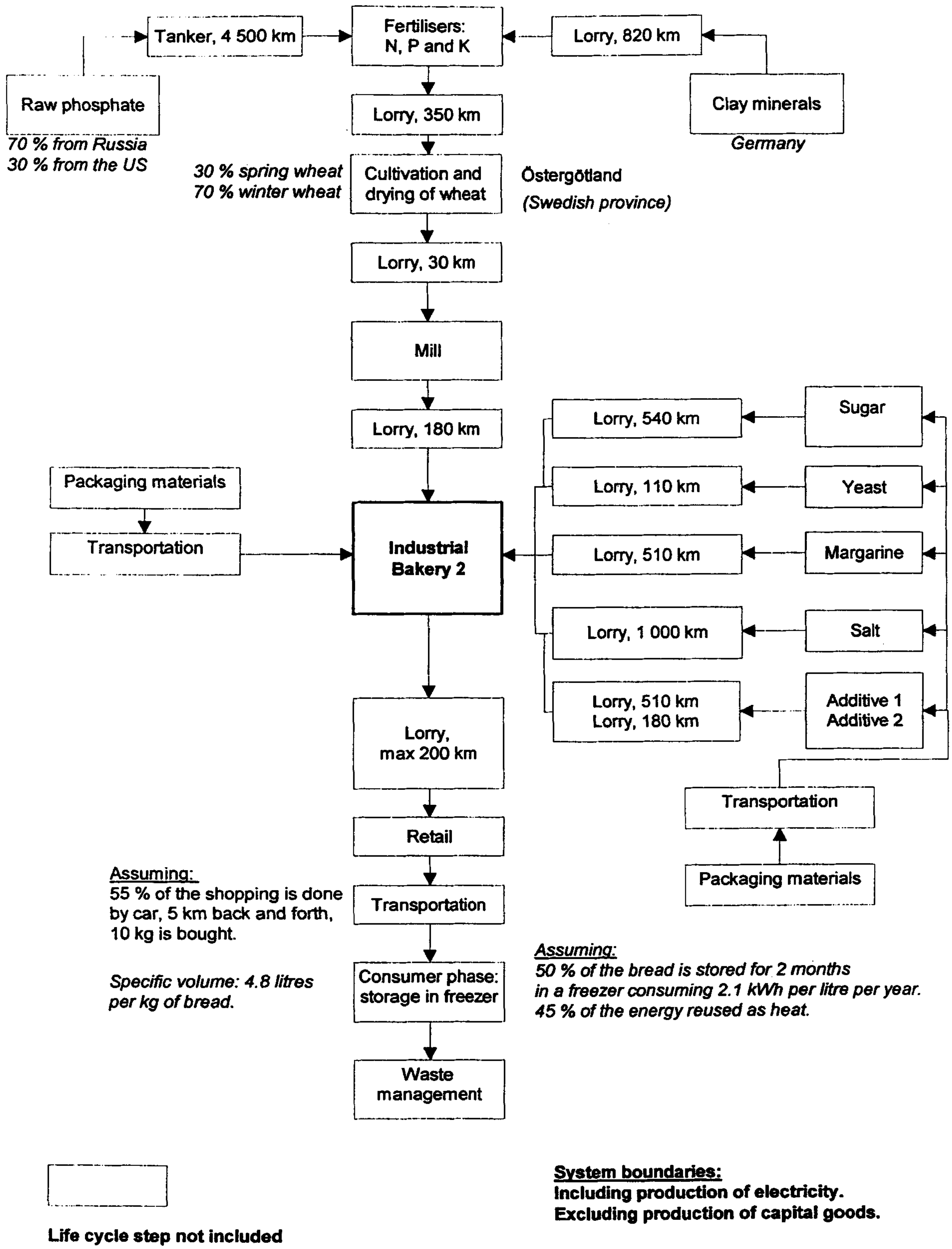

Fig. 2: The life cycle of bread from Industrial Bakery 2

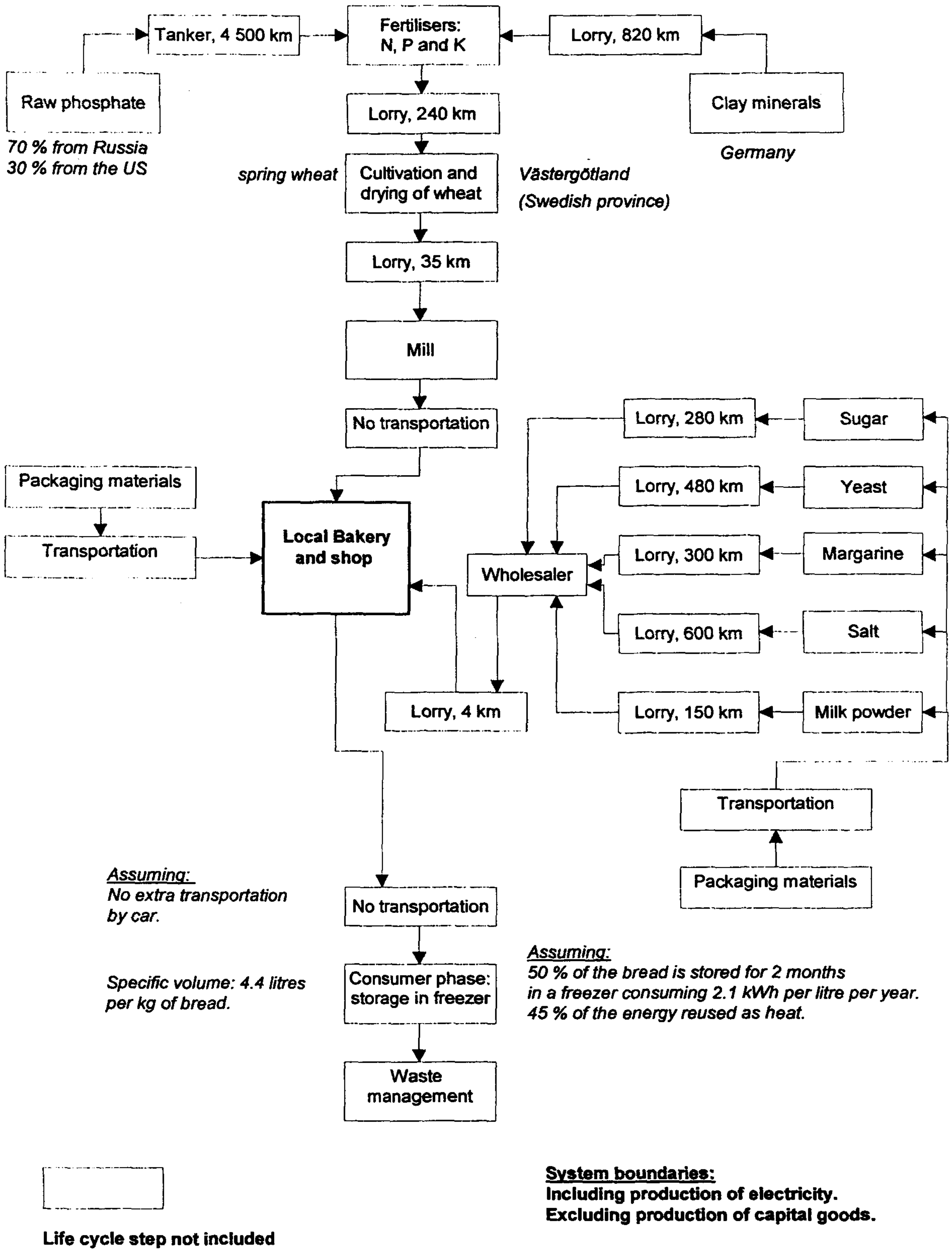

Fig. 3: The life cycle of bread from the local bakery

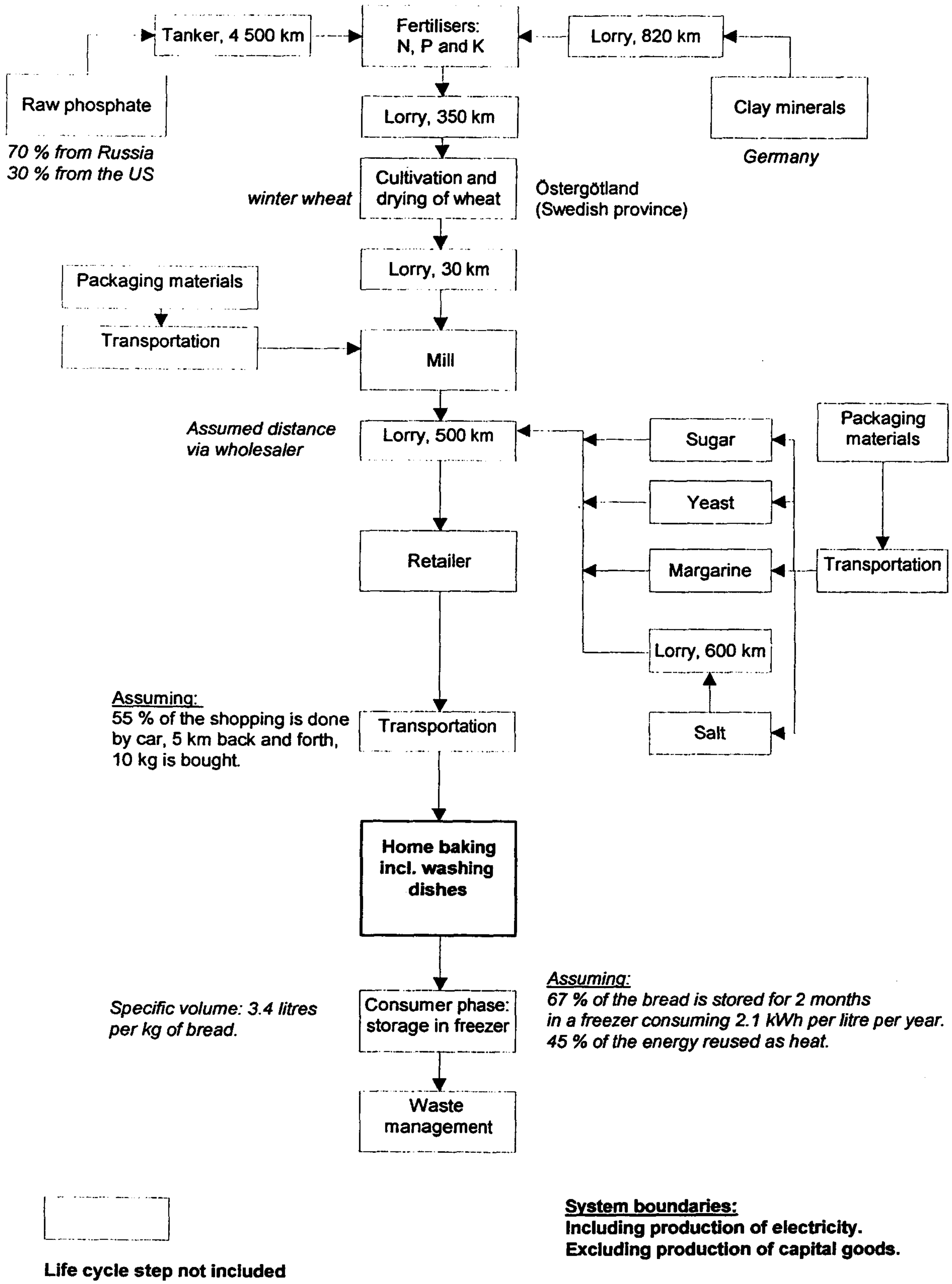

Fig. 4: The life cycle of bread baked at home

Table 1: Summary of the sub-systems, the processes they include and the scenarios investigated

Sub-system	Processes included	Scenarios
Agriculture	• Cultivation of wheat • Extraction of raw materials and production of fertilisers	
Food Processing	• Milling of wheat • Baking of bread • Cleaning in the bakeries and washing dishes in conjunction with home baking	Home baking: Water used for washing dishes heated by: • Electricity • Oil
Transportation	All transportation processes except for the transport included in the Packaging sub-system	
Packaging	Production and transportation processes included in the packaging systems for bread ingredients and bread	Waste incineration: Avoided emissions assuming the following heating alternatives are used: • Oil (scenario A) • Biofuel (scenario B)
Consumer Phase	Storage of bread in freezer	

For the production of fertilisers, data from literature (WEIDEMA et al., 1995) combined with site-specific information (from a Swedish producer) about the origin of the raw phosphate and clay minerals were used. Site-specific information for means of transport and distances were used together with general data on energy consumption and emission factors (TILLMAN, 1994).

3.4 The system boundaries

As the goal was to compare different scales of production and there are no significant differences between the ingredients and the amounts used, we decided to exclude the production of bread ingredients other than flour. However, the packaging systems and the transportation used for bread ingredients vary among the different scales and have therefore been included (→ *Figures 1 - 4*)

In the cultivation step, the assimilation of CO_2 by the crop was not taken into consideration; neither was the leakage of phosphorous and gaseous emissions such as ammonia and nitrous oxide from the fields. Models for doing this need to be worked out. Capital goods have been left outside the system boundaries. As the wholesaler and the retailer were not expected to influence the overall results, they were excluded. The production of electricity is included. For the Local Bakery system, the boundaries are somewhat wider than for the other systems. The reason is that the data used for baking and milling also includes (in the same building) a shop, the heating of two flats and the washing of the working clothes used by the employees. The cleaning of ovens and the use of cleaning agents have not been included.

The case study, which is confined to effects on the natural environment, concentrates on energy use and emissions related to energy use. The following impact categories were excluded.

- For ozone depletion, no detailed inventory has been carried out for the refrigerants used in the bakeries, in the distribution and at home.
- Human toxicity and eco-toxicity were omitted for two reasons. First, the inventory is not detailed enough with regard to the production and use of pesticides. Second, the characterisation is less straightforward and more complex than for the impact categories included. The use of several methods is recommended (LINDFORS et al., 1995).

3.5 Methodological choices, assumptions and simplifications

For the cultivation step, we have assumed that only fertilisers (no manure) are used. 100 percent of the environmental loads of agricultural production and milling were allocated to the main products wheat and flour, respectively. In the industrial bakeries, the use of energy and water for the specific production lines was not measured; it was estimated by company experts. The energy use includes the heating of the oven, baking, and production of steam for the production line, as well as the electricity used by motors, slicing and packaging machines. The water use includes water as an ingredient and water used for cleaning. A thorough account of the estimates and how they were obtained can be found in the comprehensive report (in print). The emissions were then quantified by the use of emission factors and, the environmental loads were allocated by mass for the different products produced. For the local bakery, it was necessary to carry out an economic allocation since the total annual production was not known. In order to validate the results obtained by economic allocation, this type of allocation was also carried out for the Industrial Bakery 1; the results were the same. Thus, we concluded that, as a first approximation, economic allocation could be used for the local bakery.

In order to facilitate including the transportation of bread between the retailer and the consumer, many assumptions had to be made. The process of shopping is similarly accounted for in the systems Industry 1, Industry 2 and Home Baking. For the Local Bakery system, it was assumed that the customers live nearby (walking distance) or pass on their way home. The parameters required for calculating the environmental loads caused by shopping are: the share of trips made by car; the distance driven; the amount of groceries bought; and energy requirements and emission factors for cars. In addition, the method to allocate the environmental loads for the products bought and other possible functions of the trip (for instance going home from work or driving the children somewhere) is important. The assumed values of the parameters are shown in **Figures 1 - 4**. As regards energy use and emission factors for cars, data from ERIKSSON et al. (1995) have been used. The environmental loads were allocated by weight for the products bought.

The consumer phase includes the storage of bread in a freezer. This storage can be accounted for in many ways and the calculations involve several assumptions. Important parameters are: the energy requirement of the freezer; the fraction of the required energy that can be reused as heat; the storage time; and the method of allocating the environmental loads for the different products stored in the freezer. **Figures 1 - 4** show the assumptions made. The specific volume of the bread, rather than the weight, was used in the calculations. Thus, the higher the specific volume, the greater the energy use per kg of bread.

3.6 The impact assessment

In the classification and characterisation carried out, we have followed the recommendations of LINDFORS et al., 1995. The potential contributions to the following impact categories have been estimated:

- Global warming was obtained by using characterisation factors with a time frame of 100 years for both direct (IPCC, 1994) and indirect (HOUGHTON et al., 1990 and SNV, 1992) greenhouse gases.
- Acidification was found by using the maximum scenario method (FINNVEDEN et al., 1992).
- Eutrophication was also found by means of the maximum scenario method (LINDFORS et al., 1995).
- Photo-oxidant formation was worked out by using peak ozone data (HEIJUNGS et al., 1992) for hydrocarbons, aldehydes, ethanol and methane; the scenario maximal difference (FINNVEDEN et al., 1992) was used for carbon monoxide. In addition, inventory results for nitrogen oxides (NO_x) were taken into consideration. The reason is that there is no characterisation factor available, although NO_x is an important contributor to photo-oxidant formation.

4 Results

For each of the four systems studied, the use of energy and the potential contributions to global warming, acidification, eutrophication and photo-oxidant formation are presented. Land use in the sub-system for agriculture and the use of water in the sub-system for food processing are also presented. The alternative scenarios investigated for the packaging sub-system and for food processing in the home baking system are explained in **Table 1**. **Table 2** shows a summary of the estimated contributions made by the products studied to the impact categories investigated.

Table 2: Summary of results from the energy analysis and the impact assessment. When the result depends on the waste management scenario for the packaging sub-system, both values are presented, scenario A / scenario B

	Industrial Bakery 1	Industrial Bakery 2	Local Bakery	Home Baking
Primary energy [MJ/functional unit]	22	14	12	18 (el.) or 17 (oil)
Global warming Time perspective 100 years [g CO_2-equiv./functional unit]	940 / 1,000	630 / 640	660 / 670	520 / 540 (el.) or 630 / 650 (oil)
Acidification Scenario maximum [mol H^+/functional unit]	0.15 / 0.17	0.10 / 0.10	0.10 / 0.11	0.078 / 0.082 (el.) or 0.090 / 0.094 (oil)
Eutrophication Scenario maximum [g O_2/functional unit]	160	99	120	88 (el.) or 89 (oil)
Photo-oxidant formation Characterisation results [g ethene-equiv./functional unit]	1.8	1.7	1.0	1.5 (el. and oil)
Photo-oxidant formation NO_x (inventory results) [g per functional unit]	5.4 / 5.5	3.2	2.6 / 2.7	2.4 / 2.5 (el.) or 2.6 (oil)

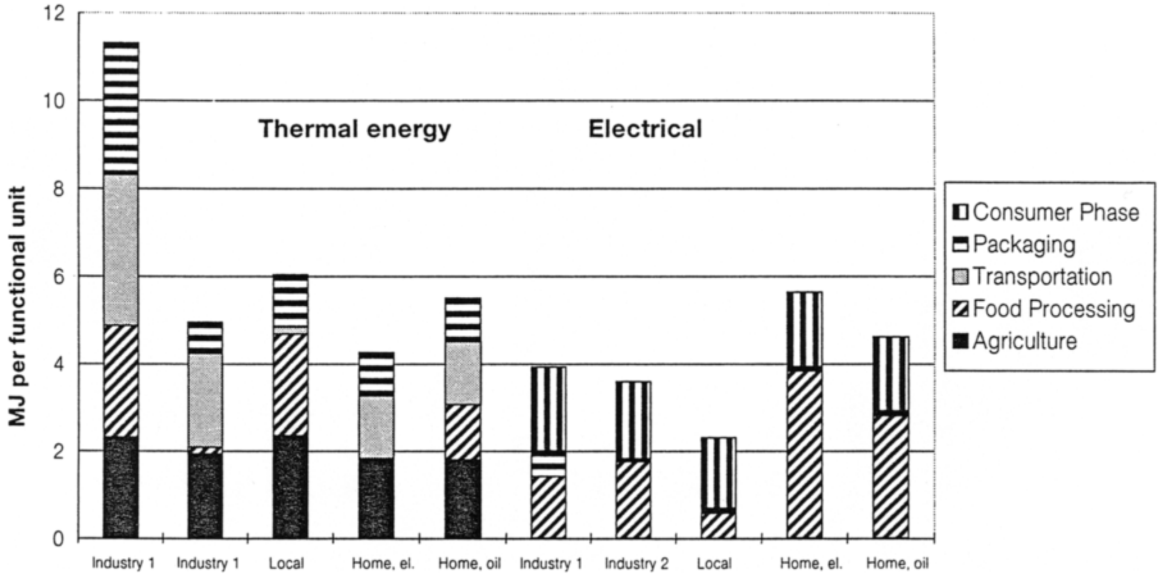

Fig. 5: The use of thermal and electrical energy in the systems studied

Comparisons made at the sub-system level, for the systems analysed, are given next. A summary of the hot spots identified in each of the systems studied is also presented. More detailed results can be found in the comprehensive report of the case study (in print).

4.1 Energy use

The use of thermal and electrical energy in the four systems for production and consumption of white loaf bread is shown in **Figure 5**. For Industry 1, the use of thermal energy is relatively high, especially in the transportation and packaging sub-systems. Industry 1 transportation reveals that approximately 60 percent of the energy is used for the bread distribution and 30 percent for shopping; in Industry 2, the corresponding figures are 40 and 50 percent, respectively. The very low use of thermal energy for transportation in the local bakery system is explained by the assumption that no extra travelling by car is done when shopping. The total use of primary energy (→ *Table 2*) was calculated using the following relationships.

- One MJ of Swedish electricity corresponds to 2.35 MJ of primary energy (PERSON AND ZACKRISSON, 1995).
- One MJ of thermal energy corresponds to approximately 1.1 MJ of primary energy.

4.2 The use of land and water

Table 3 shows, for each of the systems studied, the land use for the cultivation of wheat and the use of water in the food processing sub-system. As regards land use, the systems using a higher share of winter wheat are more efficient. The crop yields vary depending on where the wheat is cultivated. In the area supplying the local bakery, the cultivation is less intensive. In the use of water, the home baking system consumes much more than the other systems. The loads from the process of washing dishes were allocated by weight to

Table 3: The land use for cultivation of wheat and the use of water for milling, baking and cleaning (in bakeries) or washing dishes (at home)

	Land use for the cultivation of wheat [m² per functional unit]	Use of water* in sub-system Food Processing [litres per functional unit]
Industrial bakery 1	1.8	1.4
Industrial bakery 2	1.6	0.8
Local bakery	2.1	3.0
Home baking	1.5	12

* Drinking water quality

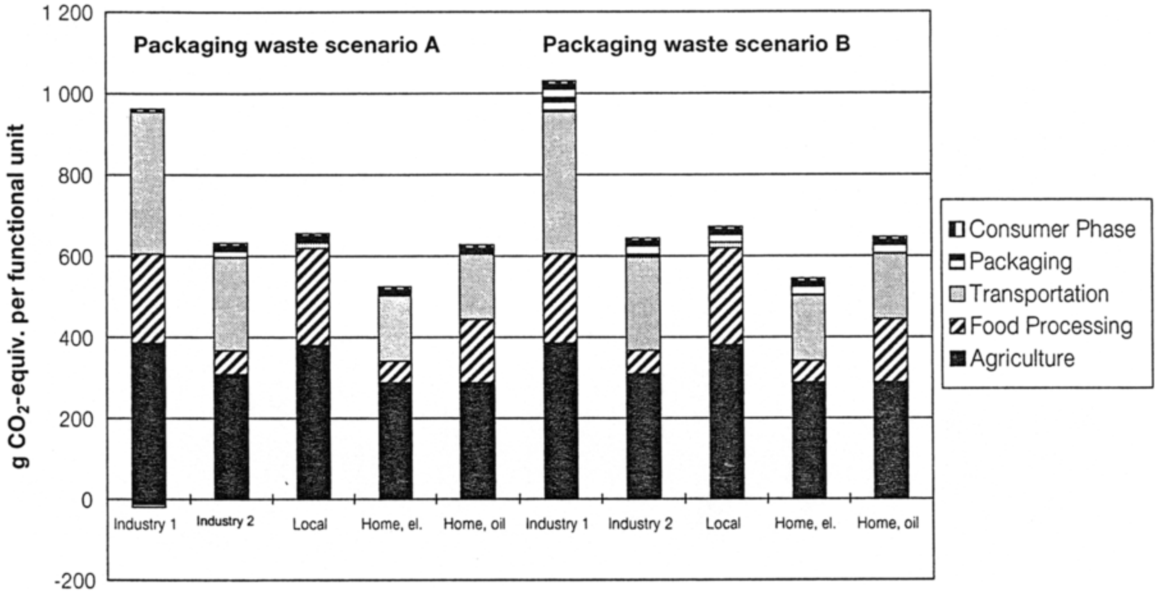

Fig. 6: The potential contributions to global warming, including both direct and indirect greenhouse gases. The time frame is 100 years

the amount of bread baked. Possibly other products (or meals) should carry part of the environmental loads caused by washing dishes.

4.3 Global warming

Characterisation results for global warming are shown in **Figure 6**. The potential contributions to global warming are related to the use of fossil fuels. Fossil fuels are used for baking in the Industry 1 (natural gas) and local bakery (oil) systems, while electricity is used in the Industry 2 and home baking systems. As the Swedish electricity production is based on hydropower and nuclear power, the contribution from the food processing sub-system in the Industry 2 system is relatively low. In the home baking system, the scenario for washing dishes influences the result. Whether or not the water is heated by the use of electricity or fuel oil makes a difference. As regards the packaging sub-system, the choice of waste management scenario is important for the results, in particular if the packaging materials are based on renewable materials. However, the influence on the total results is small.

4.4 Acidification

The maximum potential contributions to acidification are shown in **Figure 7**. For the systems studied, the amounts of

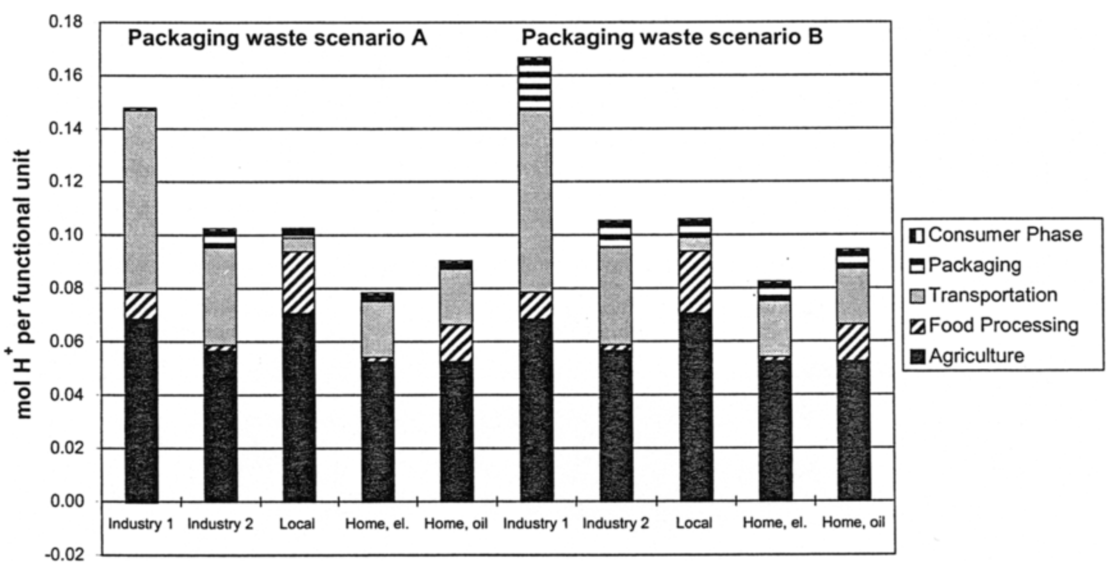

Fig. 7: The maximum potential contributions to acidification

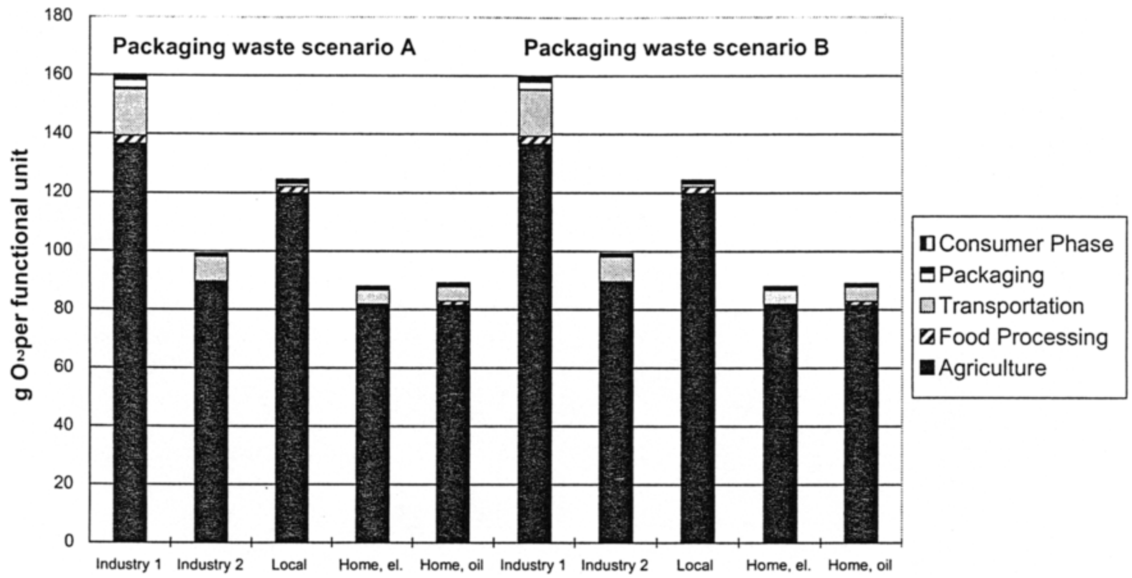

Fig. 8: The maximum potential contributions to eutrophication

sulphur dioxide and nitrogen oxides emitted are the key parameters. Both of these emissions are related to the use of fossil fuels. However, in comparison with oil and diesel fuel, the combustion of natural gas results in considerably lower emissions of sulphur dioxide. Therefore, the contribution from the food processing in the Industry 1 system is relatively low (in spite of the relatively high energy use).

4.5 Eutrophication

As regards eutrophication (→ *Fig. 8*) the results are not influenced by the packaging waste scenario. The agriculture sub-system is an obvious hot spot in all of the systems analysed. The key parameters in the agriculture sub-system are:

- the leakage of nitrogen from the fields (approximately 50 percent of the effect); and
- the emissions in conjunction with the production of nitrogen fertilisers (approximately 40 percent of the effect).

4.6 Photo-oxidant formation

Photo-oxidant formation was estimated by using results from both the inventory analysis, **Table** 4 (since there is no characterisation factor for NO_x), and the characterisation, **Figure** 9. The amounts of NO_x emitted are influenced by the packaging waste scenario, while the characterisation results are not. When choosing the model for characterisation, it is important to note what substances are included in the different models. In order to include as many of the inventory parameters as possible, the characterisation factors of HEIJUNGS et al., (1992) were employed. To the result obtained, was added the contribution from carbon monoxide estimated by using the Maximal Difference characterisation factor (ANDERSSON-SKÖLD et al., 1992 and FINNVEDEN et al., 1992). In all of the systems studied, the food processing sub-system is an obvious hot spot; the key parameter is the amount of ethanol released during baking. Transportation processes are also important, both for emissions of nitrogen oxides (→ *Table 4*), and for the weighted emissions of hydrocarbons and carbon monoxide (→ *Fig. 9*). Note also the emitted amounts of nitrogen oxides in the agriculture sub-systems; the main sources

Table 4: Inventory results for NO_x in mg per functional unit

Sub-system	Industrial Bakery 1	Industrial Bakery 2	Local Bakery	Home Baking
Agriculture	1,800	1,500	1,900	1,400
Food Processing	440	40	360	38 (el.) or 220 (oil)
Transportation	2,700	1,400	170	810
Packaging A / B	460 / 560	160 / 170	140 / 160	140 / 170
Consumer Phase	18	16	15	16

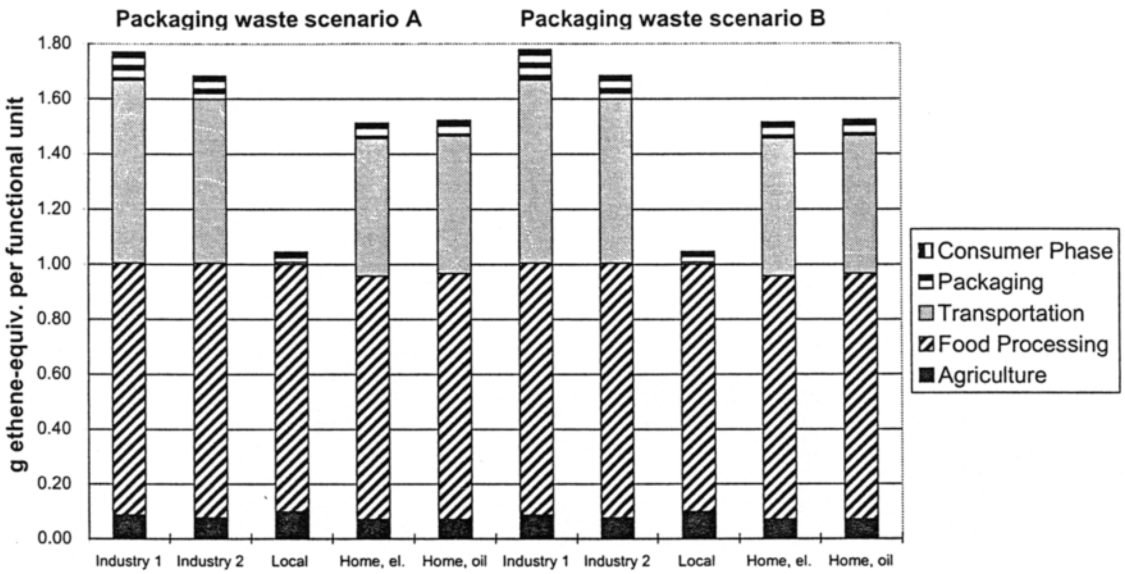

Fig. 9: The potential contributions to photo-oxidant formation (combining two characterisation models)

are the production of nitrogen fertilisers and the use of tractors in the cultivation step.

4.7 Hot spots

Here, a hot spot is defined as a sub-system to which 20 percent or more of the system's total contribution can be related. A summary of the hot spots identified for each of the systems investigated is shown in **Table 5**. Note that, for all of the systems studied, the agriculture sub-system is a hot spot for most of the impact categories included. The significance of food processing depends on the fuel used for baking and, in the home baking system, for heating of the water for washing dishes. The ethanol released when baking is the reason for food processing being a hot spot with regard to photo-oxidant formation. Transportation is important in all of the systems except for the local bakery. The reason is that this sub-system is dominated by the distribution of the bread and by shopping: in the local bakery system there is no distribution of bread and the shopping was omitted.

5 Discussion

When evaluating the results, it is important to remember that the systems compared are models of specific, existing systems. It is clear that the Industrial Bakery 1 system uses more primary energy and contributes more to global warming, acidification, eutrophication and photo-oxidant formation than all of the other systems. As regards the scale of production, the results imply that there may be a breaking point somewhere between Industry 1 and Industry 2. The

Table 5: The hot spots identified for each of the systems investigated

Impact category	Industrial Bakery 1	Industrial Bakery 2	Local Bakery	Home Baking
Primary energy	Food Processing Packaging Consumer Phase	Food Processing Consumer Phase	Food processing Consumer Phase Agriculture	Food Processing Consumer Phase
Global warming	Agriculture Transportation Food Processing	Agriculture Transportation	Agriculture Food Processing	Agriculture Transportation Food Processing, oil
Acidification	Agriculture Transportation	Agriculture Transportation	Agriculture Food Processing	Agriculture Transportation
Eutrophication	Agriculture	Agriculture	Agriculture	Agriculture
Photo-oxidant formation: characterisation results	Food Processing Transportation	Food Processing Transportation	Food Processing	Food Processing Transportation
Photo-oxidant formation: NO_x (inventory results)	Transportation Agriculture	Agriculture Transportation	Agriculture	Agriculture Transportation

baking in Industrial Bakery 1 could surely be made as energy efficient as that in Industrial Bakery 2. The question is whether the distribution area for Industry 1 is too large. The home baking system uses more primary energy than the Industrial bakery 2 and local bakery systems (→ *Table 2*).

Otherwise, the differences between the Industrial bakery 2, local bakery and home baking systems are too small to be significant. The results presented are useful to indicate, for each of the systems investigated, the relative significance of life cycle steps from an environmental point of view (screening). The uncertainties have not been quantified, but are expected to be large. A complete assessment of the uncertainties is complex and time consuming. What can be done more easily is sensitivity analyses using the scenario technique. It is important to keep in mind, for reasons discussed below, that the environmental impacts caused by the Industry 1 and local bakery systems are likely to be estimated high while the impacts caused by the Industry 2 and home baking systems are likely to be estimated low.

The energy results of the case study were compared with the results of previous studies, in particular to those of WEIDEMA et al. (1995), LÖRCHER et al. (1994), MÜLLER-REISSMANN (1990), LAUKKANEN (1984) and BEECH (1980). However, the comparisons are meaningful only at the process level or subsystem level, since the system boundaries vary. At these levels, our results appear reasonable. Only LÖRCHER et al. (1994), have quantified the potential contributions to global warming, acidification and eutrophication for the life cycle of bread (an industrial bakery system). The characterisation results cannot be compared directly, since the characterisation factors used, the substances taken into consideration and the system boundaries differ. When we adjusted for the system boundaries and employed the characterisation factors used by LÖRCHER et al. (1994), we obtained results of the same magnitude. The differences can be explained by systems-related aspects such as different distribution distances and energy sources.

The energy use is a critical parameter, since we have also used it to quantify other environmental loads and effects. For ideal reliability, it would of course have been better if energy measurements could have been carried out in the bakeries. It is possible that the bakery's primary energy use is estimated somewhat high for Industry 1 (5.5 MJ per kg bread) while somewhat low for Industry 2 (3.5 MJ per kg bread). BEECH (1980) studied the energy use of producing white, sliced bread in three UK industrial bakeries (similar rate of production as in our study) and obtained the following figures on primary energy use: 3.9, 4.2 and 4.9 MJ per kg bread (including bakery overheads). The presentation of the preliminary results at a seminar for the companies involved has led to the decision to measure the energy use of the specific production line in the large industrial bakery (Industry 1). Increasing the environmental awareness and knowledge in the companies involved is one of the most important results of the case study.

For the local bakery, the use of energy and water for milling and baking is estimated high. As mentioned above, the system boundaries are somewhat wider for this system. This could have been adjusted for. However, more meaningful than attempting to adjust for the system boundaries is to compare the results with data from manufacturers of equipment for local bakeries or to measure the energy use of important equipment in the bakery. If natural gas or electricity had been used for baking, the environmental performance, as described by the impact categories included, would have been improved.

The results of the home baking system do not depend only on the source of energy used for heating the water used for washing the dishes. Both the efficiency of the household equipment used (especially the oven) and the behaviour of the consumer are significant. Important parameters are: the amount of bread baked at a time; the duration the oven is used; the amount of water used for washing the dishes; the temperature of the water used for washing the dishes; the temperature of the incoming water; and the efficiency with which the water is heated. Since both the amount of bread baked at a time and the amount of hot water used for washing dishes are critical parameters, it should be noted that the results presented are to be regarded as a best case.

The packaging systems are, except for energy use, not hot spots in the systems investigated. The packaging system (with corrugated cardboard boxes) used by Industry 1 for the bread distribution requires more energy than the one (with reusable plastic boxes) used by Industry 2. However, part of this energy is bioenergy. When comparing the potential contributions to global warming, acidification and photo-oxidant formation, the result depends on the scenario for waste incineration (→ *Table 1* and ARNKVIST, 1997). Today, reusable plastic boxes are out of the question in the Industry 1 system, due to the long distribution distance. A standard reusable plastic box for distribution of bread (analogous to standard pallets) could be beneficial from an environmental point of view.

As mentioned already, the process of shopping is similarly accounted for in the Industry 1, Industry 2 and home baking systems, while it is not accounted for at all in the local bakery system. The many assumptions made when calculating the environmental loads caused by shopping can indeed be discussed. However, many people use their car for shopping and our results show that this may clearly influence the LCA results of a product such as bread.

The inventory analysis and the impact assessment carried out do not supply a complete picture of the environmental performance. First, there are environmental impacts that cannot be quantified. Second, important impact categories such as ozone depletion, human toxicity and eco-toxicity were excluded. Based on the experience from another case study (ANDERSSON et al., 1998), a consequence of including the impact categories human toxicity and eco-toxicity would have been that the content of heavy metals in the phosphorous fertilisers received greater emphasis. Third, alternative characterisation models exist for all of the impact categories included. When possible, we chose to quantify the maximum potential contribution. With knowledge of where the emissions occur and the sensitivity of the specific area or recipient, it would be possible to select carefully a characterisation factor for each site and emission. The Life Cycle Stressor Effects Assessment (LCSEA) under development will probably soon enable the quantification of more actual impacts on the environment (LINDFORS et al., 1998). The impact categories included (except for primary energy) favour processes using Swedish electricity over processes using fossil fuels. It is important to remember that the production and use of electricity also has environmental consequences, for example the generation of radioactive waste (nuclear power) and effects on biodiversity (hydropower).

The data used for leakage of nitrogen to water in the cultivation step (JOHNSSON AND HOFFMANN, 1996) and, consequently, also the estimated potential contribution to eutrophication are to be regarded as rough estimates. The cultivation step deserves separate and more detailed studies. Agricultural production makes special demands on the LCA methodology, demands that have already been much discussed (for example by WEIDEMA et al., 1995, COWELL AND CLIFT, 1995, VAN ZEIJTS et al. 1996, AUDSLEY et al., 1997, MATTSSON, 1996 and ANDERSSON et al., 1998). Besides the scale of production, different cultivation techniques such as integrated and organic cultivation need to be analysed and environmentally optimised. Land is a resource which has so far been given limited attention in most LCA studies (LINDFORS et al., 1995). We handled land use by using the area required for wheat cultivation; however, not only the area required but also the quality of land use is important (MATTSSON et al., 1998). When comparing different cultivation techniques (such as traditional, integrated and organic cultivation) there is a trade-off between inputs like fertilisers and pesticides and the area required.

For photo-oxidant formation, our results indicate that the amount of ethanol released during the process of baking is a key parameter. Approximately 9 g ethanol per kg of white bread is formed by fermentation and the amount released has been reported as 2 - 4 g per kg of bread (PYLER, 1988). The fact that ethanol is formed and released is well known by the bakeries, but it is not collected and no measurements have been carried out. Actually, both the pleasant smell of freshly baked bread and also the flavour of the bread are due to the large number of organic compounds formed during fermentation and baking: alcohols, acids, esters, aldehydes and ketones. The amounts are small, but all of these compounds contribute to photo-oxidant formation. If collected, the ethanol could become a valuable resource as fuel. According to the industrial bakeries, this is not yet economically feasible. However, during World War II Industrial Bakery 1 collected the released ethanol and used it as fuel for the distribution vehicles.

If the working environment were to be included, a more detailed analysis of the additives used in the industrial systems would be appropriate. Enzymes are usually added to improve the baking properties. Dust containing enzymes may pose an increased risk for allergy. In the mills there is also the risk of dust explosions.

6 Conclusions and future outlook

Based on the study presented here, it can be concluded that there is a limit beyond which the increased efficiency that can be obtained on a larger scale production is outweighed by the environmental loads from the distribution. The Industrial Bakery 1 system is beyond this limit. The other three systems, Industrial Bakery 2, the local bakery and home baking, contribute equally to global warming, acidification and eutrophication. However, the use of primary energy in home baking is relatively high. The energy efficiencies in the food processing sub-system can be ranked in the following order: local bakery (best efficiency), Industry 2, Industry 1 and home baking. For land use, it can be concluded that the systems using a greater share of winter wheat are more efficient as higher yields can be obtained. In countries where clean water is a limited resource, baking in industrial or local bakeries may be the best option, due to these systems more efficient use of water.

Generally, it can be concluded that the following aspects are important when comparing systems for the production and consumption of bread:

- the energy efficiency and the source of energy used for baking;
- the distances and logistics involved in the distribution of the bread;
- the behaviour of the consumer in conjunction with shopping (the method of allocation and assumptions associated with car use, distance and amount bought); and
- the yield of wheat and the leakage of nitrogen from the fields, both of which depend on the type of wheat (winter or spring wheat) and the cultivation site.

Drawing general conclusions is limited by the fact that the study compares specific, existing systems. The Industry 1 system may have the most remarkable potential to improve. The results of the local bakery system are sensitive to the type of energy used for baking. If, for example, electricity instead of oil had been used for baking, the use of primary energy would have been higher, but the contributions to global warming, acidification and eutrophication would be lower. The home baking system is very sensitive to the methods used by the person baking. The conclusions presented here are valid for efficient baking. A study that aims to determine what production scale has the potential to cause the least environmental impact, for a nation or a region, should not simply compare specific, existing systems. It is necessary to include the following.

- One should make sure that the systems compared are representative, and that all use the same level of technology and are separately optimised.
- The significance of location should be examined in more detail, that is, in relation to where people actually live: where should the wheat be cultivated and where should the mills, the bakeries, the wholesalers and the retailers be situated?
- Statistical information should be gathered for average consumer behaviour, for example with regard to: shopping; losses of bread; possible storage in a freezer; and, in the case of home baking, how efficiently the oven is used and the dishes are washed.

It is the hope of the authors that the results of this study will be useful as a platform, both for the environmental work of the companies involved and for future research. It would be interesting to conduct more detailed sensitivity analyses and improvement assessments for each of the systems analysed. The work presented is one of the first LCAs of a whole food system. In spite of its limitations it is a rather complete study and the collection of site-specific data ensures that the results obtained are realistic.

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LCA Literature

Eco-Factors BUWAL 297 (ecological scarcity) and Eco-Indicator 95 Weighting Factors for widely used Life Cycle Inventories

ÖBU (Swiss Association for Environmentally Conscious Management) publishes a compendium of all inventory parameters reported in three frequently used LCA inventory studies, together with their appropriate weighting factors in two well-known impact assessment (LCIA) methods. The brochure, developed together with EMPA St. Gall and Infras Zurich, lists and comments the parameters from the following Life Cycle Inventories: Energy Systems (ETH-ESU, 1996), Packaging (BUWAL 250, 1996, and Transports (INFRAS, 1995). Weighting factors are given for the method of ecological scarcity (Eco-factors BUWAL 297) and Eco-indicator 95. The list of factors goes far beyond the original LCIA publications, since every inventory parameter occurring in the inventories is discussed, and a rationale for its weighting factor given (where applicable).

This correlation tool between inventories and impact assessment methods will facilitate and improve LCA work by

- Guidance to LCA practitioners for the interpretation of inventory results. The six correlation tables correspond exactly to the parameter lists in the respective inventories, so that the weighting factors can be directly introduced.
- Standardization of the weighting factors for all occurring inventory parameters, which enhances the transparence of LCIA and contributes to a better comparability of results.

The brochure does not contain any inventory data (which can be found in the original publications). Also, it does not attempt to define "*optimal*" parameter lists for any LCA application, or prescribe which inventory items should be collected to obtain meaningful results (e.g. for the inventory of a company or production site). It is partially based on results derived from the new study BUWAL 300 (Schriftenreihe SRU Nr. 300) on the impact assessment in packaging LCAs, which will be soon available from the Swiss Packaging Institute SVI, Brückfeldstr. 18, Postfach, CH-3000 Bern 26.

The ÖBU publication "Zuordnung der Ökofaktoren 97 und der Gewichtungsfaktoren aus Eco-Indicator 95 zu wichtigen Standard-Inventaren" (in German), including a diskette with all tables (Excel 5.0) was published in September 1998 and can be ordered now (price CHF 145.-, ÖBU and SVI members, university students or faculty CHF 95.-). An English version of the tables (also Excel 5.0) is currently developed and will be available soon.

Ordering information: Swiss Association for Environmentally Conscious Management, Obstgartenstr. 28, CH-8035 Zurich/ Switzerland, phone: +41-1-364-37-38, fax +41-1-364-37-11, e-mail: oebuinfo@oebu.ch