LCA Case Studies

# Life Cycle Assessment of Different Reuse Percentages for Glass Beer Bottles

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**Abstract**. Life cycle assessment (LCA) is increasingly becoming an important tool for ecological evaluation of products or processes. In this study the environmental impacts associated with the returnable and the non-returnable glass beer bottles were assessed in order to compare different reuse percentages. The inventory analysis is performed with data obtained from two Portuguese companies (a glass bottles producer and a brewery) and completed with the BUWAL database. It includes all operations associated with the bottles' manufacture, the brewery and the wastewater treatment plant. The environmental impact assessment considers both the potential ecological and ecotoxicological effects of the emissions. The environmental impact categories included and discussed in this study are the contribution to ecological and human health, global warming, stratospheric ozone depletion, acidification, eutrophication and photochemical ozone creation. The first category is divided into three subcategories that are human toxicity, critical air volume and critical water volume. This study was performed for several reuse percentages and returnable bottle cycles, and is comprised of a sensitivity analysis. The general output is that the relative importance of the impacts associated with the use of returnable and/or non-returnable bottles depends on the number of cycles performed by the returnable bottles. According to the impact index defined in this study, the most significant impacts are the eutrophication and the final solid wastes generated, and the least significant impact is the ozone depletion.

**Keywords:** Environmental impacts; glass bottles; impact index; life cycle assessment; LCA; reuse; recycling

## Introduction

Life cycle assessment can provide opportunities for companies evaluating the environmental attributes of its products and services. It embraces cleaner production concepts such as the efficient use of raw materials, pollution prevention, source reduction, waste minimisation, internal recycling and reuse, and also features a life cycle perspective which follows products from the acquisition of raw materials to the final disposal stages. Performing an environmental assessment can not only identify and reduce environmental impacts and consequent liabilities, but may also save considerable time and money. Companies which implement eco-efficient practices will be able to respond more aggressively to competitive pressures, anticipate customer needs, protect the environment, and enhance their reputation and trust by demonstrating the careful and responsible actions of their business.

LCA was firstly defined by the Society of Environmental Toxicological and Chemistry (Consoli et al. 1993) as a methodology to evaluate the environmental burdens associated with a product, a system or an activity. The process describes quantitatively or qualitatively the use of energy and materials and the wastes released, and assesses the environmental impacts of the product or activity, from raw material acquisition, manufacturing, distribution, use, reuse, maintenance, recycling, final disposal and all transportation involved. LCA addresses environmental impacts of the system under study in the areas of ecological systems, human health and resource depletion.

The LCA methodology comprises four main stages: Goal definition and Scoping, Inventory Analysis, Impact Assessment and Interpretation. The methodological requirements for conducting these stages are provided in the International Standard ISO 14040 (1997) which describes the principles and framework, in the complimentary ISO 14041 (1998) that deals with the goal and scope definition and the inventory analysis. The last two stages of LCA methodology are described in the complimentary draft standards ISO 14042 (2000) and ISO 14043 (2000).

Packaging has been the subject of intense public debate. A major environmental concern is the increasing amounts of solid waste, of which packaging constitutes a considerable share. In order to carry out the environmental assessment for packaging, the development and application of LCA has been essential. The European Commission has sought to define some of the key terms, which have traditionally confused sensible debate on recycling and reuse, including returnable, non-returnable, reusable, one-way and recoverable packaging. In fact, the Directive on Packaging and Packaging Waste indicates that: "...reuse of packaging and recovery of packaging waste (and hence recycling) are both valid means for minimising its impact on the environment" (EC/62 Directive 1994). All the methods of waste minimisation: reduction, reuse, recycling and recovery have a role to play. There are many valuable applications of reuse, but under many circumstances other forms of recovery may have a greater environmental benefit. It will take the rigorous application and careful evaluation of life-cycle assessment to pass environmental judgement on the comparative benefits for using returnable or non-returnable packaging.

Several authors assessed the environmental burdens associated with packaging systems (BUWAL 1991, BUWAL 1998, Christiansen 1991, Habersatter 1991, Kooijman 1993, 1994, 1996, Smet 1990, UNEP 1996, Levy 1993). Others publications are related specially to the environmental analysis of glass bottles (Franklin Associates 1978, 1989, Franklin et al. 1990, Hunt et al. 1974, Lox 1994, Lundholm & Sundström 1986, 1989, Mekel et al. 1990, Vignon 1988).

This study assesses the environmental impacts associated with the returnable and the non-returnable glass beer bottles in order to compare different reuse percentages. It also investigates differences in the environmental impact of both bottles through their life cycle stages: manufacturing, washing, filling, crowning, pasteurising, labelling, conditioning, transporting and wastewater treatment. The LCA specific terms used in this paper are based on definitions given in the SETAC documents (Consoli et al. 1993). The packaging specific terms are based on definitions in the EC Council Directive on Packaging and Packaging Waste (1994).

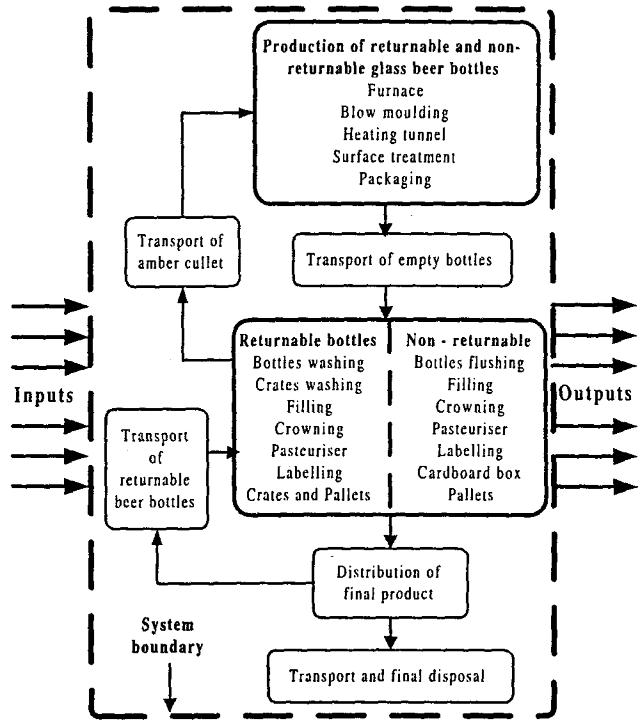


Fig. 1: Boundary for life cycle assessment of the returnable and non-returnable glass beer bottles system

## 1 Methodology for the Study

### 1.1 Goal of the study

The goal of this study is to assess the environmental impacts through the life cycle of returnable and non-returnable glass beer bottles comparing different reuse percentages. These bottles have 287g and 225g respectively and the same volume. The assessment includes the following life cycle stages: bottle manufacture, brewery and wastewater treatment plant operations and transportation.

### 1.2 Scope of the study

**Function and functional unit.** The function of this study is the distribution of beer in bottles of amber glass, 0.33 litres. The functional unit is 'the delivery of 330 litres of beer to the consumer' which corresponds to 1000 bottles (including returnable and non-returnable bottles).

**System boundary. Fig. 1** shows the system boundary limiting a flow diagram representing the different life cycle stages of the two bottle options by modules (e.g. production, filling, wastewater treatment, reuse, recycling, etc.). The inputs and outputs (materials or energy) were defined which enter and leave each module. The system boundary includes the raw material acquisition, glass bottle manufacture, cleaning, filling, closure, pasteurising, labelling, packaging, distribution, reuse, recycling, transportation of empty bottles from the bottle producer to the brewery, distribution of filled bottles to the consumer, return of bottles to refill and cullet to recycle.

**Geographical coverage.** The study was restricted to the production and distribution of these bottles in the Metropolitan area of Porto, in the North of Portugal. The distance between the two companies, bottle producer and brewery, is 30 km and the average distance to the distribution of these bottles in the Metropolitan area of Porto is 50 km. A truck is used to transport the bottles from the producer to the brewery, from the brewery to the consumer, to return bottles for refilling and cullet for recycling.

**Time-related coverage.** The chosen time period is twelve months. Apart from being the period for which the industries maintain records, it also smoothes out any atypical behaviour, such as machine breakdowns, start-ups or seasonal differences, while being sufficiently short so that genuine improvements are not masked.

**Sources of the data, their representativeness.** The data was collected from two Portuguese industries (one glass bottles producer and one brewery), from literature (BUWAL 1991, 1998) and engineering calculations conducted by the authors.

To have an idea of the data quality, a data quality indicator (DQI) was defined. The DQI was developed in the Swiss Federal Institute of Technology Zurich (BUWAL 1998) to be used in their standard questionnaire on manufacture. It provides information on data origin, category and type, relating data with a corresponding symbol. In this study, the following relationships were used:

- data origin: plant (P), literature (L) or other (X)
- data category: measured (I), calculated (II) or estimated (III)
- data type: single value (e), mean value of several single values (m) or other (x)

**Table 1** gives an overview of the data sources and their representativeness using the DQI. The majority of the inventory data have a good quality and representativeness because they are an average of several single values measured directly from the plant. The data covered by literature (BUWAL 1991, 1998) are the wastewater characterisation

**Table 1:** Overview of the DQI corresponding to the input and output values of the inventory

| Inputs / Outputs | DQI |
|---|---|
| Bottle manufacture: | |
| Material consumption | Plm |
| Water consumption | Plm |
| Energy consumption | Plm |
| Wastewater | Llm |
| Air emissions | Plm |
| Solid waste | Plm |
| Brewery: | |
| Material consumption | Plm |
| Water consumption | Plm |
| Energy consumption | Plm |
| Wastewater | Plm |
| Air emissions | Lllm |
| Solid waste | Plm |
| Brewery wastewater treatment plant: | |
| Material consumption | Llle |
| Water consumption | Llle |
| Energy consumption | Llle |
| Effluent | Plle |
| Air emissions | Plle |
| Solid waste | Plle |

from the bottle manufacture and the air emissions from the brewery. The data from the wastewater treatment plant are calculated from plant, literature and process design calculations (Metcalf and Eddy 1991, Eckenfelder 1989).

In order to have an idea of the importance of error propagation in final results, we also include a sensitivity analysis. It consists of a quantitative data quality analysis, which considers a variation of 10% more and 10% less of the data concerning materials, water and energy consumption, emissions to air, water and soil. This sensitivity analysis was extended to the values of critical concentrations used in the study. Here, the variation was one order of magnitude.

### 1.3 Life cycle inventory analysis

The relevant input and output values were calculated and totalled over the life cycle of the two types of glass bottles. The flow of material and energy in the study was followed from the acquisition of raw materials through processes, transportation, etc. to the disposal. Mata (1998) and Mata and Costa (1998, 1999a, 1999b) report the data identified and quantified in the inventory analysis.

**Calculation assumptions.** Extraction and processing of natural resources, extraction and pre-treatment of water; electricity generation; what happens in landfills, and the consumer behaviour at home (refrigerating drinks, etc.), are assumed to be similar for both cases and were therefore excluded from the study. Transportation of raw materials, energy and wastes to landfills, infrastructures, capital goods (such as buildings, machines, roads, transport vehicles, transport equipment, etc.), auxiliary material chains (closures, labels, glues, printing inks, etc.) were also assumed to be similar.

The recycling rate of glass bottles used in the calculations was 20%. The 80% not recycled, unless stated otherwise, were assumed to be stocked. The recycled material was assumed to be recycled in closed loop, here meaning that it could replace virgin material. About 18% of the raw materials in the bottle manufacture are lost as air emissions (Mata 1998, Mata and Costa 1998, 1999a, 1999b). The bottle manufacture process and its main inputs and outputs associated are presented in the **Fig. 2**.

The Portuguese brewery has two different lines for the filling of returnable and non-returnable bottles that are represented by a flow sheet in **Fig. 3** and **4**. In the returnable bottle line there is a bottle washing machine and a crate washing ma-

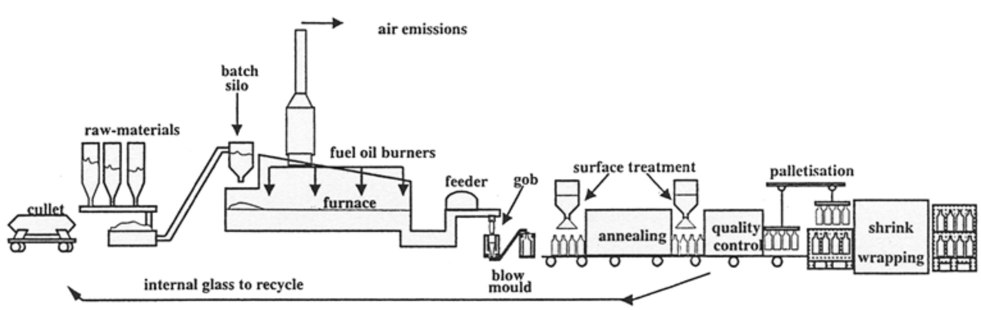


**Fig. 2:** Manufacture of glass beer bottles and the main inputs and outputs associated

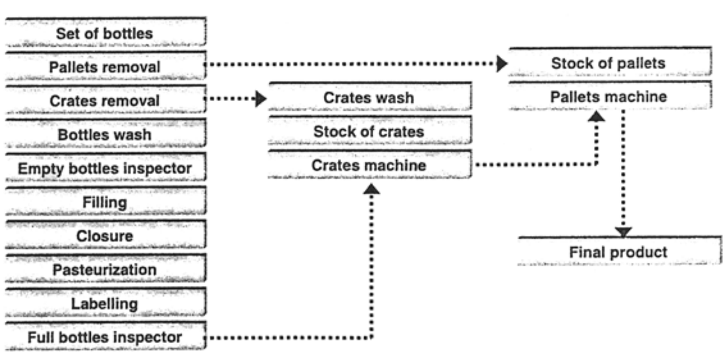


**Fig. 3:** Schematic representation of the industrial line to fill returnable beer bottles

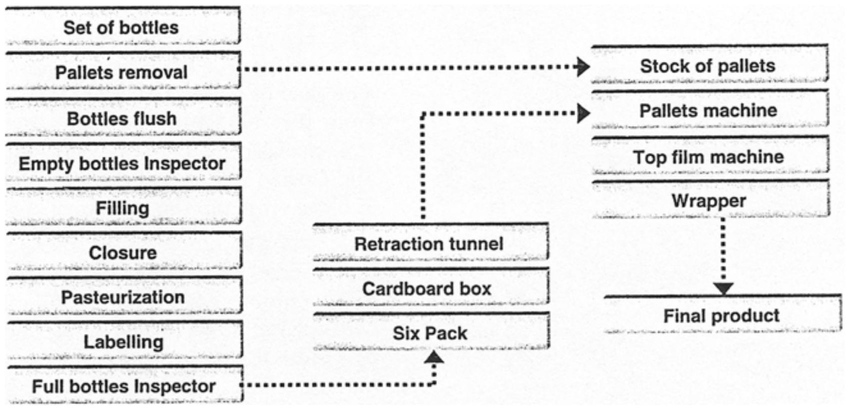


**Fig. 4:** Schematic representation of the industrial line to fill non-returnable beer bottles

chine, which don't exist in the non-returnable bottle line because they are only flushed with water. The resources used and the emissions generated by a brewery, during the processes of cleaning (washing machine or simply flushing), filling, closure (crowning), pasteurising, labelling and packaging of beer bottles are well known per bottle unit.

Brewery wastewater is generally high in organic material. Wastewater is treated biologically using both anaerobic and aerobic processes. The treatment in anaerobic reactor converts organic material to $CH_4$ and $CO_2$. In the aerobic treatment, organic material is also converted to $CO_2$ and sludge (biomass). The conversion is done with $O_2$ mechanically supplied to the reactor tank by air diffusion. The sludge generated in the wastewater treatment plant is dewatered in a belt filter press after being stabilised with lime and flocculated with polymer. The dewatered sludge has good characteristics for agricultural use. **Fig. 5** shows the wastewater treatment plant from the brewery.

According to statistical data from the brewery, oin average, a returnable bottle performs 6 to 7 cycles per year and the percentage of returnable bottle breakage in each cycle is 15%. This means that 15% of the returnable bottles need to be substituted for new ones, in order to always deliver the same volume of beer per cycle.

These assumptions allowed a comparison between the returnable and the non-returnable bottles, calculating each impact as a function of the number of reuses or cycles performed by the returnable bottle. In this comparison, all the reuse percentages were analysed (20 to 85%). The environmental impacts analysed in this comparison were: critical air and water volumes, human toxicity, global warming, ozone depletion, acidification, eutrophication, photochemical ozone creation, solid wastes, water consumption, energy consumption, raw-material consumption and auxiliary material consumption.

The category of raw-material includes the yellow sand, sodium carbonate, dolomite, lime stone, sodium sulphate, coal, iron oxide, amber cullet used in the glass bottle production.

The category of auxiliary material includes the packaging auxiliary materials (glue, labels, crown corks, cardboard, carton, crates, pallets, and plastic stretch and shrink-wraps), oils for equipment lubrication in bottle manufacture (e.g. lubrication of glass drop scissors and conveyors), tin oxide for the hot treatment and soluble polyethylene or oleic acid for the cold treatment in the bottles' manufacture, chemicals for clean, in place brewery equipment and floor cleaning agents, soap for conveyor lubrication, oils for trucks and forklifts, chemicals used for the neutralisation in the brewery's wastewater treatment plant.

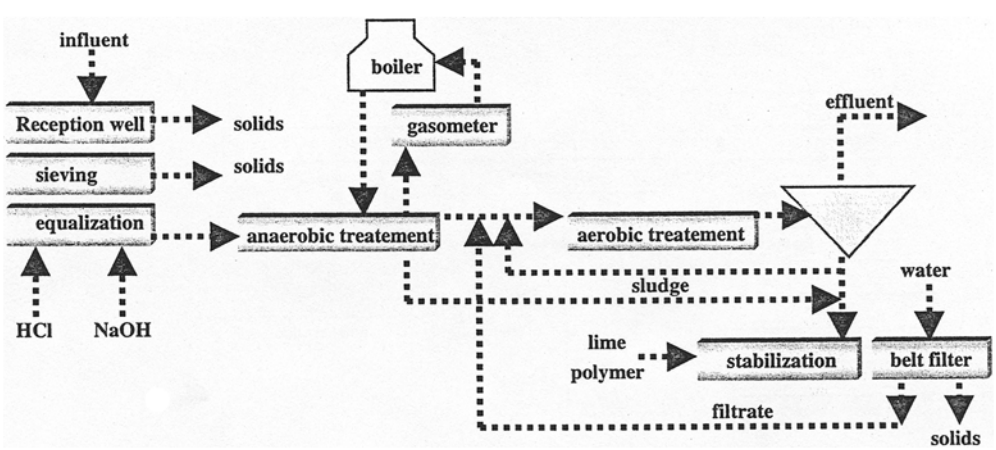


**Fig. 5:** Brewery wastewater treatment plant

It was assumed that all the potential environmental impacts have the same relative importance, i.e. the same weighting factor. Although the setting of environmental priorities reflecting social value judgements and preferences can help decisions in many cases, it introduces a certain degree of subjectivity in the study.

**Calculation procedures.** Following the data collection, calculation procedures are needed to generate the results of the inventory of the defined system for each unit process and for the defined functional unit of the product system to be modelled (ISO 14041, 1998). In order to satisfy the goal and considering the functional unit of this study, that is the delivery of 330 litres of beer, i.e. the distribution of 1000 bottles, the flows of all unit processes in the system were normalised to the functional unit.

The normalisation was made multiplying the quantity of bottles delivered by the values per bottle unit of the inventory. For example, to deliver 1000 bottles with 20% of reuse, the emissions of $CO_2$ in the first cycle were calculated for the returnable and non-returnable bottles, respectively, multiplying 200 and 800 by the corresponding values per bottle unit. For the next cycles, the emissions of $CO_2$ are only 15% of the previous value in the returnable bottle manufacture. The same procedure was used to normalise the inventory values to the several reuse percentages considered in this study, which are the following: 20%, 30%, 40%, 50%, 60%, 70% and 85%.

Tables 2 and 3 show the air emissions and the wastewater characterisation, corresponding to the processes of bottle manufacture, brewery and wastewater treatment plants for the first and n cycles. These emissions correspond to the case of 50% of reuse, i.e. both returnable and non-returnable bottles deliver the same volume of beer. The air emission data represents post-filter values, i.e. the amounts specified are those which enter the environment and the water emission values are post wastewater treatment plant.

**Table 2:** Air emissions from the bottle manufacture, brewery and wastewater treatment, corresponding to 50% of reuse

| Emissions | Bottle manufacture | | Brewery | | Wastewater treatment | |
|---|---|---|---|---|---|---|
| | Returnable (kg/330 litres) | Non-returnable (kg/330 litres) | Returnable (kg/330 litres) | Non-returnable (kg/330 litres) | Returnable (kg/330 litres) | Non-returnable (kg/330 litres) |
| **1st Cycle** | | | | | | |
| $CO_2$ | 26.3610 | 20.6663 | 6.5960 | 5.9164 | 1.9619 | 1.3080 |
| Dust | 0.5109 | 0.4005 | 0.0017 | 0.0015 | | |
| CO | 0.0143 | 0.0112 | 0.0005 | 0.0004 | | |
| $SO_2$ | 0.7797 | 0.6112 | 0.0506 | 0.0454 | 0.0221 | 0.0147 |
| $NO_x$ | 0.3582 | 0.2808 | 0.0134 | 0.0120 | | |
| $NO_2$ | | | 0.0012 | 0.0010 | | |
| $N_2O$ | 0.0131 | 0.0102 | | | | |
| HCl | 0.0107 | 0.0084 | | | | |
| HF | 0.0009 | 0.0007 | | | | |
| Pb | 0.0047 | 0.0037 | | | | |
| Cd | 0.0001 | 0.0001 | | | | |
| Zn | 0.0008 | 0.0007 | | | | |
| VOC | 0.0048 | 0.0038 | | | | |
| Hydrocarbons | | | 0.0007 | 0.0006 | | |
| CFC | | | 0.0001 | 0.0001 | | |
| $CH_4$ | | | | | 0.0052 | 0.0035 |
| **Cycle n** | | | | | | |
| $CO_2$ | 3.9542 | 20.6663 | 6.5960 | 5.9164 | 1.9619 | 1.3080 |
| Dust | 0.0766 | 0.4005 | 0.0017 | 0.0015 | | |
| CO | 0.0022 | 0.0112 | 0.0005 | 0.0004 | | |
| $SO_2$ | 0.1170 | 0.6112 | 0.0506 | 0.0454 | 0.0221 | 0.0147 |
| $NO_x$ | 0.0537 | 0.2808 | 0.0134 | 0.0120 | | |
| $NO_2$ | | | 0.0012 | 0.0010 | | |
| $N_2O$ | 0.0020 | 0.0102 | | | | |
| HCl | 0.0016 | 0.0084 | | | | |
| HF | 0.0001 | 0.0007 | | | | |
| Pb | 0.0007 | 0.0037 | | | | |
| Cd | 0.00002 | 0.0001 | | | | |
| Zn | 0.00012 | 0.0007 | | | | |
| VOC | 0.00072 | 0.0038 | | | | |
| Hydrocarbons | | | 0.0006 | 0.0006 | | |
| CFC | | | 0.0001 | 0.0001 | | |
| $CH_4$ | | | | | 0.0052 | 0.0035 |

**Table 3:** Wastewater characterisation from the bottle manufacture and brewery, corresponding to 50% of reuse

| Emissions | Bottle manufacture | | Brewery | |
|---|---|---|---|---|
| | Returnable (kg/330 litres) | Non-returnable (kg/330 litres) | Returnable (kg/330 litres) | Non-returnable (kg/330 litres) |
| **1st Cycle** | | | | |
| TSS | 283.51 | 222.26 | 0.11 | 0.07 |
| BOD | 0.14 | 0.11 | 5.36 | 3.57 |
| COD | 1.06 | 0.83 | 11.27 | 7.51 |
| Fats | 5.25 | 4.11 | | |
| N | | | 0.97 | 0.65 |
| P | 0.0131 | 0.0102 | 0.49 | 0.32 |
| Volatile Fatty Acids | 0.0107 | 0.0084 | 7.25 | 4.83 |
| **Cycle n** | | | | |
| TSS | 42.53 | 222.26 | 0.11 | 0.07 |
| BOD | 0.02 | 0.11 | 5.36 | 3.57 |
| COD | 0.16 | 0.83 | 11.27 | 7.51 |
| Fats | 0.79 | 4.11 | | |
| N | | | 0.97 | 0.65 |
| P | 0.0020 | 0.0102 | 0.49 | 0.32 |
| Volatile Fatty Acids | 0.0016 | 0.0084 | 7.25 | 4.83 |

### 1.4 Life cycle impact assessment

The selection of impact categories, indicators and models was based on guidance and requirements provided by ISO 14042 (2000). It refers to the selection of impact categories, while indicators and models shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration.

Several existing impact categories could be selected (Hunt et al. 1974, EMPA/BUS 1984, Habersatter 1991, Mekel et al. 1990, Guinée et al. 1991a, 1991b, 1991c, Christiansen 1991, Baumann et al. 1991, Finnveden 1992). For example, in the SETAC-Europe workshop (1992), the working group on classification succeeded in drafting a list of effects to be considered. It is divided into input and output-related effects. The first includes scarcely renewable and non-renewable resources (raw materials). The second includes: global warming, ozone depletion, human toxicity, environmental toxicity, acidification, eutrophication, COD discharge, photo-oxidant formation, space requirements, nuisance (smell and noise), occupational safety, final solid waste (hazardous and non-hazardous) and effects of waste heat on water.

The scope of this work is limited to ecological and ecotoxicological effects of emissions. This means that categories such as consumption of natural resources, effects of land use and nuisance were not considered. The categories that were selected for this work are focused on global and regional effects. They are the following:

**Ecological and human health:**

- Critical water and air volumes
- Human toxicity
- Global warming
- Ozone Depletion
- Acidification
- Eutrophication
- Photochemical Ozone Creation
- Final Solid Waste

**Ecological and Human Health: Critical Air and Water Volumes ($V_a$, $V_w$).** Habersatter (1991) suggested the critical volume approach. In this method, the values of water and air emissions are divided by their critical concentrations in the air and in the water. For air emission, Habersatter usesvalues of 'Maximale Immissionskonzentration' (MIK) as critical concentrations, i.e. maximum emission concentration, if such are available. Otherwise, values are approximated from 'Maximale Arbeitzplatzkonzentration' (MAK), i.e occupational exposure limits. For water emissions, Habersatter uses the quality standard values from Swiss directives for emissions into surface water. It is important to note that quality standards for human health have only a limited relevance for ecological and ecotoxicological effects.

The critical air volume, $V_{a,i}$ ($m^3$/330 litres of beer), is the volume of air required to dilute the emission of substance i to the limit set. It is calculated by dividing the value of the emission of substance i to the air, $e_{a,i}$ (kg/330litres of beer), by the critical concentration of this substance in the air, $c_{a,i}$ (mg/$m^3$) as follows:

$$V_{a,i} = 10^6 \frac{e_{a,i}}{c_{a,i}} \qquad (1)$$

The total critical air volume, $V_a$ [$m^3$/330 litres of beer], is obtained by adding the critical volumes of all the pollutants emitted by a system:

$$V_a = \sum_i V_{a,i} = \sum_i 10^6 \frac{e_{a,i}}{c_{a,i}} \qquad (2)$$

The same procedure can be used to calculate the total critical water volume $V_w$ [$dm^3$/330 litres of beer].

$$V_w = \sum_i V_{w,i} = \sum_i 10^6 \frac{e_{w,i}}{c_{w,i}} \qquad (3)$$

where $c_{w,i}$ (mg/dm³) is the critical concentration of substance i in water and $e_{w,i}$ (kg/330 litres of beer) is the emission of substance i to water.

**Human Toxicity** (HT). As an extension of the critical volume approach, Heijungs et al. (1992) have suggested a methodology that includes a generic fate analysis. As Lindfors et al. (1995) explains, the contribution to human toxicity is calculated separately for emissions to air, water and soil. Afterwards, they can be added. In the calculations it is assumed that an emission is completely dispersed in a model world. No degradation mechanisms and no partitioning between different compartments are assumed. The exposure is assessed by assuming inhalation for air emissions, drinking of water for water emissions and a more complex system for emissions to soil.
The combined contribution to human toxicity from chemical j is calculated as follows (Heijungs et al. 1992):

$$C_j = HCA_j E_{ja} + HCW_j E_{jw} + HCS_j E_{js} \quad (4)$$

where E is the emission [kg] and HCA [kg of body weight/kg substance], HCW [kg of body weight/kg substance] and HCS [kg of body weight/kg substance] are the weighting factors of this emission to the air, water and soil, respectively

The unit of the contribution to human toxicity from chemical j is the [kg], which can be interpreted as [kg of body weight] that has been contaminated to the toxicity level.

In this study, the weighting factors from the "CML provisional method for human toxicity" (Heijungs et al. 1992) are adopted.

**Global Warming** (GW). Global Warming Potential (GWP) is a measure of the potential contribution of different gases to the greenhouse effect. It reflects the potential to absorb infrared radiation of one mass unit of pollutant compared with one mass unit of carbon dioxide ($CO_2$) which is used as a reference gas. The absorption properties of greenhouse gases are therefore expressed in terms of relative $CO_2$.

The Global Warming Potentials that have been presented by the Intergovernmental Panel on Climate Change (IPCC) in 1992 are used as weighting factors. The GWP will have different values depending on over which time span the integration is done. It is suggested to use the most recent IPCC values for a time period of 100 years as a reference. These values can be used to convert the airborne emissions (in kg) to an equivalent emission of $CO_2$, which has the same effect with regard to global warming (Houghton et al. 1992).

Contribution to Global Warming

$$= \sum_i GWP_i x E_i \left[ \text{kg } CO_2 \quad \text{equivalents / funct.unit} \right] \quad (5)$$

where Ei is the mass of substance i emitted to the air and GWPi is the Global Warming Potential of the substance i.

**Ozone Depletion** (OD). For airborne emissions which contribute to the depletion of the ozone layer, the concept of Ozone Depletion Potentials (ODP) has been developed (UNEP 1992). It reflects the potentials to deplete the ozone layer of one unit of mass pollutant compared with one unit mass of CFC-11. The ODP are therefore given as CFC-11 equivalents and can be used to convert the airborne emission (in kg) to an equivalent emission of CFC-11, which has the same effect in regard to ozone depletion. They are dependent on the atmospheric lifetime of the compounds and on the release of reactive chlorine or bromine from the compounds and the corresponding ozone destruction within the stratosphere.

These values can be used to convert the airborne emissions (in kg) to an equivalent emission of CFC-11, which has the same effect with regard to ozone depletion.

Contribution to Ozone Depletion

$$= \sum_i ODP_i x E_i \left[ \text{kg CFC}-11 \quad \text{equivalents / funct.unit} \right] \quad (6)$$

where ODPi is the Ozone Depletion Potential of the substance i emitted to the air.

**Acidification** (Ac). Acidification is a measure of the phenomenon known as acid rain, which is caused by gaseous pollutants. It is calculated on the basis of hydrogen ions that can be produced per mole of sulphur dioxide ($SO_2$). The contribution to acidification of different airborne emissions can be determined by weighting them with their Acidification Potentials (AP), which reflect the ability to release protons compared with sulphur dioxide ($SO_2$). The Acidification Potentials can therefore be presented as $SO_2$ equivalents (CML 1992).

These values can be used to convert the airborne emissions (in kg) to an equivalent emission of $SO_2$, which has the same effect with regard to acidification.

Contribution to Acidification

$$= \sum_i AP_i x E_i \left[ \text{kg } SO_2 \quad \text{equivalents/funct.unit} \right] \quad (7)$$

where APi is the Acidification Potential of the substance i emitted to the air.

**Eutrophication** (Eu). Eutrophication is a measure of the increase in biomass due to the addition of nutrients to water or soil. It is calculated with reference to the capacity of phosphate formation, i.e. as $PO_4^{3-}$ equivalents. A separation is made between terrestrial and aquatic systems and both systems are reflected in different levels of aggregation. When $PO_4^{3-}$ is used as a reference substance, an Eutrophication Potential (EP) can be derived for all the substances that contribute to eutrophication. The EP is used to aggregate emissions of substances that contribute potentially to eutrophication.

Contribution to Eutrophication

$$= \sum_i EP_i x E_i \left[ \text{kg } PO_4^{3-} \quad \text{equivalents / funct.unit} \right] \quad (8)$$

where EPi is the Eutrophication Potential of the substance i emitted to the water.

The Eutrophication Potential values were calculated by CML (1992) for a number of substances that contribute potentially to eutrophication.

**Photochemical Ozone Creation (POC).** Photochemical smog is a measure of volatile organic compounds released to air, compared on the basis of their potential to create ozone photochemically. It depends on the region, different sun intensities and background concentrations. The contribution of different airborne emissions to the formation of photochemical oxidants can be determined by weighting them with their Photochemical Ozone Creation Potentials (POCP), which reflect the ability to produce photochemical oxidants compared wit ethylene, $C_2H_4$. These values can be used to convert the airborne emissions (in kg) to an equivalent emission of $C_2H_4$, which has the same effect with regard to the formation of photochemical oxidants.

**Formation of Photochemical Oxidants**

$$= \sum_i POCP_i x E_i \left[ kg\ C_2H_4 \quad equivalents/funct.unit \right] \qquad (9)$$

where POCPi is the Ozone Creation Potential of the substance i emitted to the air.

The POCP depend upon local conditions like existing background levels of VOC and NOx and different meteorological conditions. The POCP values, which have been published by Derwent and Jenkins (1990) for the UK, are used in this study.

**Final Solid Waste (FSW).** The final solid waste, $M_{swi}$, is the sum of all the solid wastes generated by the system and is stated as a mass per functional unit [kg/functional unit].

$$M_{SW} = \sum_i M_{SW,i} \qquad (10)$$

## 2 Results and Discussion

### 2.1 Analysis of each impact versus the reuse percentage

In the following, we present and discuss the results of this study for each impact category and considering several reuse percentages between 20 and X%. In order to get a better feeling of the influence of the reuse rate on impacts, we will use an impact index, $I_n$, defined as

$$I_n = \frac{\text{impact for } X\% \text{ reuse}}{\text{impact for } 20\% \text{ reuse}} \qquad (11)$$

In **Fig. 6** the impact indexes of the several impact categories are presented.

**Ecological and Human Health: Critical Water and Air Volumes.** Critical air volume was calculated considering the contribution of dust, CO, $SO_2$, NOx, HCl, HF, Pb, Cd and hydrocarbons in air emissions.

Critical water volume was calculated considering the contribution of undissolved material, BOD, COD and fats in water emissions.

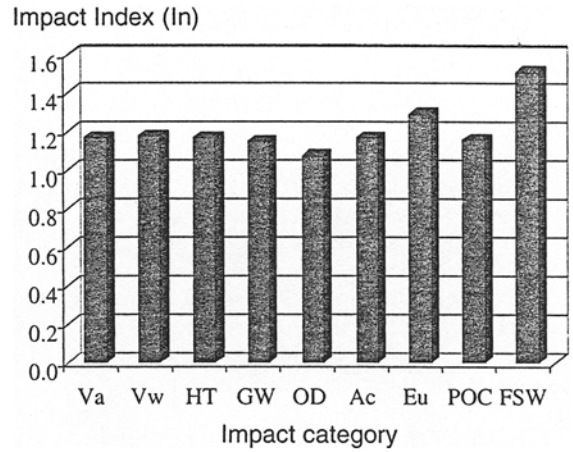


**Fig. 6:** Impact index for several impact categories

Fig. 7 shows the critical air and water volumes calculated for several reuse percentages. The impact indexes for critical air and water volumes are respectively 1.16 and 1.17. These results suggest that the critical water and air volumes associated with the distribution of 330 litres of beer increase with the reuse percentage and are thus higher for returnable bottles.

**Human Toxicity.** The most important contribution comes from air emissions. In this case study, water and soil emissions do not contain components that contribute to human toxicity (Heijungs et al. 1992). In air emissions, the CO, $SO_2$, NOx, HF, Pb, Cd and Zn were considered to calculate the contribution to human toxicity of the delivery of 330 litres of beer. Fig. 7 shows the contribution to human toxicity due to air emissions. The impact index here is 1.17 and the trend is the same as observed for the previous case.

**Global Warming.** The $CO_2$ is the component of air emissions that contributes more to global warming. It is generated during fermentation and used in carbonating the beer, and to flush bottles, cans and kegs before filling. In this case study, $N_2O$, hydrocarbons and specially $CH_4$ also contribute to this environmental effect.

Fig. 7 shows the contribution to the global warming of the delivery of 330 litres of beer, comparing several reuse percentages. The impact index is 1.15, again indicating the same trend, i.e. returnable bottles have higher impacts than non-returnable ones.

**Ozone Depletion.** The components that contribute to the ozone depletion in this study are some CFC, since they are used in cooling systems in a brewery. Fig. 7 shows the contribution to the ozone depletion of the delivery of 330 litres of beer, comparing several reuse percentages. The impact index is 1.07, indicating the same trend.

**Acidification.** Several components of air emissions were considered to calculate the acidification. The most important is the $SO_2$. The others are HCl, HF and NOx. Fig. 7 shows the contribution to the acidification of the delivery of 330 litres of beer. The impact index for acidification is 1.17, suggesting that the contribution to acidification also increases with the reuse percentage.

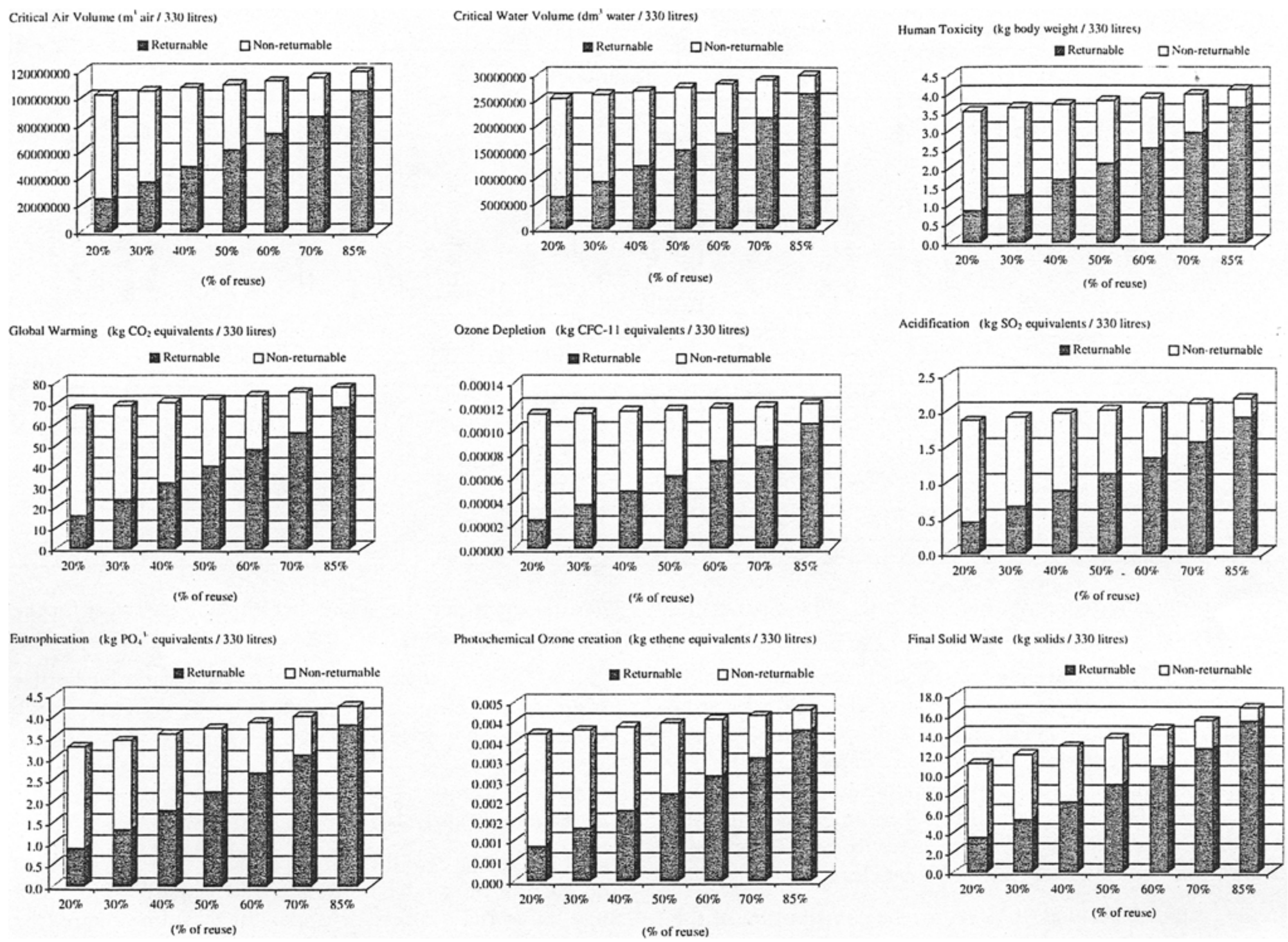


**Fig. 7:** Environmental impacts for the delivery of 330 litres of beer, as a function of reuse percentage

**Eutrophication.** In addition to the eutrophicaton effect we considered the contribution of COD, N and P from water emissions and NOx and $N_2O$ from air emissions. Fig. 7 compares this contribution for several reuse percentages. The impact index for eutrophication is 1.29, suggesting that the contribution to eutrophication also increases with the reuse percentage.

**Photochemical Ozone Creation.** In addition to the photochemical ozone creation we considered the contribution of VOC, hydrocarbons and $CH_4$. Fig. 7 shows how this contribution evolves as a function of the reuse percentages. The impact index here is 1.16, indicating the same trend as previously observed.

**Final Solid Waste.** The solid waste from the bottle manufacture consists of scrap, oils and waste from cullet treatment plant (metals, mirror glass, paper, plastics, ceramic materials, stones, sand, textiles, etc.), used oils, oil cans, petrol cans, spray cans, scrap, wasted raw-materials, pine wood, cardboard, plastics and scrap.

The solid waste from the brewery consists of broken glass bottles, cardboard, carton, paper, plastic, metals and pine wood from auxiliary packaging materials, surplus yeast, spent kieselguhr and grains from beer production, used oils cans, petrol cans, spray cans, scrap, grit, paper pulp and glue from the bottle-washing machine, waste oil and grease, waste paints and thinners, sludge from wastewater treatment.

Before being filled, the non-returnable bottle is simply flushed with fresh water, but the returnable bottle is sent to a bottle washer that removes all impurities inside and outside. Inside the bottles, impurities include residual beer mould, cigarette butts and other things. Externally, impurities may include labels, tin foil and dust particles. Bottle washing is likely to consist of soaking, rinsing, sterilisation and re-rinsing.

Fig. 7 shows how the impact from solid wastes varies with the reuse percentage. The impact index is 1.51, suggesting that the amount of final solid wastes associated with the distribution of 330 litres of beer in glass bottles increases with the reuse percentage and is thus higher for returnable bottles.

### 2.2 Comparison between returnable and non-returnable bottles

In order to compare the returnable with the non-returnable bottle, each impact was calculated as a function of the number of reuses or cycles performed by the returnable bottle. Per cycle, 15% of returnable bottles break. This means that 15% of these bottles need to be substituted for new

**Table 4:** Contribution of the returnable bottles for the environmental impacts compared with the non-returnable bottles

| % Reuse | Impact Category | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Critical air and water volume | Human toxicity | Global warming | Ozone Depletion | Acidification | Eutrophication | Photochemical Ozone Creation | Solid Wastes | Water consumption | Energy consumption | Raw-materials consumption | Auxiliary Materials consumption |
| 20% | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller |
| 30% | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller |
| 40% | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller | Smaller | Larger | Smaller | Smaller | Smaller | Smaller |
| 50% | Smaller | Smaller | Smaller | Larger | Smaller | Larger | Smaller | Larger | Larger | Smaller | Smaller | Larger |
| 60% | Smaller after the 3rd cycle | Smaller after the 3rd cycle | Smaller after the 4th cycle | Larger | Smaller after the 3rd cycle | Larger | Smaller after the 3rd cycle | Larger | Larger | Smaller after the 4th cycle | Smaller after the 3rd cycle | Larger |
| 70% | Smaller after the 5th cycle | Smaller after the 5th cycle | Larger | Larger | Smaller after the 5th cycle | Larger | Smaller after the 6th cycle | Larger | Larger | Larger | Smaller after the 4th cycle | Larger |
| 85% | Larger | Larger | Larger | Larger | Larger | Larger | Larger | Larger | Larger | Larger | Larger | Larger |

ones, in order to deliver the same volume of beer per cycle. All the reuse percentages (20 to 85%) were analysed.

In this comparison, the environmental impacts analysed are: critical air and water volumes, human toxicity, global warming, ozone depletion, acidification, eutrophication, photochemical ozone creation, solid wastes, water consumption, energy consumption, raw-materials consumption and auxiliary material consumption. Table 4 resumes the contribution of the returnable bottles for the environmental impacts comparing with the non-returnable bottles.

In the case of 20% and 30% reuse, the contribution of the returnable bottles for all the environmental impacts is smaller than that of the returnable bottles.

Reusing 40%, the returnable bottles contribute less for the environmental impacts, except for solid wastes.

For 50% reuse, the contribution of returnable bottles to global warming, acidification, photochemical ozone creation, critical air and water volume, human toxicity, energy and raw-material consumption is smaller than that of the non-returnable bottles after the second reuse. The contribution of returnable bottles to eutrophication, ozone depletion, solid waste, water and auxiliary material consumption is larger even after several reuses.

Reusing 60%, the contribution of returnable bottles to global warming and energy consumption is smaller than that of the non-returnable bottles after the fourth reuse and the contribution of returnable bottles to acidification, photochemical ozone creation, human toxicity, and critical air and water volume is smaller than that of the non-returnable bottles after the third reuse. The other impacts are larger for the returnable bottles, even after several reuses.

For 70% reuse, the contribution of returnable bottles to photochemical ozone creation is smaller than that of the non-returnable bottles after the sixth reuse and the contribution to acidification, human toxicity and critical air and water volume is smaller than that of the non-returnable bottles after the fifth reuse. The other impacts are larger for the returnable bottles even after several reuses.

With 85% reuse, the contribution of the returnable bottles for all the environmental impacts is larger than that of the non-returnable bottles.

### 2.3 Sensitivity analysis

Fig. 8 shows the evolution of the impacts for the returnable and the non-returnable bottles, considering 50% reuse as a function of the number of cycles. In the same figure, the error band for the impacts generated is presented assuming more or less 10% on all the base data, e.g. materials, energy and water consumption and emissions. This variation of 10% originates an error of about 0.1 on the environmental impacts. However, the relative position of the curves for both bottles is not affected for all the impact categories.

Fig. 9 shows the evolution of critical air and water volumes for the returnable and the non-returnable bottles, considering 50% reuse as a function of number of cycles and the error band assuming more or less one order of magnitude on the critical concentrations. Although this variation originates with an error of 9 and 0.9 for the variation of more and less one order magnitude, respectively on the critical concentrations, it doesn't affect the superiority or inferiority of one bottle versus the other, i.e. the relative position of the critical volume curves for both bottles.

## 3 Conclusions and Recommendations

The findings of this study may take the form of conclusions and recommendations to decision-makers, consistent with the goal and scope of the study. This LCA study allowed the following conclusions:

- In the packaging areas of breweries, the processes of bottle and crate washing, pasteurisation, rinsing and cleaning of equipment, cleaning of floors, soap lubrication of bot-

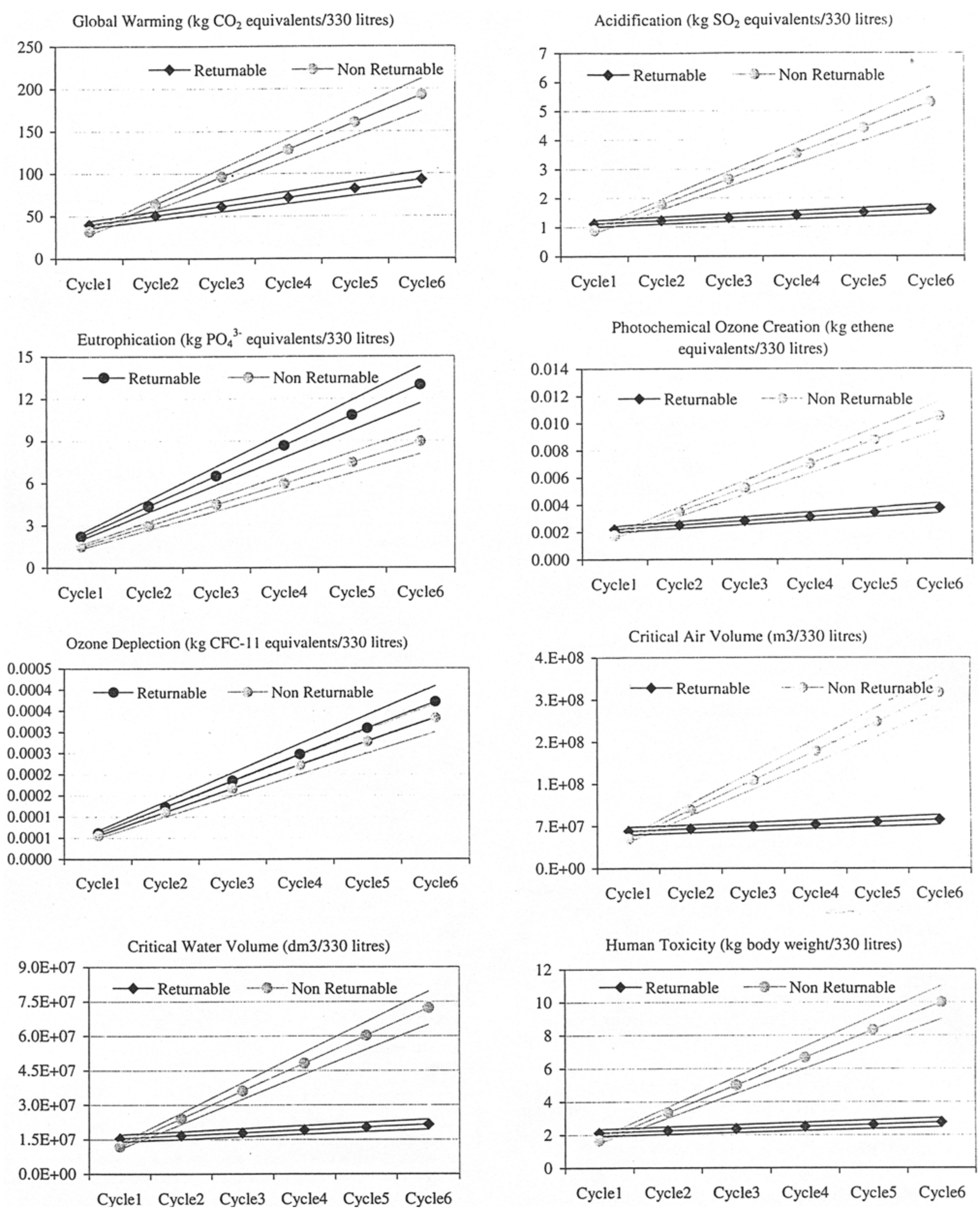


**Fig. 8:** Environmental impacts for returnable and non-returnable bottles considering 50% reuse, as a function of number of cycles and error band assuming more or less 10% on all the base data

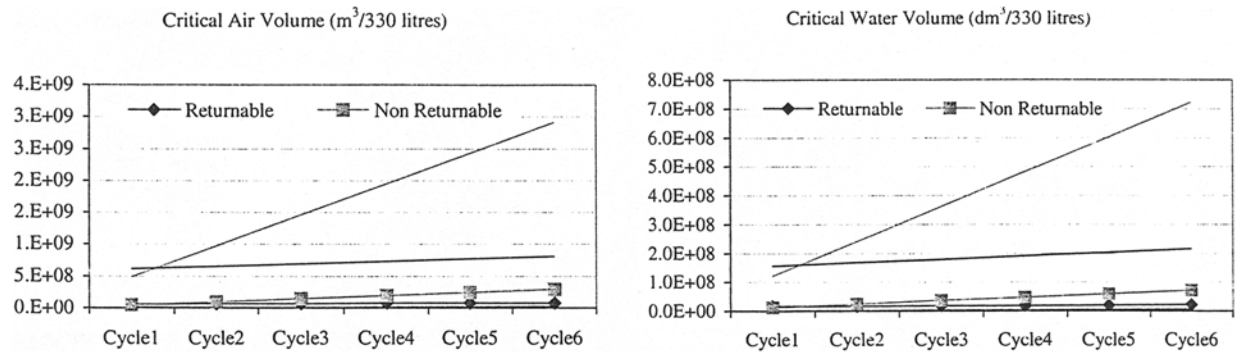


**Fig. 9:** Critical volumes for returnable and non-returnable bottles considering 50% reuse, as a function of number of cycles and error band assuming more or less one order of magnitude on the critical concentrations

tle conveyors, vacuum pumps for filling and flushing of fillers, consumption of large amounts of water and energy.

- Wastewater from the brewery is treated biologically using both anaerobic and aerobic processes. The anaerobic process generates large amounts of sludge that need to be dewatered. That sludge can be used in agriculture, depending on some factors, such as the soil characteristics.
- Large quantities of solid waste are generated in the packaging operations of a brewery which consists of paper, plastics and metals from packaging materials, surplus yeast, spent kieselguhr and grains from beer production, grit, small pieces of broken glass, paper pulp and glue from the bottle washing machine.
- The returnable bottles can perform an average of 6 cycles per year before being recycled. For this reason, the environmental impacts related to the bottle manufacture are smaller for the returnable bottles after the second reuse, since only 15% of returnable bottles need to be produced to deliver 330 litres of beer.
- Considering 50% reuse, i.e. the same number of returnable and non-returnable bottles, the contribution of returnable bottles to global warming, acidification, photochemical ozone creation, critical air and water volume, human toxicity, energy and raw-material consumption is smaller than that of the non-returnable bottles after the second reuse. The contribution of returnable bottles to eutrophication, ozone depletion, solid waste, water and auxiliary material consumption is larger even after several reuses.
- From the sensitivity analysis conducted, it was concluded that possible errors in the input and output data don't affect the superiority or inferiority of one bottle versus the other much.
- Since the inventory data demonstrate a good representativeness according to the data quality indicator, we can conclude that the results of this study have a good reliability.
- The impact index shows that eutrophication and final solid wastes generated are the most significant impacts of this case study. The critical air and water volume, human toxicity, global warming, acidification and photochemical ozone creation are not so significant and the least significant is the ozone depletion.
- In a decision making process, and specially regarding the distribution of beer in returnable or non-returnable bottles, it is necessary to analyse not only the environmental, but also the economic, technological and social implications of the proposed options in order to choose the better reuse percentage and to have a more sustainable glass beer bottle system.

**Nomenclature**

| | |
|---|---|
| Ac | acidification |
| AP | acidification potential |
| $c_a$ | critical concentration in the air |
| Cj | combined contribution to human toxicity |
| $c_w$ | critical concentration in the water |
| E | mass of the emission |
| Eu | eutrophication |
| EP | eutrophication potential |
| $e_a$ | emission to air |
| $e_w$ | emission to water |
| FSW | final solid waste |
| GW | global warming |
| GWP | global warming potential |
| HCA | weighting factor for air emissions |
| HCW | weighting factor for water emissions |
| HCS | weighting factor for soil emissions |
| HT | human toxicity |
| $I_n$ | impact index |
| $M_{sw}$ | mass of solid wastes |
| OD | ozone depletion |
| ODP | ozone depletion potential |
| POC | photochemical ozone creation |
| POCP | photochemical ozone creation potential |
| Va | critical air volume |
| Vw | critical water volume |

**Subscripts**

| | |
|---|---|
| i | substance emitted |
| j | chemical emitted |

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