Life cycle assessment

A comparison of three methods for impact analysis and evaluation*

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For the evaluation of data resulting from the inventory stage of a life cycle assessment, two sets of environmental indices based on Swedish data have been calculated according to the 'ecological scarcity method' and the 'environmental theme method'. These are compared with indices from the method for 'environmental priority strategies in product design'. The relative importance of CO_2, SO_2 and NO_x in the three evaluation methods, expressed as index ratios CO_2:SO_2:NO_x, was calculated to be 1:200:250, 1:220:350 and 1:150:6100, respectively. Additional index comparisons are presented. Differences in the results from the three methods depend on effects considered, how the algorithms are constructed, and background data. The discussion focuses on similarities and differences in mathematical expressions and on the evaluation of certain substances.

Keywords: life cycle assessment; environmental impact; valuation

Introduction

Environmental life cycle assessment (LCA), used for comparison of environmental impacts of products, is generally carried out in four steps: goal definition, inventory, classification (or impact analysis) and evaluation[1]. Depending on the purpose of the study, an LCA may also include improvement analysis[2]. The environmental influence of a product can be described using the inventory table, i.e. the calculated resource use and amounts of pollutants. These results are difficult to compare when the products give rise to very different types of emissions, e.g. product A gives rise mainly to emissions to air and product B to water. In order to determine which product has the least environmental impact, resource use and discharged substances need to be transformed into comparable parameters. In spite of the difficulty of describing and evaluating complex environmental effects, several methods of impact analysis and evaluation have been developed. In this study, three methods are compared: the ecological scarcity (ECO) method[3], the environmental theme (ET) method[4,5] and the environmental priority strategies in product design (EPS) method[6]. Additionally, the three methods have been applied to identical inventory data on milk packaging systems in Sweden.

The goal of all three methods is to set a one-dimensional value on resource use and emissions in order to calculate the total environmental impact of a product. In this paper, we compare the environmental load indices of selected substances, as calculated for the three methods. Indices have been calculated for Swedish conditions. We discuss the differences in the ways the three methods obtain their one-dimensional index. The relation between environmental loads, indices and the total impact of the product is given by:

$$TI(\text{method}) = \sum_j (LI_j(\text{method}) \times \text{Load}_j) \qquad (1)$$

where TI(method) = total impact as calculated according to one of the three methods; LI_j (method) = load index j according to one of the three methods, i.e. environmental impact per mass unit of emission of j; Load_j = environmental load of j (emission or resource

*The terminology used in this article differs somewhat from the terminology in 'Guidelines for Life Cycle Assessment: A "Code of Practice"', published by SETAC (Society of Environmental Toxicology and Chemistry) in August 1993. Owing to the date of submission of this article, the SETAC terminology could not be followed. In this article, the first version of EPS is subject to comparison. A second version of EPS has been completed after the date of submission

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use) of the product, mass unit; j = substance; method = ECO, ET or EPS.

Description of methods

The ecological scarcity (ECO) method

Scarcity is an economic term referring to the relation between supply and demand. The concept of ecological scarcity for product assessment was introduced in a Swiss study[3]. Ecological scarcity is defined for a given area by the relation between the critical load of a pollutant and the actual load of anthropogenic emissions of that pollutant.

The environmental index is called the ecofactor. To obtain the total environmental impact, each product-specific emission (Load_j) is multiplied by its corresponding ecofactor (substance and area specific), and added together as expressed in the following equation, where the ecofactor is a function of ecological scarcity:

$$TI(\text{ECO}) = \sum_j (\text{ecofactor}_j \times \text{Load}_j) \qquad (2)$$

The value of the ecofactor, in units of ecopoints, is calculated according to equation (3). After evaluating a number of algorithms, Braunschweig concluded that the following algorithm, where the ecofactor is proportional to the scarcity, is preferable because it is simple and requires no arbitrary assumptions[7]:

$$\text{ecofactor}_j = \frac{\text{Load}_{j,\text{tot}}}{\text{Load}_{j,\text{crit}}} \times \frac{1}{\text{Load}_{j,\text{crit}}} \times \text{constant} \qquad (3)$$

where $\text{Load}_{j,\text{tot}}$ = the current total level of anthropogenic emission or deposition of substance j within a certain area; $\text{Load}_{j,\text{crit}}$ = the critical load of a substance j defined for a certain area; constant = 10^6 to express the ecofactor in ecopoints g^{-1} if the emissions are given in tonnes. The first quotient expresses ecological scarcity. The second quotient is a standardizing factor, implying that the emission of 1 g of pollutant for which the critical load is high is not as severe as the emission of 1 g of a pollutant for which the critical load is low.

Critical loads can be defined either as ecological critical loads (sustainable loads) or as politically maximum acceptable limits (political targets). Theoretically, two different sets of ecofactors can therefore be calculated, depending on the definition of the critical loads, but this is usually difficult in practice owing to incomplete information. Given that different regions have different sensitivities to pollutants and different levels of pollution, ecofactors are specific for the regions for which they are calculated. Ahbe *et al.* calculated the critical loads according to the Swiss national environmental protection laws and regulations[3]. These limits are a combination of ecological, human health and political considerations. In our study, the aim was to use ecological critical loads in the calculation of ecofactors, as specified below. When these were not available, political targets were used. Figures on total emissions were taken from official Swedish environmental statistics. These figures are listed in *Table 1*.

For carbon dioxide, the total load used was the 1988 Swedish emissions[8]. The critical load was taken as 80% of the total load, according to step one of the Toronto climate conference[9].

The ecofactor for nitrogen oxides was calculated as the weighted arithmetic average for the ecofactor of land-deposited nitrogen oxides and the ecofactor of sea-deposited nitrogen oxides. The nitrogen oxide load of 1985 was used as the total of land-deposited nitrogen[10]. The specific ecological critical load for land deposition has been estimated to be 10, 8 and 3 kg ha^{-1} yr^{-1} for the Swedish regions of Götaland, Svealand and Norrland, respectively[11]. We approximated that these regions make up 25, 25 and 50% of the total land area, respectively, when calculating the critical load. From estimates of the eutrophication in various parts of the sea surrounding Sweden[12], we calculated the ecological critical load for sea deposition. About 35% (30–40%) of the total nitrogen load in the sea consists of deposition of airborne nitrogen oxides[12].

For sulfur dioxide, the total load used was the average annual deposition from the years 1983, 1985 and 1987[13]. Specific ecological critical loads have been estimated at 5 kg ha^{-1} yr^{-1} in Götaland and Svealand, and 3 kg ha^{-1} yr^{-1} in Norrland[14].

The total volatile organic compound (VOC) load was calculated as a 1986–1988 average[15]. Based on model calculations of photochemical ozone formation, it has been suggested that the ecological critical load is 50% less than the present load[16].

Total loads of mercury, lead and zinc used are from 1987–1988[17]. The critical loads were derived from the North Sea Declaration, according to which the emissions of certain toxic substances, such as mercury and lead, are to be reduced by 70% in relation to the 1985 levels, while emissions of other substances, such as zinc, are to be reduced by 50% in relation to the 1985 levels[18].

For non-hazardous waste, the total load, taken

Table 1 Data used for the calculation of Swedish ecofactors in the ECO method

Pollutant	Total load (10^6 kg yr^{-1})	Critical load (10^6 kg yr^{-1})
Carbon dioxide (as CO_2)	63000	50400
Sulfur dioxide (as SO_2)	606	352
Volatile organic compounds (VOC)	410	205
Nitrogen oxides to land (as N)	79	330
Total nitrogen to sea (totN)	138	51
of which airborne nitrogen	48	
Mercury	0.0032	0.00144
Lead	0.74	0.292
Zinc	1.24	0.945
Non-hazardous waste	6000	6000
Hazardous waste	49.5	38.5

as the sum of deposited waste from households, incineration and industry except mining[19], was assumed to be equal to the critical load. For hazardous waste, the amount treated annually by the Swedish Waste Conversion Company, SAKAB, was taken as the total load. SAKAB's nominal capacity to treat hazardous waste was taken as the critical load[20].

For oxygen-consuming pollutants to water, no data were available to estimate the critical load. The Swiss ecofactor was applied in calculations.

The only resources considered in the ecoscarcity method are energy resources, since energy use leads to degradation of energy quality according to the law of enthropy. Primary energy consumption is attributed an ecofactor of 1 ecopoint MJ^{-1}.

The environmental theme (ET) method

This method was developed by McKinsey & Company, Inc., The Centre of Environmental Science in Leiden (CML) and The Dutch National Institute for Health and Environment (RIVM), in a study initiated by the Association of the Dutch Chemical Industry (VNCI) and the Dutch government[4,5].

In this method, the total impact is calculated in three steps. (1) The environmental loads of the product are grouped (sorted) into selected environmental themes, and by using a measure of the relative equivalence of the pollutants, the impacts caused by the product are calculated per theme. (2) The sum of equivalent loads of a theme is divided by the corresponding total pollution of the same theme within the geographical delimitation relevant to the study, e.g. a country, resulting in an impact fraction, IF_i, indicating how much the product contributes per theme to the environmental problems of the chosen geographical delimitation (equation (4)). (3) The impact fractions may be summarized to a total impact after applying weight factors (W_i), to take account of the relative severity of the different environmental themes (equation (5)):

$$IF_i = \frac{\sum_{j=1}^{p} \mathrm{Load}_j \times \mathrm{Eqv}_{i,j}}{\sum_{k=1}^{r} \mathrm{Load}_{k,\mathrm{tot}} \times \mathrm{Eqv}_{i,k}} \tag{4}$$

$$TI(\mathrm{ET}) = \sum_{i=1}^{m} (W_i \times IF_i) \tag{5}$$

where IF_i = impact fraction, product specific emissions, sorted into the theme i, divided by the total contribution to the same theme within the studied area; i = environmental theme, e.g. acidification, ozone depletion, global warming; W_i = weight factor of theme i; Load_j = emission of substance j from studied system; $\mathrm{Load}_{k,\mathrm{tot}}$ = total amount within system of pollutant k contributing to environmental theme; $\mathrm{Eqv}_{i,j}$ = equivalency of product-related emission j within theme i; $\mathrm{Eqv}_{i,k}$ = equivalency of substance k contributing to theme i.

To obtain the specific substance environmental index, LI_j(ET), equations (4) and (5) are transformed to:

$$LI_j(\mathrm{ET}) = \sum_{i=1}^{m} \left(\frac{W_i \times \mathrm{Eqv}_{i,j}}{\sum_{k=1}^{r} \mathrm{Load}_{k,\mathrm{tot}} \times \mathrm{Eqv}_{i,k}}\right) \tag{6}$$

The ET method gives some freedom in the choice of themes and in the way the weight factors are determined. The themes in the Dutch study were: global warming, ozone depletion, acidification, eutrophication, photochemical ozone formation, dispersion of toxic substances, disruption, disposal of waste and depletion of natural resources. In the Dutch study, *ad hoc* weight factors were derived in a delphi-like process, to weigh the themes of the particular study, but the numerical values of the factors were not explicitly stated in the report. In our study, we derived weight factors from political targets. Weight factors were set as the ratio between the total load within the environmental theme and the Swedish 1995 political target load for the same theme[21]. Target loads for 1995 were derived through linear interpolation whenever the government environmental policy had set targets to be reached in the future.

We introduced two new themes, compared to VNCI: chemical oxygen demand (COD) discharge in kilograms as discussed at the SETAC–Europe workshop in Leiden[22], and electricity consumption. Another difference is that instead of using the cost of disposal to determine equivalence, waste and hazardous waste were treated as two separate themes, in each of which mass equivalents were used. Within the themes resource depletion (only fossil fuels included), acidification, eutrophication and toxicity, equivalents were taken from VNCI[5]. Photooxidant creation potentials (POCP) were taken from model calculations for Sweden by IVL (96 h average ozone formation)[23]. Global warming potentials were from IPCC[24]. Ozone depletion potentials (ODPs) were from WMO[25], except for tetrachloroethene and methylene chloride, for which we estimated the ODP to be 0.01. Disruption was excluded.

Theme totals, policy objectives and resulting weight factors are listed in *Table 2*. Where there is no political decision about reduction, the policy target has been to keep the current level constant.

The theme of global warming includes total emissions of carbon dioxide, methane, CFCs and nitrous oxide reported by the Swedish Environmental Protection Agency[26], with the addition of traffic emissions of nitrous oxide, reported by Robertson[27] and perfluorocarbons, reported by Abrahamson[28]. Total emissions of ozone-depleting substances in 1988 were taken from the Swedish Environmental Protection Agency[29] assuming an average ODP of 0.9. Target 1995 emissions were assumed to be 5% of 1988 emissions, including non-regulated ozone-depleting substances. Emissions to air of sulfur dioxide, nitrogen oxides, ammonia and hydrochloric acid, reported in official statistics from

Table 2 Environmental themes, equivalent national Swedish contributions, policy targets (target year 1995) and resulting weight factors (1/(1–0.01 × policy target in %)) for each theme

Environmental theme	National contribution (unit)	Policy target	Weight factor
1 Global warming	9.0×10^{13} (g CO_2-eq.)	Constant or less emission	1
2 Ozone depletion	4.1×10^{9} (g R11-eq.)	95% reduction	20
3 Acidification	7.6×10^{11} (g SO_2-eq.)	50% reduction	2
4 Eutrophication	6.4×10^{11} (g NO_x-eq.)	40% reduction	1.67
5 Photochemical ozone formation	1.84×10^{11} (g ethene-eq.)	30% reduction	1.43
6 Toxic chemical dispersion	1.27×10^{8} (tox.-eq.)	60% reduction	2.5
7 Oxygen demand (COD)	2.5×10^{12} (g)	Constant	1
8 Waste disposal	3.5×10^{13} (g)	20% reduction	1.25
9 Hazardous waste formation	4.95×10^{11} (g)	Constant	1
10 Resource depletion	7.46×10^{11} (oil scarc.-eq)	Constant	1
11 Electricity use	4.54×10^{11} (MJ)	10% reduction	1.11

Sweden[30], were included in the acidification total. The eutrophication total was made up of the total waterborne nitrogen and phosphorus loads, reported for 1987[15] plus the 1990 atmospheric downfall of oxidized nitrogen to the oceans from Swedish emissions, reported by EMEP[31]. Emissions (1988) of non-methane hydrocarbons[23] were multiplied by an estimated average POCP of 0.4 (ethene = 1), to yield the POCP theme total. In the VNCI study, it was assumed that metals cause approximately 60% of the total equivalent toxic release[5]. The same percentage was assumed for Sweden. Emissions of metals were established according to official statistics from Sweden[17]. The reduction target was derived from the North Sea Declaration[18]. The theme total of the waste category is made up of the total amount of household waste and the amount of industrial waste deposited[32]. The target is our estimate of the resulting reduction, based on legislation about source separation of wastes. The reduction target in electricity consumption was derived from the Swedish Energy policy[21], which states that nuclear power is to be phased out by the year 2010, there is to be no increase in the emission of greenhouse gases and no new hydroelectric plants in hitherto unexploited rivers, and our estimate of the development potential of alternative electricity production.

The environmental priority strategies in product design (EPS) method

The EPS method was developed by the Swedish Environmental Research Institute (IVL) together with The Swedish Federation of Industries and Volvo Car Corporation in 1991[6]. Two types of load indices are calculated: resource and emission indices.

$$\text{Resource index} = C \times B/A$$

where A = worldwide per capita of finite natural resources, B = estimated resource irreplaceability factor, C = a scale factor to match the emission indices. It is not clear whether resources here are defined as reserves or reserve base[33].

$$\text{Emission index} = \sum_i (F_1 \times F_2 \times F_3 \times F_4 \times F_5)_i \times F_6$$

The functions of the factors are as follows. F_1 is an evaluation factor which, in this first version, represents existing environmental and health costs on a scale from 0.01 to 100, as an image of society's evaluation of the environmental problem i; F_2 is the intensity and frequency of the occurrence of the problem on a scale from 10^{-6} to 10; F_3 describes the geographical distribution (0.001–100); F_4 represents the durability of the problem (0.1–100). Thus, factors F_2, F_3 and F_4 describe the extent of an environmental problem, which is valued by F_1. F_5 shows how much 1 kg of the substance contributes to the problem (10^{-4}–10^{9}). F_6 is the average cost of reduction per kg pollutant by means of end-of-pipe as a measure of the possibility of immediate action against the problem (10^{-6}–10).

The total impact is calculated as follows:

$$TI(\text{EPS}) = \sum_j (\text{emission index}_j \times \text{Emi}_j) + \sum_k (\text{resource index}_j \times \text{resource use}_j)$$

where Emi_j = emitted amount of pollutant. The load indices as of May 1991 were used in the comparison. In the report[6] describing EPS, the background data used to obtain the indices are not published.

Comparison of methods

Differences in the equations

The comparison of methods, with respect to the function of different parts of the emission index equations, is summarized in *Table 3*.

Different approaches. It is well known that one pollutant can have many effects on environment, health and society and that many pollutants can contribute to one environmental problem. The emission of a pollutant into the environment can be seen as the start of a chain of changes, where the first change is called a primary effect, the next a secondary effect, and so on. At the start of the chain, the changes are often chemical or physical in nature. Biological changes usually occur as higher order effects[34]. The difference between the methods lies in where, and consequently

Table 3 Method comparison: equations for emission index calculation compared by functionalities

Method	Approach for evaluation of environmental influence	Description of environmental influence	Standard factor	Special feature
EPS $\text{index} = \sum_i (F_1 \times F_2 \times F_3 \times F_4 \times F_5)_i \times F_6$	The price society is willing to pay to avoid the problem, F_1	Extent of problem, $F_2 \times F_3 \times F_4$	Fraction of total problem, F_5	Cost of immediate action, F_6
ECO $\text{Index} = \frac{\text{Load}_{\text{tot}}}{\text{Load}_{\text{crit}}} \times \frac{1}{\text{Load}_{\text{crit}}} \times \text{constant}$	Critical load of pollutant, politically or ecologically defined, $\text{Load}_{\text{crit}}$	Ecological scarcity, $\text{Load}_{\text{tot}}/\text{Load}_{\text{crit}}$	Fraction of critical load, $1/\text{Load}_{\text{crit}}$	-
ET $\text{Index} = \sum_i \left(\frac{W_i \times \text{Eqv}_{ij}}{\sum_k \text{Load}_{k,\text{tot}} \times \text{Eqv}_{i,k}} \right)$	*Ad hoc*, severity of theme, $W_{(\text{delphi})}$ or $W_{(\text{pol})}$	Theme equivalent, Eqv_{ij}	Fraction of total theme, $1/\Sigma\ \text{Load}_{\text{tot}} \times \text{Eqv}$	-

on what, the evaluation is made in the chains linking specific pollutants to environmental problems: evaluation of an emitted substance (e.g. CO), evaluation of a physico-chemical environmental change (e.g. global warming owing to change in radiative forcing), or evaluation of the effect of the change on human life (e.g. the value of lost land due to sea-level rise, headaches, and other effects).

The EPS method calculates the sizes of different influences of an emission on health and the environment. Each influence is evaluated by the price society is willing to pay to avoid the influence or the actual cost it gives rise to. The priced influences per pollutant are added up.

Instead of evaluating each of the influences of a pollutant, all evaluations can be condensed and expressed as the level of pollution at which most of the problems will be avoided. This level is the critical load as used in the ECO method.

In the ET method, different environmental problems are judged in relation to one another. A weight factor expresses the relative severity of a problem (theme). It is applied directly to a group of pollutants added up on the basis of their physico-chemical equivalence.

As can be seen from columns 2 and 3 in *Table 3*, together factors F_1, F_2, F_3 and F_4 of EPS correspond to the weight factor in ET and to ecological scarcity in ECO.

Standard factor. The ECO method uses the critical load as its standard factor, while the ET and EPS methods use the total load. If the critical load is used as the standard factor instead of the total load, relatively more weight (higher index) is given to a pollutant of which the total emission exceeds the critical level. On the contrary, when total emissions are below the critical level, the ET and EPS methods result in relatively higher indices than the ECO method. Lack of knowledge about the ecologically sustainable level is one practical reason for using the total amount as the standard factor.

Extra features. A feature particular to the EPS expression is a factor (F_6) considering the cost of immediate action to counteract pollution. It is thought that since expensive end-of-pipe devices are less likely to be installed, this indicates a probability that the environmental problem will grow worse although the price of emission control does not reflect the propagation of environmental problems.

Other types of differences

Apart from structural differences between the expressions, the choice of data for the calculation also influences the size of the indices.

Potential versus documented effects. In the calculation of EPS indices, primarily documented consequences of pollution have been considered. This probably follows from using an economic approach, since a price is more easily found for documented than potential consequences of pollution. Potential effects of pollution are considered more in the other two methods. In the ET method, pollutants are added up on the basis of their physico-chemical equivalences. Since these equivalents are area-independent, they calculate the potential consequences of the emissions. In the ECO method, precautionary considerations can be taken when setting the critical level.

Geography. Since, in both the ECO and the ET methods, the loads are expressed as absolute levels rather than levels per unit area, the indices become specific to the region for which they are calculated. It is therefore impossible to mix index lists of different geographic regions and use them on inventory data from international industrial production unless the regions are of the same size. In contrast, the EPS method gives global indices, since F_3 describes how much of the earth is being affected and F_5 relates to the global total load.

Different standards and statistics. Values can be formed by relation to ecological, economic and political standards, respectively, and several sets of indices can be calculated. The ECO and ET methods allow for some flexibility in choosing standards relevant to the purpose of the study. Critical loads can be defined as ecologically sustainable loads. The weight factors can be decided using a delphi process. Both methods allow political targets as standards. The flexibility of the EPS method lies in how environmental influence is priced.

The quality and accuracy of data have to be considered. Statistical data on total loads may vary from one statistical source to another, because these may be estimates or there may be different systems of bookkeeping for environmental data in different countries. For example, in the same source[10], the figures given for total emissions of sulfur dioxide in Sweden range from 464 to 502 kton yr^{-1} (1980). For several reasons, environmental policies do not express the same ambitions. In 1988, the Toronto conference recommended, as a first step, a 20% reduction of CO_2 emissions, while the Swedish Parliament decided in 1991 to maintain the current level.

For the credibility of indices, statistical sources and standards should always be stated. In our study, mostly official Swedish environmental statistics were used. Critical loads were derived from ecologically sustainable loads, if such existed, otherwise political targets were used. The weight factors were based solely on Swedish political targets. Data used for the calculation of EPS indices have not been published.

Relative scales. In EPS, different aspects of environmental influence are represented on relative scales (F_1–F_6). Their lengths have been decided arbitrarily. As the lengths differ, some aspects are made more important and have more impact on the size of the index.

Directness. Using ECO or EPS indices, evaluation is a one-step procedure, whereas two steps are required in the ET method. The two-step approach is an adjustment to the delphi process, since classification transforms emissions into environmental problems to which we can relate. It also expresses the aim of using science, as far as possible, before subjective judgements are applied.

Resource use as environmental loading. In all three methods, resource use is assessed by the emissions caused and/or by the waste generated. In both ET and EPS methods, an evaluation of the resource itself is also made on the basis of the global supply of the resource. In the ECO method there is a theoretical possibility of calculating an index representing the scarcity of a resource, but Ahbe *et al.* argue that such an index is not relevant, since resources in themselves are not environmental loadings[3]. In the ECO method, energy is valued in itself, because energy, contrary to matter, is not fully recyclable according to the laws of thermodynamics.

Results

Indices

Load indices of the three methods for selected substances are presented in *Table 4*. For comparison, all indices are given relative to carbon dioxide within each method. The table is interpreted as follows: 1 g of sulfur dioxide is judged approximately as severely as 200 g of carbon dioxide for all evaluation methods. Nitrogen oxides are judged particularly severely in the EPS method as compared with the other methods, whereas metals are judged particularly severely in the ECO and ET methods as compared with the EPS method.

Application example—milk packaging

Inventory data for two milk packaging systems were used to illustrate the outcome of the methods. These two types of packaging (1 l brick-shaped cartons and refillable polycarbonate bottles) were chosen because the inventory itself did not display enough differences in order to rank them. (For details about the packaging systems see ref. 35.)

In spite of large differences in the indices, the differences in the results for the two milk packaging systems are small. The calculated total environmental impact ratio (milk carton/polycarbonate bottle) according to the three methods, ECO, ET and EPS, were 0.98 (1.04 with Swiss indices from Ahbe *et al.*[3]), 1.00 and 1.14, respectively. Thus, the two milk packaging systems are judged as environmentally equally good or bad, within the range of data accuracy.

Further analysis of the data is needed to find out why the results appear so similar. It could be a coincidence. If many substances are present in the inventory table, some substances with relatively high indices with one index method are compensated by

Table 4 Environmental indices (relative to CO_2 = 1) for selected substances for the three methods. The absolute figures for CO_2 are: ECO, 0.0248 (ecopoints g^{-1}); ET, 0.011 (g^{-1}); EPS, 0.04 (environmental load units kg^{-1})

Substance	ECO	ET	EPS
CO_2	1	1	1
SO_2	197	218	151
NO_x	254	348	6130
VOC	393	280	258
Hg (g)	68 600 000	4 250 000	250
Hg (aq)	68 600 000	28 000 000	250
Pb (g)	349 500	5138	0.25
Pb (aq)	349 500	33 660	0.25
Zn (aq)	56 000	86 850	0.00025
COD	154	36	0.00025
CO	1	30	1
totN	2133	650	250
Waste	6.7	3.2	0.0025
Hazardous waste	1350	180	–
Electricity	40	250	–
Oil (as resource)	40	121	4.2

other substances having high indices with the other index methods.

The major contributor to the calculated total impact (*Table 5*) was consistently nitrogen oxides, regardless of method and product. Only when using Swedish indices of the ECO method did nitrogen oxides become the second most dominant impact source, after hazardous waste (polycarbonate bottle) or solid waste (milk carton). *Table 5* clearly forms a basis for environmental improvement priorities. As acidification is a major problem in Sweden, it is somewhat surprising that sulfur dioxides are not among the major contributors, except when Swiss indices of the ECO method were used.

Discussion

All the methods are new and are still under development. More accurate physico-chemical equivalents are being sought. The EPS method is being revised. In its second version, the different aspects of environmental influence are expressed on absolute instead of relative scales, the factor considering the cost of immediate action is omitted, and a different approach will be used for resource indices[36]. Efforts are being made to find ecological critical loads for more substances.

The ECO method presupposes that the (ecological) critical load can be determined independently of the loads of other substances. This is a problem, especially when several pollutants contribute to the same environmental problem. A point of criticism about the ET method is that using the total load as reference level/standard factor does not give an incentive to combat pollution that exceeds ecological critical loads, and therefore has a conservative effect on today's environmental problems. Willingness to pay seems to be used as a distinct evaluation method in EPS. Although there are several problems associated with the different techniques of placing monetary values on non-market goods, in which willingness to pay is one aspect of evaluation in one of the techniques[37], these are not discussed in detail by the EPS authors.

Table 5 Major contributors (%) to the calculated total impact for 1 litre refillable polycarbonate (PC) milk bottles and for 1 litre milk carton of polyethylene-coated paperboard, evaluated with the EPS method, the ECO method and the ET method. CH = Swiss indices[3]; S = Swedish indices, this work; NL = Dutch indices from VNCI[5], assuming all weight factors = 1

		ECO		ET	
Contributor	EPS	CH	S	NL	S
PC bottle					
Electricity				22	12
Oil	3			15	21
SO_2		8			5
NO_x	93	61	20	11	30
CO_2	2	6	9	7	10
HC			9	11	8
Waste				16	7
Haz. waste		14	49		
Total	98	89	87	82	93
Carton					
Electricity				20	16
Oil	2			7	14
Thermal energy			14		
NO_x	95	59	21	8	34
CO_2					
HC	1.5	7		11	10
COD			12		
Waste		19	35	44	19
Total	98.5	85	82	90	93

To describe the impact of emissions, it is necessary to take the dispersion of the pollutants into account. In the ECO method, it has been approximated that the pollutants are deposited in the same area where they are emitted (e.g. Swedish emissions are deposited in Sweden). The ET method avoids the dispersion problem by using units of potential impact. The EPS method circumvents the problem by using indices calculated as global averages.

In our opinion, the overall goal of using LCA should be to reduce environmental impact. Critical loads are goal-oriented, whereas total loads are descriptive. Therefore, we think that using a critical load as standard factor, rather than a total load, is preferable, as it gives a stronger impetus for environmental improvement. For some substances, it may be easier to find a critical load for a group of substances, rather than for each of them, e.g. CFCs. For others, e.g. certain toxic substances, it may be easier to find critical loads than equivalents. We would therefore welcome a development leading to an index method that is mainly substance specific, uses an approach with critical loads, but groups certain pollutants using equivalents. The types of critical loads (based on ecology or policies or other) to be used depend on the purpose of the intended LCA.

The problem of not being able to mix indices of different regions when assessing inventory data from international industrial production is solved by dividing the indices by the size of the region (giving e.g. ecopoints per unit area), although this also requires information about the dispersion of pollutants. This, in turn, could be handled by the use of geographic information systems, as suggested in a previous paper[38].

Being one-dimensional, the indices become a currency for environmental influence. Although they are developed in the field of LCA, other possible uses, such as in 'green' accounting or in the trading of emission rights, need to be investigated.

These evaluation methods are attempts to rationalize decision-making concerning the environment. Having several evaluation methods allows the decision-maker (in a company or authority) to select the method best suited for the project and to the frames of reference with respect to the basis for evaluation: the carrying capacity of the natural environment, politically decided loads, society's willingness to pay, or others. There is a fundamental difference between an anthropocentric and a biocentric conception of the world. This leads to different procedures for evaluating environmental problems and, ultimately, to different indices on resource use and emissions. A method will never be considered valid if it does not correspond to one's fundamental conception of the world (anthropocentric or biocentric). Because of this, different evaluation methods will be used by different decision-makers. We think there is a need for discussion among LCA practitioners in order to reflect on what these different conceptions mean in regard to the disagreements on LCA methodology.

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