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Screening life cycle assessment (LCA) of tomato ketchup: a case study

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Abstract

A screening life cycle assessment (LCA) of tomato ketchup has been carried out. The purpose was to identify ‘hot-spots’, that is parts of the life-cycle that are important to the total environmental impact. The system investigated includes agricultural production, industrial refining, packaging, transportation, consumption and waste management. Energy use and emissions were quantified and some of the potential environmental effects assessed. Packaging and food processing were found to be hot-spots for many, but not all, of the impact categories investigated. For primary energy use, the storage time in a refrigerator (household phase) was found to be a critical parameter. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Life cycle assessment; LCA; Foods; Tomato products; Ketchup

1. Introduction

The current systems for food production require large inputs of resources and cause several negative environmental effects. The systems are optimised to satisfy economic demands and the nutritional needs of a rapidly growing world population. Environmental issues, however, have not been central.

There are many difficulties in conducting life cycle studies of food products. Ideally, a complete study should include agricultural production, industrial refining, storage and distribution, packaging, consumption and waste management, all of which together comprise a large and complex system. The lack of public databases hinders collection of suitable data. Another difficulty is that life cycle studies involve many scientific disciplines. In the 1970s and early 1980s, the use of energy in food production systems was widely studied [1,2]. Most food life cycle studies carried out so far treat either agricultural production or industrial refining; for example, the cultivation of tomatoes has been studied [3]. There have been only a few studies that attempted to cover the entire life cycle of a food product; for example, a screening life cycle inventory (LCI) of rye bread and ham with emphasis on establishing the energy and material flows [4].

The aim of the study presented here was to carry out a screening life cycle assessment (LCA) to learn more about the options and limitations of applying the method to food production systems. Tomato ketchup was chosen as a suitable product. As the work was done in close co-operation with a Swedish producer of tomato ketchup and an Italian producer of tomato paste, it was possible to obtain a large amount of site-specific inventory data. The impact assessment made includes the following environmental effects: global warming, ozone depletion, acidification, eutrophication, photo-oxidant formation, human toxicity and ecotoxicity. Intermediate inventory results have already been reported [5]. A more thorough description of the model system, the assumptions made and the data used, can be found in the comprehensive report (in preparation).

2. Method

2.1. Goal definition

The main goal of the case study, part of a research project funded by the Swedish Waste Research Council,

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was to identify key issues associated with the life cycle of tomato ketchup, such as (1) the steps of the life cycle which give rise to the most significant environmental input and output flows, that is hot spots, and (2) major gaps in the data available. The comprehensive report (in preparation) includes, in addition to the screening LCA: a comparison of the current packaging system for ketchup and an alternative one, and an improvement assessment of a selected part of the life cycle.

2.2. The product and the system investigated

The product studied is one of the most common brands of tomato ketchup sold in Sweden; it is marketed in 1 kg red plastic bottles. The complete system investigated is shown in Fig. 1. The packaging systems for tomato paste and ketchup are shown in Figs. 2 and 3, respectively. The life cycle can be described briefly as follows. Tomatoes are grown and processed into tomato paste in the Mediterranean countries; then the tomato paste is transported to Sweden and processed (together with other ingredients and water) into ketchup. Thereafter, the ketchup is packaged, delivered to retailers and, finally, consumed. The tomato paste is packed in aseptic bags which are placed in steel barrels. Each bag contains 200 l of tomato paste. The plastic bottle used for ketchup is made of polypropylene (PP) and is blow-moulded. It consists of five layers: an inner wall of PP; adhesive; a barrier layer of ethylenevinylalcohol (EVOH); adhesive; and an outer wall of PP.

The model system was divided into six subsystems. For the packaging and household subsystems, alternative scenarios were analysed. Table 1 shows a summary of the subsystems, the processes they include and the scenarios investigated. For the packaging subsystem, the waste management scenarios investigated are further defined in Table 2.

2.3. The functional unit

The functional unit (FU) is defined as 1000 kg of tomato ketchup consumed, assuming a 5% loss in the household phase. We prepared a questionnaire which was answered by 30 persons and collected their ketchup bottles at the point of disposal. This very limited survey indicated: (1) that the household scenarios are realistic as to storage time; and (2) that the losses vary significantly, that is values from 0.5% to 26% were recorded. The 5% loss assumed was validated as a reasonable estimate; other losses can easily be simulated with the scenario technique.

2.4. The inventory analysis and data collection

For the inventory analysis, a summary of the processes included, the data sources and the principles of allocation applied are shown in Table 3. Our ambition was to use site-specific inventory data, whenever possible. To collect this data and other information, we used our own questionnaire, interviews and environmental reports. The Swedish producer of ketchup has several suppliers of tomato paste in Italy, Spain and Portugal; the inventory data for tomato paste were collected from one of the suppliers in Italy. The data for cultivation of tomatoes were collected from one of the farms supplying the Italian tomato paste plant. Most of the inventory data were collected in 1993 and 1994.

2.5. The system boundaries

Procedures and results from the inventory analysis have already been presented [5]. Since then, the system investigated has been expanded to include: production of electricity; cultivation of sugar beets; production of raw sugar; treatment of the waste water from production of both the sugar solution and the ketchup; shopping; and the household phase. Thermal energy was accounted for as the amount used for combustion. Whenever emission factors were used, emissions from the fuel extraction (precombustion emissions) were included. For electricity from a grid, average country-specific data for electricity production were used when the geographic location of the process was known. Otherwise average figures for European electricity were used (see Table 3). These figures are based on data for the ‘Union for the Connection of Production and Transportation of Electricity, UCPTE 88’ as presented by BUWAL [6].

To compare the environmental impacts of the two waste management scenarios for the packaging materials (see Tables 1 and 2), system expansion with a marginal substitute, oil, was applied [9,13]. Thus, for waste incineration, the energy recovered was subtracted from the scenario’s total energy use. The energy recovered was also assumed to mean a reduced need of oil for heating purposes. The emissions from scenarios including waste incineration were therefore adjusted: the emissions that would have resulted, if oil had been used to generate the amount of energy recovered, were subtracted from the total emissions of the scenario.

The treatment of waste water, at the municipal plant, was included for the production of ketchup and sugar solution; the other food processing plants have their own waste water treatment. Since the municipal plant treating the effluent from the ketchup production receives 90% of its load from this particular food industry, site-specific data from this waste water treatment plant were used. For treatment of the effluent from sugar solution production, general data on efficiencies and energy use for an assumed waste water treatment plant with mechanical, biological and chemical treatment were used [12]. This type of plant is the most common in Sweden.

Due to data gaps, the following steps were left outside

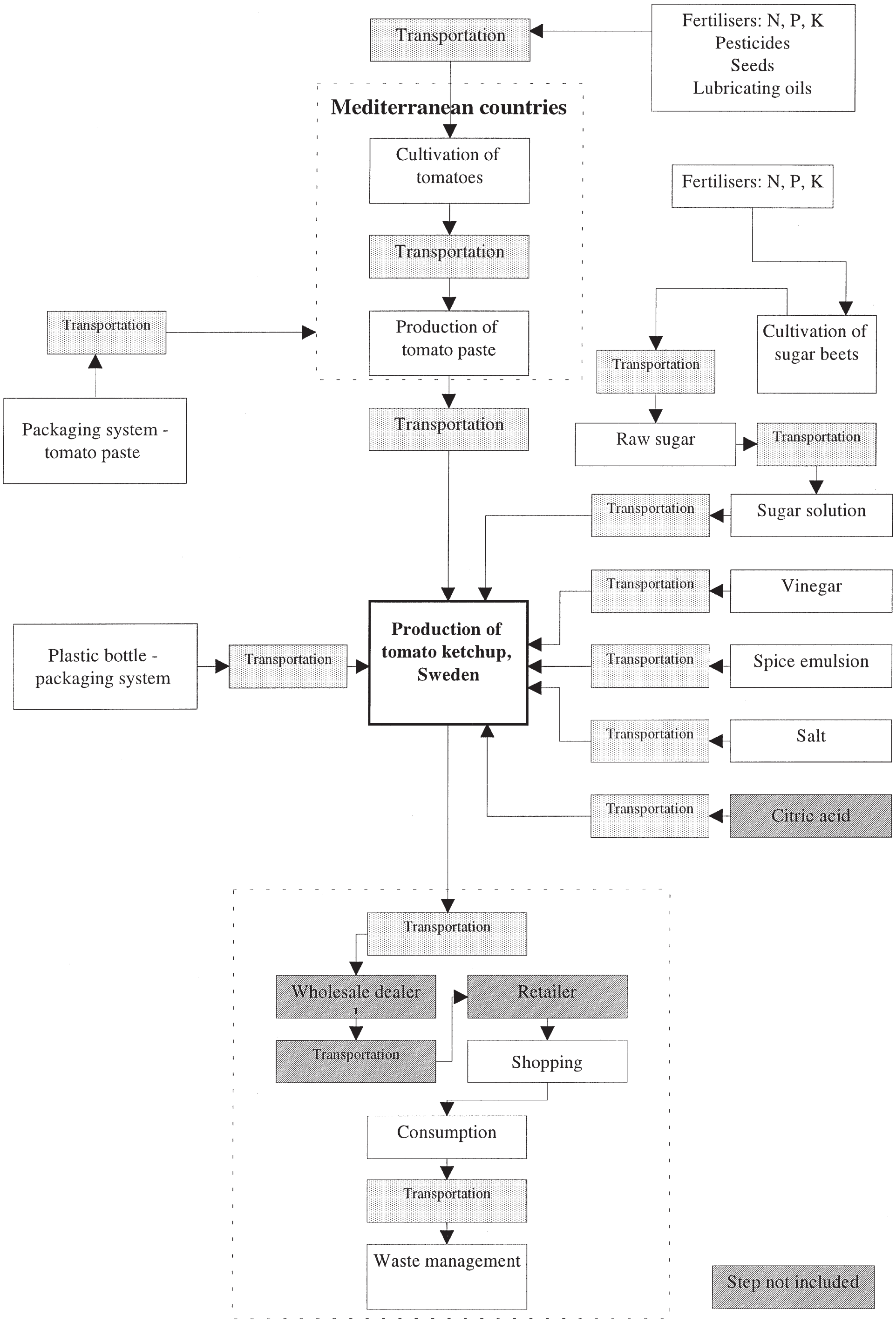

Fig. 1. Principal flow chart of the life cycle of the Swedish tomato ketchup.

the system boundaries: the production of capital goods (machinery and buildings); the production of citric acid; the wholesale dealer; transportation from the wholesaler to the retailer; and the retailer. Likewise, for the ketchup bottles, the production of adhesive, EVOH, pigment, labels, glue and ink were omitted due to lack of accessible data. The aseptic bags used for the tomato paste contain 7% polyethyleneterephthalate (PET) and 0.03% aluminium; these materials were omitted, due to the small amounts in which they occur. For the household phase, leakage of refrigerants was left outside the system boundaries.

In the cultivation steps, the assimilation of CO_2 by the crops was not taken into consideration; neither was leakage of nutrients and gaseous emissions such as ammonia and nitrous oxide from the fields. Models for

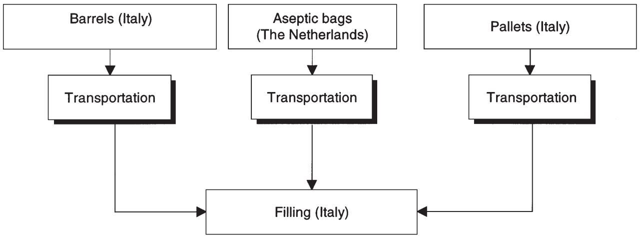

Fig. 2. The tomato paste packaging system investigated.

doing this need to be worked out. For pesticides, a quantitative inventory and impact assessment were found to be beyond the scope of this study. The types and amounts of pesticides applied are closely related to the weather, which means that inventory data need to be collected for longer time periods. In addition, models for leakage and degradation mechanisms as well as weighting factors for many of the active substances involved are unavailable.

2.6. Methodological choices, assumptions and simplifications

For the production of tomato paste and ketchup, allocation was made by weight. The results obtained were validated in the following ways.

- At the tomato paste plant, mass allocation yields the following requirements per tonne of product: 5.9 GJ thermal and 0.38 GJ electrical energy. As to thermal energy use, the specific production line is dominated by the evaporation and sterilisation steps for which data on the use of steam and electricity were collected and requirements of 5.1 GJ thermal and 0.18 GJ electrical energy per tonne tomato paste were calculated.

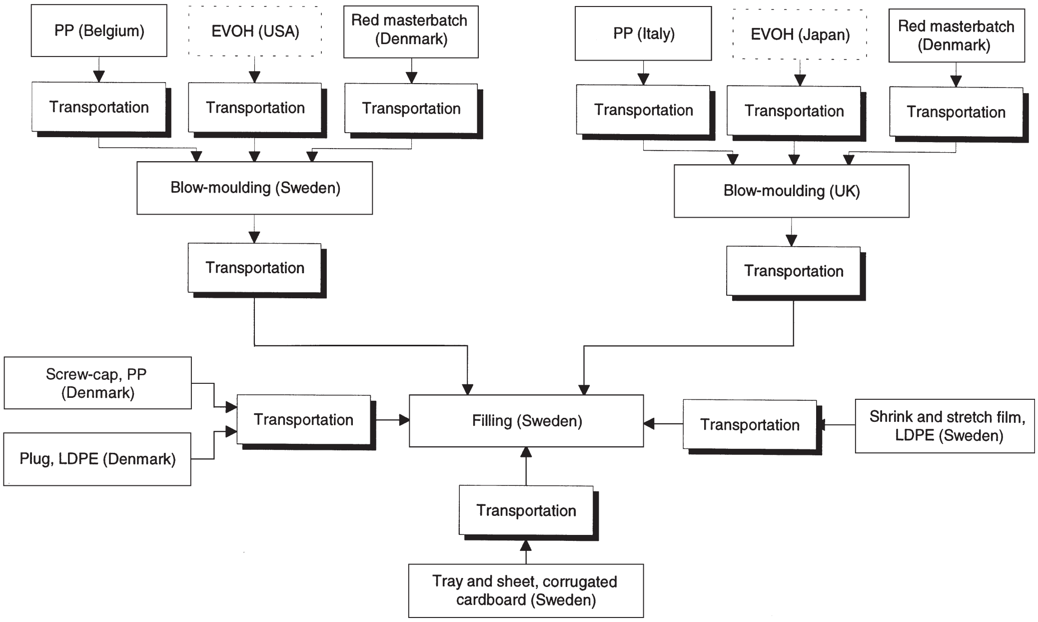

Fig. 3. The ketchup packaging system investigated. LDPE is short for low density polyethylene. The dotted lines around EVOH indicate that the production of EVOH was not included within the system boundaries.

Table 1
The ketchup production subsystems, the processes included and the scenarios investigated

Subsystem	Processes included	Scenarios
Agriculture	Cultivation of tomatoes and sugar beets. Production of inputs to the cultivation steps	
Food processing	Production of tomato paste, raw sugar, sugar solution, vinegar, spice emulsion, salt and ketchup	
Packaging	Production and transportation processes included in the packaging systems for tomato paste and ketchup	Waste management: (1) Landfill, (2) Material recycling and/or incineration with energy recovery
Transportation	All transportation processes except for the transports included in the packaging subsystem	
Shopping	Transportation from retailer to household	
Household	Storage of ketchup bottle in refrigerator	Storage time: (A) One month, (B) One year

Table 2
The tomato paste and ketchup packaging systems and the different waste management scenarios

	The tomato paste packaging system	The ketchup packaging system
Scenario 1	Steel barrels, plastic materials and wood pallets: to landfill	Plastic materials: to landfill. Corrugated cardboard: 80% to recycling and 20% to landfill. Wood pallets: reused 100 times, then to landfill
Scenario 2[a]	Steel barrels: 70% to recycling and 30% to landfill. PP: 80% to incineration and 20% to landfill. LDPE and wood pallets: to incineration	LDPE: to incineration. PP: 80% to incineration and 20% to landfill. Corrugated cardboard: 80% to recycling and 20% to incineration. Wood pallets: reused 100 times, then to incineration

[a] Incineration means that the inherent energy is recovered.

Table 3
The processes included, the sources of data and the principles of allocation used for the inventory analysis

Process	Type or source of data	Source of emission factors	Principle of allocation used
Fertiliser N	[4]	[6][a] c[b]	
Fertilisers P and K	[7][a] [4][b]	[6][a] c[b]	
Pesticides	[4]	[6]	
Lubricating oils	[7]	[6]	
Seeds	[7]	[6]	
Tomatoes	Site-specific estimates, Italy	[6]	
Sugar beets	[4] and site-specific estimates, Sweden	[8]	
Tomato paste	Site-specific, Italy	[6]	By weight, for the main products of the plant
Raw sugar	Site-specific, Sweden	c	
Sugar solution	Site-specific, Sweden	[9]	
Vinegar	Site-specific, Sweden		
Spice emulsion	Site-specific, Sweden		
Salt	[4]	[9]	
Tomato ketchup	Site-specific, Sweden	c	For emissions caused by use of thermal energy, by weight for the main products of the plant. For water emissions, by flows of water through the different production lines
Packaging system for tomato paste	[6]: PP, [9]: steel, LDPE and wood		
Packaging system for ketchup	[6]: PP, [9]: LDPE, corrugated cardboard and wood. Site-specific: blow-moulding and red master-batch		
Transportation	Site-specific: type of vehicle and distance	[8]	
Shopping	Own estimates	[10]	
Household phase	Own estimates		
Electricity production	Average, country-specific. Average, Europe	c, [11]	
Waste management	Packaging materials, as specified above. Waste water: site-specific and [12]		

[a] Tomatoes.
[b] Sugar beets.
c: The software 'LCA Inventory Tool' (LCAiT).

Thus, the results obtained by mass allocation appear reasonable. Besides tomato paste, canned peeled whole tomatoes and diced tomatoes are produced. Literature data were used to check the stability of the results; for canned fruits and vegetables, requirements of 5.2 GJ thermal and 0.20 GJ electrical energy per tonne have been reported [2].

- Co-products in the ketchup plant are salad dressing, cooking oil, jam, mayonnaise and horse-radish; however, the ketchup dominates by mass: 66% of the total production. Mass allocation yields the requirement of 1.7 GJ thermal energy per tonne of product. (The requirement of 0.38 GJ electricity was recorded for the ketchup production line.) According to literature data, the energy requirements of the product groups 'pickles, sauces and salad dressings' and 'cooking oils' are of similar magnitude (ketchup can be regarded as a sauce). For pickles, sauces and salad dressings, the energy requirement 2.6 GJ thermal plus 0.48 GJ electrical energy per tonne has been reported;

for cooking oils, the corresponding figures are 3.0 GJ thermal plus 0.24 GJ electrical energy [2]. Since jam is heated in a process similar to that used for ketchup, the thermal energy requirement per mass unit should be comparable to the one for ketchup. Mayonnaise and horse-radish are produced in relatively small volumes.

To enable including the transportation of ketchup between the retailer and the consumer, many assumptions had to be made. The basic parameters for calculating the environmental loads caused by shopping are:

- the proportion of trips made by car, assumed to be 55%;
- the distance driven, assumed to be 2.5 km each way; and
- the amount of groceries bought, assumed to be 10 kg.

The environmental loads were allocated by weight for the products bought.

To include the loss occurring in the household phase, all of the results from the inventory analysis were multiplied by 1.05. This was done to link the environmental loads caused by the losses to their actual geographic location. For the rest of the system, the calculations were carried out as if there were no losses. For example, all of the tomatoes harvested were assumed to be used in the production of tomato paste. All of the tomato paste produced was assumed to be used in the production of tomato ketchup, and so on.

For the cultivation steps, we have assumed: that only fertilisers (no manure) are used; and that agricultural land is contaminated with 660 mg zinc, 100 mg arsenic and 60 mg cadmium per kg phosphorous applied as fertiliser [4].

2.7. The impact assessment

In the classification and characterisation done we have followed the Nordic Guidelines [12]. The contributions to the following impact categories were assessed.

- Global warming was obtained, for direct greenhouse gases, by using Global Warming Potentials (GWPs) of the time-horizons 20, 100 and 500 years [14]. Indirect greenhouse gases were included to check the influence on the results [15,16].
- Depletion of stratospheric ozone was worked out by using the inventory results for methane, nitrous oxide, carbon monoxide and non-methane hydrocarbons, since these substances contribute directly or indirectly to the effect. No substances for which Ozone Depletion Potentials (ODPs) are available were identified in the inventory analysis.
- Acidification was assessed by using the 'protons released approach' with its minimum and maximum scenarios.
- Eutrophication was found by means of the 'scenario-based approach' which divides the category into five subcategories. As a complement to the characterisation results, the inventory parameter BOD (Biological Oxygen Demand) was taken into consideration; for some processes BOD is known but not COD (Chemical Oxygen Demand), and vice versa.
- Photo-oxidant formation was obtained by using the concept of Photochemical Ozone Creation Potentials (POCPs) [15,17,18] and inventory results were used for substances that lack available weighting factors.
- Human toxicity was assessed by using the CML provisional and Tellus methods; ecotoxicity was handled with the CML provisional method [18,19]. In addition, for radioactive waste and radon, the inventory results were taken into consideration.

3. Results

The use of primary energy and potential contributions to global warming, ozone depletion, acidification, eutrophication, photo-oxidant formation, human toxicity and ecotoxicity, at subsystem level, are presented next.

3.1. Energy use

The use of primary energy and the energy sources are shown in Fig. 4. The scenario for the household subsystem (time for storage in the refrigerator) is critical. The figure used for storage in the refrigerator is 4.73 Wh per litre and day [4]. Primary energy use in this subsystem varies between approximately 10% and 50% of the total. It is clear that the energy requirements of the food processing and the packaging subsystems are also important. In food processing, approximately one third of the energy requirement is for the production of tomato paste; one third for the other ketchup ingredients; and one third for the ketchup itself. For the packaging subsystem, the scenario is not as critical as for the household subsystem. Note that the transportation subsystem and the process of shopping have similar energy requirements. The contribution of transportation to the packaging subsystem is not known, since the form of literature data does not allow one to distinguish efficiently the energy used for production from that used for transportation.

3.2. Global environmental effects

The characterisation results for global warming are shown in Fig. 5. The food processing and the packaging subsystems make large contributions to global warming because of their high consumption of fossil fuels. The low contribution from the household subsystem is due

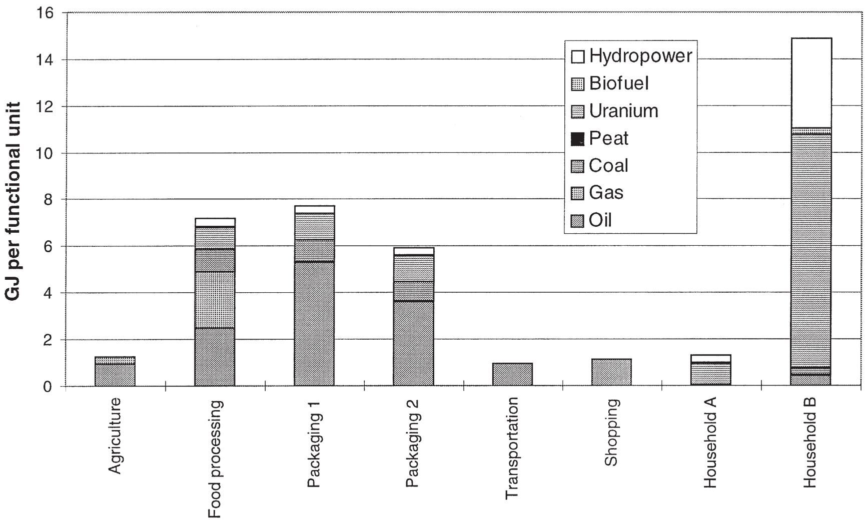

Fig. 4. The use of primary energy in the ketchup production system.

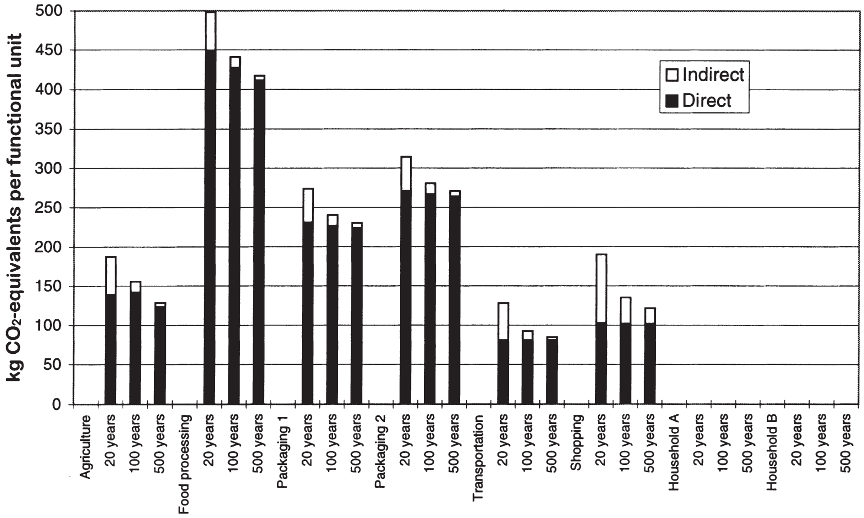

Fig. 5. The assessed contributions to global warming.

to the assumption that only Swedish electricity is used and the fact that the Swedish electricity model is dominated by hydropower and nuclear power; for a 100-year time frame, the contributions made by the households A and B are approximately 2.2 and 26 g CO_2-equivalents per functional unit (FU), respectively. The contributions made by indirect greenhouse gases are, except for the process of shopping, relatively small; they decrease with longer time frames.

For ozone depletion, the inventory results for methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO) and non-methane hydrocarbons (NMHC) are shown in Table 4.

3.3. Regional environmental effects

The contributions assessed for the regional environmental effects, acidification, eutrophication and photo-oxidant formation, are shown in Tables 5–9. For acidification, the food processing subsystem is an obvious hot-spot (see Table 5). Since the geographic location is of significance, it is relevant to analyse the food processing subsystem further. Depending on the characterisation model chosen, the sulphur dioxide (SO_2) emitted in the production of tomato paste is responsible for between 70% and 90% of the effect. This life cycle step is here located specifically in northern Italy; the combination of high energy use and the choice of fuel (heavy fuel oil) is the cause of the high SO_2-emission. The reason for the negative contribution shown by the Packaging 2 scenario is an avoided emission of SO_2, due to the assumption that the energy recovered from waste incineration replaces heat produced by combustion of oil. The differences between the results of the minimum and maximum characterisation models vary. The minimum model excludes the acidifying potential of nitrogen com-

Table 4
Inventory results for emissions contributing to ozone depletion in g per FU

Subsystem	CH_4	N_2O	CO	NMHC
Agriculture	21	130	370	420
Food processing	620	38	62	540
Packaging 1	120	5.7	160	900
Packaging 2	120	5.7	210	860
Transportation			330	98
Shopping	29	2.2	7600	770
Household A	7.8×10^{-5}	2.3×10^{-4}	1.2×10^{-3}	6.1×10^{-4}
Household B	9.1×10^{-4}	2.7×10^{-3}	1.4×10^{-2}	7.2×10^{-3}

Table 5
Characterisation results for acidification in mol H^+ per FU

Subsystem	Minimum	Maximum
Agriculture	8.4	38
Food processing	94	120
Packaging 1	15	25
Packaging 2	− 7.4	3.7
Transportation	13	44
Shopping	1.2	9.0
Household A	1.1×10^{-4}	2.3×10^{-4}
Household B	1.4×10^{-3}	2.7×10^{-3}

pounds; thus, the smaller the emissions of nitrogen compounds from a subsystem, the less difference between the models.

For eutrophication, the agriculture subsystem is an obvious hot-spot, even though leakage of nutrients in the cultivation steps was omitted (see Table 6). The relatively high contribution made by agriculture to the ‘P-limited’ subcategory is due to emissions of phosphate from the production of phosphorous fertilisers. For the ‘N to air’ subcategory (terrestrial eutrophication), the agriculture, transportation and food processing subsystems are hot-spots. When emissions of nitrogen compounds dominate, the ‘N-limited + N to air’ and ‘Maximum’ subcategories show similar results. As a complement to the characterisation results, as well as to highlight the effect of including or excluding the waste water treatment, the inventory results for the parameter BOD are presented in Table 7.

Characterisation results for photo-oxidant formation are shown in Table 8; inventory results for nitrogen oxides and other organic compounds are shown in Table 9. For the characterisation results, it is important to note which substances are included in the different characterisation models. While the ‘Local, Europe’ model includes the emissions of hydrocarbons (HC), aldehydes, ethanol and methane, the other models include *only* the emissions of ethanol and carbon monoxide. Ethanol is a parameter that occurs only in the production of vinegar; hence the relatively high contribution to photo-oxidant formation from the food processing subsystem. The high contribution made by the packaging subsystem, according to the ‘Local, Europe’ model, is due to the emissions of HC.

Table 7
Inventory results for biological oxygen demand (BOD)

Subsystem	BOD (kg per FU)
Agriculture	8.1×10^{-5}
Food processing excluding waste water treatment	8.4
Food processing including waste water treatment	0.27
Packaging 1	0.15
Packaging 2	0.15

Table 6
Characterisation results for eutrophication in kg O_2 per FU

Subsystem	P-limited	N-limited	N to air	N-limited plus N to air	Maximum
Agriculture	31	8.4	9.7	18	49
Food processing	0.79	1.2	6.9	8.1	8.4
Packaging 1	0.35	0.35	2.8	3.1	3.1
Packaging 2	0.35	0.35	3.1	3.5	3.5
Transportation	1.1×10^{-3}	5.3×10^{-3}	8.4	8.4	8.4
Shopping	1.2×10^{-3}	5.9×10^{-3}	2.2	2.2	2.2
Household A			3.4×10^{-5}	3.4×10^{-5}	3.4×10^{-5}
Household B			3.9×10^{-4}	3.9×10^{-4}	3.9×10^{-4}

Table 8
Characterisation results for photo-oxidant formation in g ethene-equivalents per FU

Subsystem	Regional, Sweden[a]	Local, Sweden[a]	Regional, Europe[a]	Local, Europe[b]
Agriculture	15	13	12	160
Food processing	32	60	43	190
Packaging 1	6.6	5.9	5.3	340
Packaging 2	8.6	7.7	6.8	330
Transportation	13	12	11	37
Shopping	300	270	240	290
Household A	4.8×10^{-5}	4.3×10^{-5}	3.8×10^{-5}	2.3×10^{-4}
Household B	5.6×10^{-4}	5.0×10^{-4}	4.5×10^{-4}	2.7×10^{-3}

[a] Assessed by using the POCPs of Finnveden et al. and Andersson-Sköld et al. [15,17].
[b] Assessed by using the POCPs of Heijungs et al. [18].

Table 9
Inventory results for substances (without weighting factors) contributing to photo-oxidant formation

Subsystem	NO_x (kg per FU)	Other organic compounds (g per FU)
Agriculture	1.1	1.2
Food processing	1.1	3.4
Packaging 1	0.45	
Packaging 2	0.51	
Transportation	1.4	
Shopping	0.36	
Household A	5.1×10^{-6}	
Household B	6.0×10^{-5}	

3.4. Toxicity

The characterisation results for human toxicity and ecotoxicity are presented in Tables 10–12. According to both the Tellus method for human toxicity and the CML provisional method for ecotoxicity, the agriculture subsystem is a hot-spot even though leakage of pesticides was not quantitatively included. The reason is the content of heavy metals in phosphorous fertilisers. The inventory results for radioactive waste (caused by the production of electricity) and emissions of radon (caused by the extraction of coal) are presented in Table 13.

Table 11
Contributions to human toxicity assessed according to the Tellus method

Subsystem	Carcinogens (g isophorone-equiv. per FU)	Non-carcinogens (g xylene-equiv. per FU)	Combined ranking
Agriculture	4100	23,000	28,000
Food processing		8.0	8.0
Packaging 1		4.2	4.2
Packaging 2		4.2	4.2
Transportation		0.019	0.019
Shopping		0.021	0.021
Household A			
Household B			

4. Conclusions and discussion

The most important goal of any life cycle study is, of course, to improve and optimise the system. Based on the study carried out, we have identified parts of the life cycle that are critical to the total environmental impact as well as some major gaps in the available data. The use of energy has often been employed as an indicator of environmental impact. The results presented illustrate the complexity in a scientific evaluation of a product's environmental performance; the results of the energy

Table 10
Contributions to human toxicity assessed according to the CML provisional method in kg body weight per FU

Subsystem	Air emissions	Water emissions	Soil emissions	Total
Agriculture	1.2	0.026	1.3×10^{-3}	1.2
Food processing	4.5	1.9×10^{-6}		4.5
Packaging 1	0.94	1.8×10^{-5}		0.94
Packaging 2	0.11	1.7×10^{-5}		0.11
Transportation	1.6	3.0×10^{-7}		1.6
Shopping	0.41	3.4×10^{-7}		0.41
Household A	8.4×10^{-6}			8.4×10^{-6}
Household B	1.0×10^{-4}			1.0×10^{-4}

Table 12
Contributions to ecotoxicity assessed according to the CML provisional method

Subsystem	Water emissions (m^3 per FU)	Soil emissions (kg soil per FU)
Agriculture	180	8600
Food processing	680	
Packaging 1	2700	
Packaging 2	2600	
Transportation	58	
Shopping	66	
Household A		
Household B		

analysis do not always point in the same direction as those of the impact assessment. The need for simulations to facilitate environmental improvements and optimisation is evident.

For many of the impact categories, the packaging and food processing subsystems were found to be hot-spots. For primary energy use, the length of time for storage in a refrigerator (household phase) was found to be a critical parameter. With a storage time of one year, the use of primary energy in the household phase is as high as the energy use of the packaging and food processing subsystems together. An example of an impact category with a different result is eutrophication; for this effect, the agriculture subsystem is an obvious hot-spot. For the impact categories ozone depletion and photo-oxidant formation, it is not possible to draw any general conclusions. For ozone depletion, each parameter from the inventory must be evaluated separately. However, as long as freons from refrigerators leak, the household phase can be expected to contribute significantly. For photo-oxidant formation, it is necessary to compare carefully the results from the different characterisation models and to keep in mind the parameters they include. According to the characterisation results, the shopping, packaging and food processing subsystems are hot-spots. For NO_x, the transportation subsystem is a hot-spot.

For toxicity, the agriculture, food processing and packaging subsystems were found to be hot-spots. The CML provisional method and the Tellus method for human toxicity provide different but complementary results. One of the reasons is that the CML provisional method includes some of the more common emissions to air (for example SO_2, NO_x and CO), while the Tellus method does not. Consequently, life cycle steps with high use of fossil energy show high contributions to human toxicity when the CML provisional is used. Ecotoxicity hot-spots are life cycle steps with emissions of heavy metals, phenol or crude oil. If leakage of pesticides, their intermediates and break-down products had been quantitatively considered, the agriculture subsystem would have been an even worse toxicological hot-spot.

Although uncertainties have not been quantified, they are expected to be relatively large. The results from the energy analysis are more accurate than the characterisation results; figures for fuel or electricity consumption of a process, at least at plant level, are usually available and accurate since they represent costs. The fact that certain types of emissions represent costs, for example CO_2 taxation in Sweden, has lead to monitoring and a search for methods of reduction. However, emission data are less exact in general than figures on energy use. The characterisation models introduce additional uncertainties; however, they make it easier to interpret the results since the parameters from the inventory are numerous.

The most important omissions and their possible influence on the results are summarised below.

- Production of capital goods was left outside the system boundaries. The steps most likely to be affected by including the production of capital goods are cultivation and the production of tomato paste. In the cultivation step many different machines are used and each farm usually has its own. Many of these machines are used only a few times per year. Similarly, tomato paste is produced for only a few weeks each year. The energy requirements of capital goods used for the cultivation of tomatoes was estimated, using literature

Table 13
Inventory results for radioactive waste and radon

Subsystem	High radioactivity (cm^3 per FU)	Medium radioactivity (cm^3 per FU)	Low radioactivity (cm^3 per FU)	Rn-222 (Bq per FU)
Agriculture				
Food processing	0.78	8.9	8.9	400
Packaging 1	0.71	8.1	8.1	180
Packaging 2	0.71	8.1	8.1	180
Transportation				
Shopping				
Household A	7.5×10^{-4}	8.5×10^{-3}	8.5×10^{-3}	
Household B	8.8×10^{-3}	0.10	0.10	

data for France, to be 180 MJ per FU including machinery and buildings [4]. Adjusting the calculations made for the cultivation of sugar beets (site-specific data), results in an extra requirement of 193 MJ per FU. Altogether, this corresponds to approximately 30% of the total estimated energy requirement of the agriculture subsystem.

- The wholesale and retail step was also left outside the system boundaries. Literature data for this life cycle step indicate that the energy requirements for other products are not at all negligible: 1.43 MJ per kg beer for storage at the wholesale trader in Switzerland and 1.66 MJ per kg bread in the Netherlands [20,21]. Data on the total annual energy use of the wholesale and retail step are available for Sweden [22], but there is a major data gap that hinders quantification of the share which should be allocated to ketchup.

The practical application of this study is to provide a platform for improvement analyses. The calculation model constructed (simple spreadsheets in Microsoft Excel) allows for simulations by means of which alternative scenarios for each step can be calculated and evaluated. The main problem encountered in our endeavour to apply the LCA methodology to a food system was, besides the great gaps in accessible data, how to handle the agricultural production and the consumer phase; for both these phases, collection of representative data is only one difficulty. Agricultural production makes special demands on the LCA methodology [4,23–26]. For instance, it is difficult to determine the system boundary between the technological system and nature; agricultural production takes place in nature itself and is actually a part of the environmental system. Ideally, all of the crops in a crop rotation system should be studied, since a crop may be influenced by the previous crops; the environmental loads should then be allocated between the different crops. An allocation problem is how to handle common agricultural co-products such as straw and animal manure. Models to estimate the leakage of nutrients and pesticides in cultivation, for different soils, climate and crops, are needed in LCAs of food products; the models for characterisation of human toxicity and ecotoxicity also need further development. In particular, the energy analysis indicates that the household phase and the behaviour of the consumer in conjunction with shopping (car use, distance and amount bought) may be very important. In addition, the 5% loss in the household phase is equivalent to 5% of the total environmental impact. Accordingly, emphasis on the household phase is recommended in future studies.

In the food processing industries, the data required for life cycle studies are seldom available for the specific production line; thus, allocation or measurements must be conducted. Measurements are very valuable for validation of simple allocation principles for common products and processes in the food industry. For food systems, the handling of waste water deserves more attention. Waste water treatment requires energy and chemicals; this produces emissions. It would be relevant to simulate alternative scenarios for the waste water handling. In the right place, waste water from the food industry would be a source of nutrients or a resource for production of biogas.

The case study reported here 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 contributes to the high quality of data presented. One of the reasons for the choice of tomato ketchup is that its life cycle represents a rather common food-product life cycle: it includes a harvest, a preservation process (seasonal production), storage, transportation and, finally, further processing into a consumer product. The conclusions are of course specific for the tomato ketchup studied; however, similar results could be expected for jam and juices. Another reason for the choice of ketchup was the interest of the Swedish ketchup producer and their willingness to participate. Without such support, it would not have been possible to obtain site-specific data.

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