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Aggregating and evaluating the results of different Environmental Impact Assessment methods

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Abstract

The role of life cycle analysis (LCA) in identifying and measuring the environmental impact of extended supply chains, i.e., chains involving both forward and reverse activities, is very important. Particularly, in the case of alternative supply chain management policies or scenarios, life cycle analysis may significantly help to quantify the environmental result of these alternatives for the purpose of comparison and decision making. It is debatable, however, whether such comparison is always possible. Indeed, life cycle analysis has often raised discussion and disagreements, especially regarding the stage of Impact Assessment (valuation), and, until now, there is no generally accepted framework of analysis. In this paper, different models are used in order to extend the usability of the Environmental Design of Industrial Products method of Impact Assessment. Furthermore, research results that are produced by applying different methods of Impact Assessment are examined in the cases of the recovery and disposal chains of lead–acid batteries.

Keywords: Impact Assessment methods; Analytic Hierarchy Process; LCA polygon; Environmental index

1. Introduction

Environmental life cycle analysis can be defined as the compilation and evaluation of the material and energy flows and of the potential environmental impacts of the life cycle of a product. The term product is in this context broadly defined to include not only physical products but also services. The product life cycle is here defined as the system, consisting of models of the technological activities used for the various stages of the product: from extraction of raw materials for the product and for ancillary materials and equipment, through the production and use of the product, to the disposal of the product, ancillary materials and equipment, if any (Ekvall, 2000). According to ISO standardization guidelines (ISO, 1997a,b, 1998a,b), a life cycle analysis (LCA) study can be divided into four steps: goal and scope definition, inventory analysis, Impact Assessment (IA), and interpretation. There are numerous purposes of LCA. The ISO 14040 standard (ISO, 1997a) lists the following applications: identification of improvement possibilities, decision-making, choice of environmental performance indicators, and market claims. In addition, application of LCA not only contributes in providing insight about the environmental issues associated with the product system studied, but also with environmental issues in gen-

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eral (Baumann, 1998). All these applications aim at change, or improvement: some in more direct ways (decision-making), some in more indirect ways, such as influencing market behavior or identifying improvement possibilities.

Several different methods have been developed for the assessment of environmental impacts generated by production systems. All these methods aim at identifying all the parameters that contribute to the preservation and protection of the natural environment or have other impacts such as human health, labor accidents, etc. However, making a choice between alternative methods is not so simple, especially when more than one criteria must be taken into account. In this paper, the problem of aggregating different environmental criteria (impact categories) in order to measure and compare the environmental performance of alternative supply chain scenarios, is examined.

In this LCA study, the alternative end-of-life scenarios for used starter batteries are examined by using particular environmental IA methods. However, by comparing the environmental results of each end-of-life scenario, it is not clear which of the examined scenarios contribute more to environmental degradation. After the implementation of the IA phase, the ability to measure and compare the environmental effects of end-of-life scenarios is increased due to the fact that all outputs are attributed to various environmental impact categories (depending, of course, on the IA method). However, sometimes it is still difficult to make a safe judgment concerning the scenario to be selected. This is because, in order to determine the best end-of-life scenario from an environmental perspective, all the environmental impact categories included in an IA method should be assessed. This, however, is not always feasible.

The final choice of the environmentally best alternative end-of-life scenario can be made with the help of decision-making methods. In this paper, the LCA study of alternative end-of-life scenarios is integrated with the Environmental Design of Industrial Products (EDIP) method and the final results are aggregated in a unified single environmental index.

The paper is structured as follows. Section 2 consists of a short literature review on different IA methods, which produce either a single or more than one index. In Section 3, the decision-making methods of Analytic Hierarchy Process and LCA polygon are analyzed. The alternative end-of-life scenarios of starter batteries are presented in Section 4, while the results from the implementation of the above mentioned decision-making methods are presented in Section 5. Finally, some conclusions regarding the comparison of the results for the selected IA methods are drawn in Section 6.

2. Impact Assessment methods

An important phase in a typical LCA is IA, which follows the inventory of the inputs and outputs of the systems examined. In the IA, the inventory is translated into potential contributions to various impacts within the main groups of predefined impact categories. During this phase, it is also attempted to identify related hazards, thus assisting manufacturers to prioritize areas for action in order to get the best results for their investments (Curran, 1991; Berkhout, 1995; Lee et al., 1995).

For the evaluation of environmental effects several different methods have been used (Hanssen et al., 1994; Krozer and Vis, 1998; Hertwich et al., 1997; Daniel and Pappis, 2003). Thus, the health hazard scoring (HHS) system uses the analytical hierarchy process to weight workplace toxic effects and accident risks (Srinivasan et al., 1995). The material input per service-unit (MIPS) aggregates the mass of all the material input required to produce a product or service (Bringezu et al., 1994; Schmidt-Bleek, 1994; Hinterberger et al., 1994). The Swiss ecopoint (SEP) method scores pollutant loadings based on a source's contribution to an acceptable total pollution load and an environmental scarcity factor (Abhe et al., 1990). The sustainable process index (SPI) determines the area that would be required to operate a process sustainability, based on renewable resource generation and toxic degradation (an extension of the dilution volume approach) (Sage, 1993; Narodoslawsky and Krotscheck, 1995). The environmental priority strategies (EPS) characterizes the environmental damage caused by equivalency potentials and expresses it in monetary terms, derived from environmental economics (Steen and Ryding, 1992; Hanssen, 1998; Rydh, 1999). The Society of Environmentally Toxicology and Chemistry's life cycle (SETAC LCA) IA method aggregates pollutants with similar impacts to equivalency potentials and uses decision analysis to assign weights to different adverse effects (ISO 14042: 2000 (E)). The method of critical volume gives the amount of clean water and air that would be needed to assimilate the emissions in order to satisfy some quality standards for air and water (Lindfors et al., 1995). The Eco-indicator method weights the units of polluted air according to maximum accepted concentration (MAC values) health standards. The units of polluted water are based on standards for inlet water for drinking water companies (Goedkoop, 1995). The Tellus method, which is based on controlling the costs of a number of pollutants, was used to establish prices for some criteria regarding air pollutants (Tellus Institute, 1992).

A method to get a more accurate interpretation of parameters, which influence the eco-balance, and probably has gained the widest acceptance, is the use of the so-called "impact categories and equivalency factors", which is based on the SETAC LCA method (Hertwich et al., 1997; ISO 14042: 2000 (E)). In this method, different approaches are used according to the type of the environmental problem. The IA for LCA as defined by the SETAC method, customized to the EDIP method, includes three main groups (resources consumption, ecological impacts and impacts on the working environment) and may be global, regional or local (Wenzel and Hauschild, 1997).

Some of the above methods produce a single index trying to represent the total environmental effect of the examined system while other methods express the environmental effects with more than one index. For example, the methods of critical volume or MIPS provide their results in one end-point (ISO 14040: 1997 (E); ISO 14041: 1998 (E)).

3. Decision-making methods and techniques

3.1. Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (Forman et al., 1986; Harker, 1987a,b; Harker and Vargas, 1987; Saaty, 1990a, 1990b; Saaty and Vargas, 1987; Golden et al., 1989) is a method of measurement, which is applied to decision making in order to assist decision makers to describe the general decision operation by decomposing a complex problem into a multi-level hierarchic structure of objectives, criteria, sub-criteria and alternatives. The AHP provides a fundamental scale of relative magnitudes expressed in dominance units to represent judgments in the form of paired comparisons. A ratio scale of relative magnitudes expressed in priority units is then synthesized to obtain a ranking of the alternatives.

In the AHP, there are four modes for scaling weights to rank actions: (i) absolute mode, (ii) distributive mode, (iii) ideal mode and (iv) the supermatrix approach (Saaty and Vargas, 1993).

By applying AHP in decision-making, several problems are coming into question. These problems are referred mainly to the rank reversal (Dyer, 1990) during addition of a new alternative action or the operation of normalization, which effaces the differences of discriminatory power of the criteria (Saaty and Vargas, 1987). So, the choice of the appropriate AHP mode does not ensure that the assessed priorities and ranks of the actions will be right. Especially in IA, the examined end-of-life scenarios are compared, inter alia, on the ground of the impact they produce on predefined damage categories (criteria). These criteria could represent different environmental impact categories, safeguard subjects, social and economic agents, quality of landscape, etc. according to the selected IA method. Evaluation in respect to these criteria may present great difficulties in terms of prior knowledge of standards, which influence their importance (e.g. political target, carrying capacity of the environment, etc.).

In order to obtain the true values of the priorities, the supermatrix approach is suggested. A matrix is created, which is composed of the weights of actions according to the criteria, and of the weights of criteria according to the actions (Harker, 1987a,b). However, the number of paired comparisons required by this approach often places a limitation on the actual size of the matrix. A simple solution is to rescale the weights of criteria in such a way as to undo the effects of the normalization, which takes place when the local weights of the actions are determined. This rescaling takes place with the introduction of two kinds of criteria weights (Giangrande, 1994): intrinsic weights and specific weights.

An intrinsic weight (iw) expresses a scaling constant that reflects the importance that the decision maker ascribes to a criterion regarding the goal, on the ground of his system of values. Assessing of the intrinsic weights of the criteria must take into consideration the characteristics of the decision situation and not the actual actions. These weights are assessed in terms of the potential achievement of the goal.

The specific weights (sw) measure the discriminatory power of the criteria and depend on the kind of normalization applied to the local weights of the actions (ideal or distributive mode). If the local weights are normalized so they sum up to one, the specific weights measure the average (or total) performance of the actual actions on the criteria. Similarly, if the local weights are normalized so that the maximum weight is one for each criterion, the specific weights measure the relative importance of the higher performances of the actions on the criteria. In both cases, the specific weights do not depend on the importance of the criteria regarding the goal, but only on the performances of the actions under consideration.

For the elimination of the negative effects of the normalization of the local weights of the actions, a calculation of the rescaled weights of the criteria (w) by multiplying the intrinsic weights by the specific weights and normalizing the products is done as appeared in Formulae (1)–(3). The principle of hierarchic composition is then applied with these assessed weights.

$$w_{c_1} = \frac{\mathrm{iw}_{c_1}\mathrm{sw}_{c_1}}{\mathrm{iw}_{c_1}\mathrm{sw}_{c_1}+\mathrm{iw}_{c_2}\mathrm{sw}_{c_2}+\ \dots\ +\mathrm{iw}_{c_n}\mathrm{sw}_{c_n}}, \qquad (1)$$

$$w_{c_2} = \frac{\mathrm{iw}_{c_2}\mathrm{sw}_{c_2}}{\mathrm{iw}_{c_1}\mathrm{sw}_{c_1}+\mathrm{iw}_{c_2}\mathrm{sw}_{c_2}+\ \dots\ +\mathrm{iw}_{c_n}\mathrm{sw}_{c_n}}, \qquad (2)$$

$\dots,$

$$w_{c_n} = \frac{\mathrm{iw}_{c_n}\mathrm{sw}_{c_n}}{\mathrm{iw}_{c_1}\mathrm{sw}_{c_1}+\mathrm{iw}_{c_2}\mathrm{sw}_{c_2}+\ \dots\ +\mathrm{iw}_{c_n}\mathrm{sw}_{c_n}} \qquad (3)$$

where w_{c_i} is rescaled weights of the criteria, iw_{c_i} is intrinsic weights, sw_{c_i} is specific weights.

For each end-of-life scenario, based on the various criteria, an environmental score is computed for the IA data and the associated environmental impacts. The AHP method is employed to weigh the criteria according to the relative importance attached to each criterion by the decision-maker. These computed environmental scores and assigned weights are next combined to produce an environmental score representing the environmental merit of the policy.

3.2. LCA polygon

Georgakellos (1997) proposed LCA polygon as a technique which aims to contradistinguish the results that are reached from the Inventory Analysis. According to the above method, impact categories are described in a radial system of axis. In a hypothetical system of n impact categories, a regular n-sided polygon is formed, the edges of which are inscribed in a circle. Each radius ending on an edge of the circle is a measuring axis for each impact category. The geometry of the shape suggests that the successive axes form equal angles. The point where the axes meet corresponds to a value of 0. The values corresponding to the edges of the circle are by definition the normalized maxima (with a value equal to 1) for each category and correspond to the environmental policies for the reduction of environmental pollution. Thus, to every impact category corresponds a value in $[0, 1]$. Each of the axes expresses different natural values, thus having different individual characteristics (scale and units).

The actual values for different impact categories are given for the corresponding axes, forming a new n-sided polygon, which is called LCA polygon. The examination of alternative end-of-life scenarios (e.g. in product design) or the comparison of such scenarios leads to the formation of alternative polygons, in the same radial system. The environmental efficiency of each policy is then described by comparing the areas of the two polygons. The larger the area, the worse the environmental profile of the policy.

The area of a regular n-sided polygon inscribed in a circle of a radius R is calculated by Formula (4).

$$E = \frac{1}{2}nR^2 \sin\left(\frac{360^\circ}{n}\right) \qquad (4)$$

The LCA polygon is not a regular one, so its area E' can be calculated by the sum of the areas of the n triangles formed. Let E'_i $(i = 1, 2, \dots, n)$ be a triangle area and E' the sum of these areas. It is important to point out that in cases where an impact category has a value of 0, the corresponding triangles have an area value equal to 0.

It is:

$$E' = E'_1 + E'_2 + \dots + E'_n \qquad (5)$$

$$E'_i = \frac{1}{2}R_i\, R_{i+1} \sin\left(\frac{360^\circ}{n}\right) \qquad (6)$$

for $i = 1, 2, \ldots, n-1$.

$$E'_n = \frac{1}{2} R_n\, R_1 \sin\left(\frac{360^\circ}{n}\right) \qquad (7)$$

Consequently, the area of LCA polygon is calculated by:

$$E' = \frac{1}{2} \sin\left(\frac{360^\circ}{n}\right) \left(R_n\, R_1 + \sum_{i=1}^{n-1} R_i\, R_{i+1}\right) \qquad (8)$$

Eq. (8) determines the area of an LCA polygon after a random arrangement of the impact categories in the radial system of axis. However, the arrangement of the n axes in the polygon influences the total value of the area surface because the products $R_i\, R_{i+1}$ in Eq. (8) take different values. This problem may prove to be crucial, especially when approximate values are compared. For this reason, the areas for all the possible triangles and different impact categories arrangements are calculated and then the average area is calculated. The number of the triangles with sides R_i and R_{i+1}, $i = 1, 2, \ldots, n-1$ is given by the combinations of 2 out of n axes:

$$\binom{n}{2} = \frac{n(n-1)}{2} \qquad (9)$$

The average area of the LCA polygon $E_{\text{av}}^{\text{pol}}$ is the average area of each triangle $E_{\text{av}}^{\text{tr}}$ multiplied by n:

$$E_{\text{av}}^{\text{pol}} = nE_{\text{av}}^{\text{tr}} = \frac{1}{2} \sin\left(\frac{360^\circ}{n}\right) \left\{ n \left[\frac{2\sum_{i,j=1,\, i<j}^{n} R_i\, R_j}{n(n-1)} \right] \right\} \qquad (10)$$

Obviously, the average area of the LCA polygon is independent of the arrangement of the impact categories, thus more objective. The index E_{LCA} may be used to describe the ratio of the average area of the LCA polygon $E_{\text{av}}^{\text{pol}}$ over the area E of the regular polygon.

$$E_{\text{LCA}}\ (\%) = \left(\frac{E_{\text{av}}^{\text{pol}}}{E}\right) \times 100 \qquad (11)$$

The LCA polygon may also be used for the comparative evaluation of the results, which will take place after the IA phase, in which the environmental impacts of the systems examined are analyzed. The aggregation of the decision parameters may significantly help decision makers in aspects related to the environmental performance of a system. However, the problem arising due to the complex multidimensional parameters still exists and causes difficulties in identifying the net environmental performance of a system.

4. A case study

4.1. Alternative end-of-life scenarios for used batteries

For the purposes of this paper, we use the results of a case study regarding application of LCA in starter lead–acid batteries. Moreover, two alternative end-of-life scenarios are studied and compared. The first scenario deals with the recovery chain, i.e., the flow of used products from consumers to recovery facilities. The second scenario deals with the disposal chain, in which used products are carried to landfills.

4.1.1. Reverse logistics network

Regarding the reverse supply chain of starter batteries, the situation is described as follows.

At the beginning, the batteries are usually deposited at a car electrician's shop, where cars are brought for battery replacement. In rare cases an individual himself replaces the used battery. This means that most of the used batteries enter the reverse flow chain instead of ending up in a landfill. The batteries containing their liquids are stored in columns in the electrician's shop. Imported batteries have no liquids, because of the international legislation restrictions on transportation.

Collectors buy used batteries from the car electrician's shops and they transfer them using pick-up trucks. Then, they forward them to wholesalers trading used materials. Sometimes, the collector forwards the batteries directly to the recycling unit. Collectors do not store batteries. Wholesalers store for some time used batteries in yards, together with other used materials (brass, iron, aluminum, etc.), and then they transport them with trucks to the recycling unit. The batteries are unloaded next to the breaker and then they are loaded to the breaker, using a small lifting machine. The casing of some truck batteries is made of bakelite. Such batteries are broken manually and their lead is pushed to the next stages of the production process, while the bakelite is transferred to a landfill. During disaggregation, lead oxides, plastic, paper and battery liquids are extracted. The lead oxides and plastic are further processed in the unit but the paper is disposed of as waste.

Lead oxides are stored next to the vessel of water and are wet. For this reason they remain in outdoor storage sites until they get dry and then they are forwarded to the furnace for the remaining processes. In the furnace, apart from the lead oxide, some ancillary materials are also inserted. Pure lead is produced in fluid form. Pure lead is placed in moulds and, after that, is driven outdoors and is transformed to grids of smaller size. Then, it is stored in columns until it is sold.

4.1.2. Disposal

Disposal of used batteries concerns an alternative channel that a used battery may go through if it is not collected at the different storage points (car electrician's shops or wholesale collection points) and then transported to the recycling units. Disposal comprises two basic procedures, namely collection/ transportation and landfilling or dumping. It should be noted that dumping of used batteries is not a usual practice.

The increasing uncertainty in different IA methods due to lack of data and the restricted capabilities of all methods to cover all aspects of environmental impacts has led to the suggestion that, when feasible, LCA studies should be implemented using as many IA methods as possible (ISO 14042: 2000 (E)). The EDIP method, unlike the other IA methods mentioned in Section 2, does not result in a single index, which would represent the net environmental score of a policy. By adding such a feature to this IA method, its worthiness would be enhanced.

In the sequel, the decision-making techniques, which were presented in Section 3, are used in order to formulate an index for the EDIP method.

4.2. Application of the Analytic Hierarchy Process

In order to apply AHP in the final results of LCA it is necessary to make the following assumptions:

- The evaluation of the alternative end-of-life scenarios, which simultaneously take the value of zero following some criteria, either due to lack of inventoried data of substances that contribute to the corresponding environmental impacts or of reliable data, are not included in the matrices.
- The weights of the criteria that are not included in the matrices are not taken into account because they affect the weights of other criteria and, consequently, the final decision.
- The intrinsic weights of the impact categories are computed based on the weighting taking into consideration the EDIP method (Daniel and Pappis, 2003).
- The principle of hierarchic composition takes place for the overall estimation of each end-of-life scenario in the three main impact categories (ecological impacts, resources consumption and impacts on the working environment) as described in the EDIP method. In a similar way with criteria, the main impact category of "impacts on the working environment" is not included in the computation due to lack of data.
- The impact categories of the EDIP method are considered to be of equal importance.

The matrices used for AHP are formulated according to the normalized values of each end-of-life scenario at the stage of IA. The criteria refer to the sub-categories of the impact categories and include "environmental impacts" and "resources consumption" and are presented in Tables 1 and 2.

As a first step the values of the criteria are further normalized so as the corresponding sum for the subcategory be equal to 1. The formulated matrices are presented in Tables 3 and 4.

Table 1
Environmental impact criteria

Criteria	Reverse supply chain	Disposal chain
Global warming	1.70E − 05	8.65E − 09
Photochemical ozone formation	1.60E − 06	3.40E − 05
Acidification	2.60E − 06	1.00E − 04
Nutrient enrichment	1.76E − 05	2.03E − 05
Persistent toxicity	2.90E − 02	2.28E − 01
Human toxicity	1.33E − 02	8.73E − 06
Ecotoxicity	5.21E − 03	1.72E − 03
Slag and ashes	4.55E − 03	0.00E + 00
Bulk waste	1.30E − 04	1.30E − 04
Hazardous waste	1.16E − 03	6.40E − 02

Table 2
Resources consumption criteria

Criteria	Reverse supply chain	Disposal chain
Carbon (C)	3.40E − 07	0.00E + 00
Oil	2.90E − 07	4.98E − 09
Iron (Fe)	2.33E − 06	0.00E + 00
Lead (Pb)	7.43E − 04	2.13E − 03
Copper (Cu)	0.00E + 00	9.53E − 07
Antimony (Sb)	0.00E + 00	9.72E − 06

Table 3
Normalized environmental impact criteria

Criteria	Reverse supply chain	Disposal chain
Environmental impacts		
Global warming	0.99949	0.00051
Photochemical ozone formation	0.04494	0.95506
Acidification	0.02534	0.97466
Nutrient enrichment	0.46438	0.53562
Persistent toxicity	0.11284	0.88716
Human toxicity	0.99934	0.00066
Ecotoxicity	0.75180	0.24820
Slag and ashes	1.00000	0.00000
Bulk waste	0.50000	0.50000
Hazardous waste	0.01780	0.98220

The next step is the calculation of the intrinsic weights and the specific weights of the criteria. The weight of each criterion is a result of the distance-to-target method and the political targets. From time to time, international summits, the European Union (EU), countries and organizations, set reduction targets for the main impact categories. Environmental impacts may be regarded as global, regional or local. In this paper, the political targets, as defined by relevant regulations for each environmental impact category applying globally, in the EU and Greece, have been used (Wenzel and Hauschild, 1997; Daniel and Pappis (2003)). The calculation of intrinsic weights (iw) is based on their actual importance for the protection of the environment. The corresponding contribution (positive or negative) of the whole end-of-life scenario is not taken into account. The specific weights (sw) are calculated based on the performances of the alternative end-of-life scenarios in respect to the particular criteria, that is, the average (or total) performance of the actual scenarios in respect to the criteria. The overall weights are calculated using Formula (3) and the results are presented in Tables 5 and 6.

Table 4
Normalized resources consumption criteria

Criteria	Reverse supply chain	Disposal chain
Resources consumption		
Carbon (C)	1.00000	0.00000
Oil	0.98312	0.01688
Iron (Fe)	1.00000	0.00000
Lead (Pb)	0.25861	0.74139
Copper (Cu)	0.00000	1.00000
Antimony (Sb)	0.00000	1.00000

The next step is the final evaluation of the alternative end-of-life scenarios, which is done using the following formula:

$$A_{ij} = \sum a_i w_{cj} \tag{12}$$

where a_i is the alternative end-of-life scenarios, w_{cj} the overall weights of the alternative end-of-life scenarios i according to criterion j, A_{ij} the final evaluation of the end-of-life scenario i according to criterion j.Obviously, A_{ij} is the product of the columns of Tables 3 and 4 with the corresponding w_{cj} of Tables 5 and 6, as indicated in Formula (12). The results are presented in Table 7.

In the final step, the main impact categories are evaluated following the same process, taking into account the corresponding weights according to Formula (13). The main impact categories (environmental impacts and resources consumption) are considered to be of equivalent importance, thus $w_k = 0.5$.

$$E_i = \sum A_{ij} w_k \tag{13}$$

where A_{ij} is the alternative end-of-life scenarios, w_k the weight of the main impact category k, E_i is the overall evaluation of the end-of-life scenario i.

For each end-of-life scenario [reverse supply chain (RC) and disposal chain (D)] the results are the following:

$$E_{\mathrm{RC}} = 0.1659 \times 0.5 + 0.2421 \times 0.5 = 0.2040$$
$$\Rightarrow E_{\mathrm{RC}} = 20.40\%$$
$$E_{\mathrm{D}} = 0.8341 \times 0.5 + 0.7579 \times 0.5 = 0.7960$$
$$\Rightarrow E_{\mathrm{D}} = 79.60\%$$

Table 5
Weights with respect to the environmental impact criteria

Criteria	Environmental impacts			w_{cj}
	Criterion weight	Intrinsic weights (iw_{cj})	Specific weights (sw_{cj})	
Global warming	1.43	0.089	4.90E − 05	0.00003
Photochemical ozone formation	1.28	0.080	1.02E − 04	0.00006
Acidification	1.186	0.074	2.95E − 04	0.00016
Nutrient enrichment	1.2	0.075	1.09E − 04	0.00006
Persistent toxicity	2.5	0.156	7.40E − 01	0.83128
Human toxicity	2.8	0.175	3.83E − 02	0.04821
Ecotoxicity	2.3	0.144	1.99E − 02	0.02062
Slag and ashes	1.1	0.069	1.31E − 02	0.00648
Bulk waste	1.1	0.069	7.48E − 04	0.00037
Hazardous waste	1.1	0.069	1.88E − 01	0.09274

Table 6
Weights with respect to the resources consumption criteria

Criteria	Resources consumption			w_{cj}
	Criterion weight	Intrinsic weights (iw_{cj})	Specific weights (sw_{cj})	
Carbon (C)	0.0058	5.21E − 03	1.18E − 04	0.00001
Oil	0.023	2.07E − 02	1.02E − 04	0.00005
Iron (Fe)	0.0085	7.63E − 03	8.09E − 04	0.00013
Lead (Pb)	0.048	4.31E − 02	9.95E − 01	0.93370
Copper (Cu)	0.028	2.52E − 02	3.31E − 04	0.00018
Antimony (Sb)	1	8.98E − 01	3.37E − 03	0.06593

Application of AHP concludes by stating that the reverse supply chain has a better environmental performance than the disposal chain. The nature of AHP indicates that it can definitely assist decision-making in LCA. However, it can only be used in cases of comparisons of alternative end-of-life scenarios.

4.3. Application of the LCA polygon

The last two assumptions made for the application of the AHP also apply in the case of the LCA polygon. The graphic representation of the method by describing the impact categories in a radial system of axis, so that a regular *n*-sided polygon is formed, leads to Figs. 1–4.

However, these figures are the result of the random arrangement of the impact categories in the radial system and the area of the LCA polygon is dependent on this. The areas for all the possible triangles and different impact categories arrangements are calculated and then the average area is calculated, as described in Section 3.2. The average areas of the polygons define the environmental score of the alternative end-of-life scenarios. The results are summarized in Table 8.

Table 7
Final evaluation results of the end-of-life scenarios

Impact categories	Reverse supply chain (%)	Disposal chain (%)
A_{ij}		
Environmental impacts	16.59	83.41
Resources consumption	24.21	75.79

Table 8
Percentage area of the examined end-of-life scenarios according to the LCA polygon method

End-of-life scenario	Index E_{LCA} (%)	
	Environmental impacts	Resources consumption
Reverse supply chain	0.15	0.27
Disposal chain	1.87	5.51

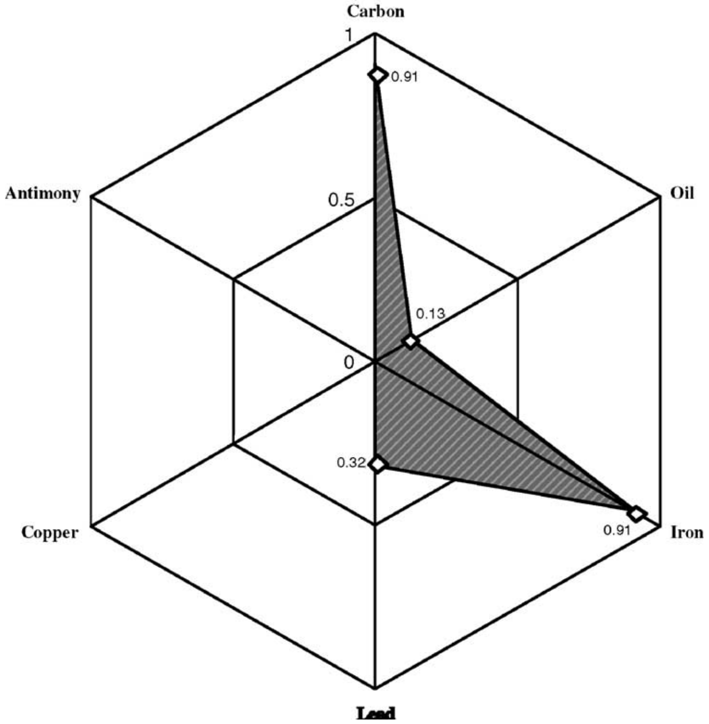

Fig. 1. LCA polygon of the reverse supply chain resources consumption.

The final step is to apply the principle of hierarchic composition (Formula (14)). The main impact categories (environmental impacts and resources consumption) are considered to be of equal importance, thus $w_k = 0.5$.

$$E_i = \sum E_{\mathrm{LCA}i}\, w_k \tag{14}$$

where $E_{\mathrm{LCA}i}$ is the ratio of the average area of the LCA polygon E to the area of the regular polygon, w_k the weight of the main impact category k, E_i the overall evaluation of the end-of-life scenario i.

For each end-of-life scenario [reverse supply chain (RC) and disposal chain (D)] the results are the following:

$$E_{\mathrm{RC}} = 0.15 \times 0.5 + 0.27 \times 0.5 = 0.21$$

$$E_{\mathrm{D}} = 1.87 \times 0.5 + 5.51 \times 0.5 = 3.69$$

A normalization of these values according to their sum gives the results:

$$E_{\mathrm{RC}}(N) = \frac{0.21 \times 100}{(0.21 + 3.69)} = 5.4\%$$

$$E_{\mathrm{D}}(N) = \frac{3.69 \times 100}{(0.21 + 3.69)} = 94.6\%$$

The LCA polygon method leads to the same conclusion: the reverse supply chain has a better environmental performance than the disposal chain. A crucial advantage of the LCA polygon method is that it can be used not only for the comparison between alternative management policies or scenarios, but also for a standalone estimation of the environmental performance of a policy or scenario. Furthermore, it provides a means for the graphic representation.

5. Application of other Impact Assessment methods

As mentioned above, LCA studies should be implemented using as many IA methods as possible. In-

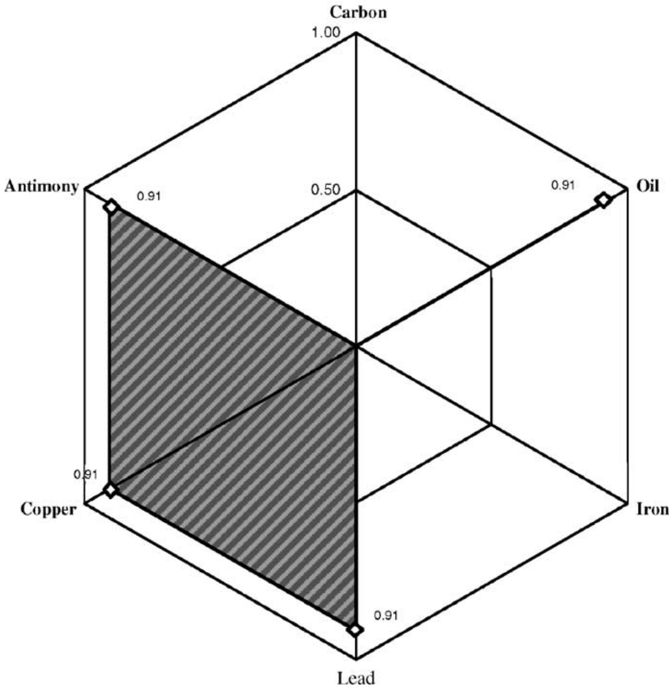

Fig. 2. LCA polygon of the disposal chain resources consumption.

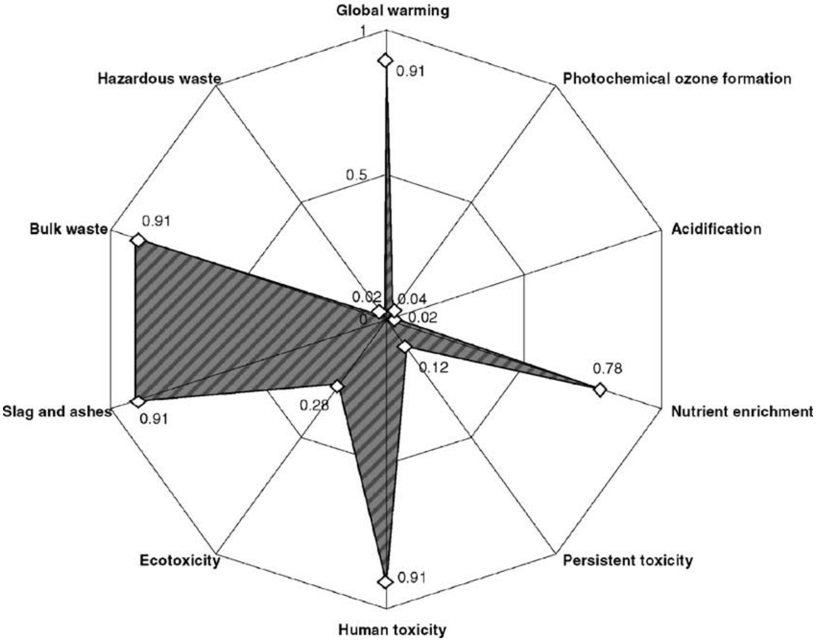

Fig. 3. LCA polygon of the reverse supply chain ecological impacts.

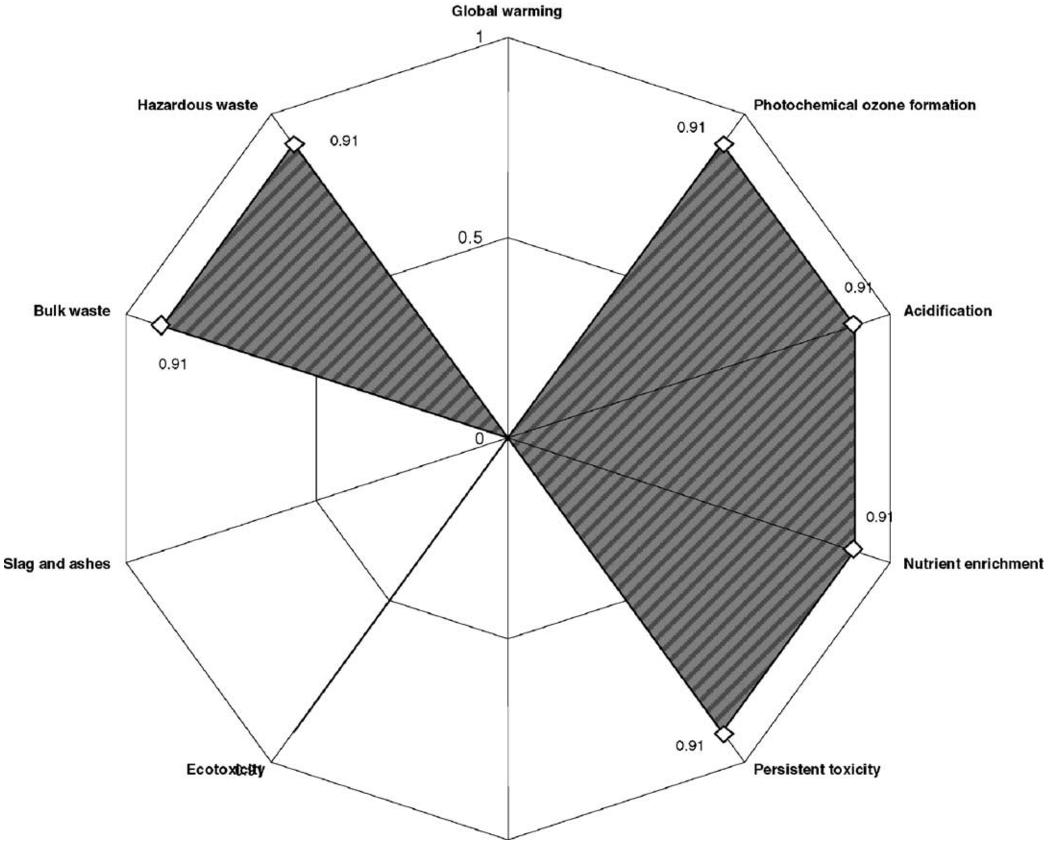

Fig. 4. LCA polygon of the disposal chain ecological impacts.

deed, the effectiveness of analysis is improved and decision makers can be more confident to choose the IA method, which fits better the specific features of the system examined. For this case study the software pack SimaPro 4.0S has been used in order to have the results of many IA methods available for analysis. These IA methods are: Ecopoints 1990, Ecopoints 1997, Eco-indicator 95, Eco-indicator 99 (H) and EPS 2000. SimaPro aggregates the results of for each method in order to give the ability to make comparisons. The graphs that were produced with the application of these methods are available from the authors upon request.

5.1. Ecopoints 1990

According to this IA method, the environmental burden produced by the reverse supply chain is bigger than the one produced by disposal. In almost all impact categories the disposal chain appears to have a better environmental performance. The results are the expected ones because this method evaluates only some pre-selected substances and ignores their contribution in other impact categories. For example, SO_2 is proved to contribute in global warming along with CO_2. In addition, many important substances, which have been recorded in inventory analysis (lead in soil), have been ignored. Finally, the method does not take into account resources consumption.

5.2. Ecopoints 1997

The same situation commented regarding Ecopoints 1990 exists also in Ecopoints 1997, though some additional impact categories have been included. According to the results the major environmental burden would occur from the reverse supply chain.

5.3. *Eco-indicator 95*

In contrast with the former two IA methods, the environmental index corresponds to generalized impact categories and not to certain substances. The different waste management scenarios appear to have similar environmental performances. However, as it will be seen later, the aggregation of the results in a single index leads to the overall predominance of the reverse supply chain, as this IA method appears to have a tendency to "punish" certain environmental burdens.

5.4. *Eco-indicator 99 (H)*

The newest version of Eco-indicator, which is enriched in impact categories and the index of recorded substances, results in more balanced results in comparison to the previous version of the method. Therefore, Eco-indicator 1999 appears also to have a tendency to "punish" certain environmental burdens.

5.5. *EPS 2000*

From the results of EPS 2000 the disposal chain seems to have a better environmental performance in most impact categories. However, the aggregation of the results in a single index will result in predominance of the reverse supply chain, since EPS 2000 has also a tendency to "punish" certain environmental burdens.

The aggregate results according to all methods presented in this paper are presented in Fig. 5.

6. Discussion

Application of weights in IA is based on the principles, which have been formulated by the decision maker in order to serve particular political or social targets. This usually leads to different results, although

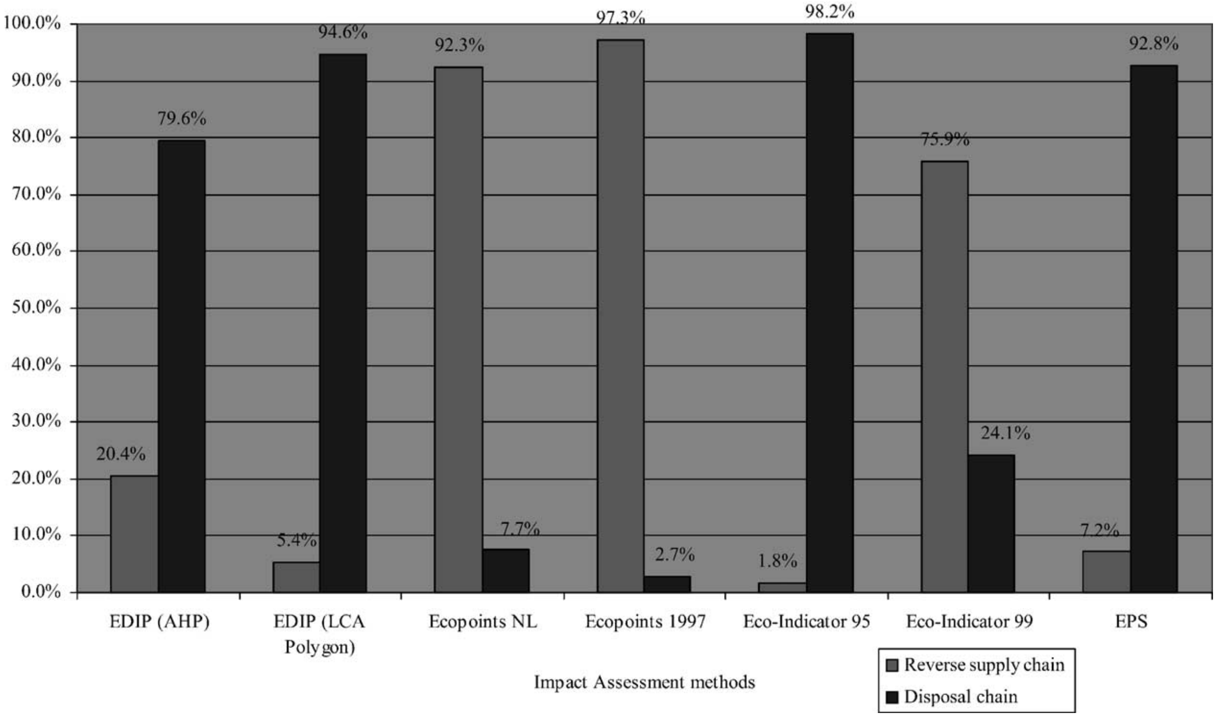

Fig. 5. Aggregate results of the waste management policies according to different LCA Impact Assessment methods.

the results are produced from the same inventory analysis. Another important factor that affects the results is the lack of data for certain substances, which characterizes all IA methods. Finally, the attribution of different weights to impact categories is reflected in the results of LCA.

The examination of different IA methods raises certain questions regarding the interpretation of the results. The situation is unambiguous in cases where the results are presented by means of a single index. If this is not the case, there is ground for contradictory interpretation of the results, especially if the numeric values to be compared are similar. The development of a single overall index, which would utilize the results of IA in a simple and objective way, would be very helpful. Such index should be produced using simple and objective methods as much as possible. In this paper, decision-making methods and techniques have been used for this purpose in the case of the EDIP method. Further development and use of these methods and techniques in other IA approaches may contribute to:

- the development of a common basis for the valuation of the results of the inventory analysis;
- the minimization of the effect of subjectivity to the analysis;
- the integration of the results of different IA methods;
- the next phase of LCA, i.e. Interpretation, where both environmental and economic criteria may be assessed.

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