Analythical Hierarchy Process (AHP) in Decision-Making for End-of-Life of Products

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Abstract

The proposed EU Waste from Electronic and Electrical Equipment (WEEE) Directive sets targets for the reuse and recycling of EEE reaching end-of-life (EOL). How a producer determines which is the best strategy for his/her products (reuse, part reclamation, remanufacturing, recycling) is not addressed. The producer must meet targets in the WEEE Directive, consider other environmental regulations, and make sure he is economically efficient. Economic costs and values are expressed in money (Euro), environmental impacts in a multitude of units. It is extremely difficult (if not impossible) to express them all in a single unit. Therefore the decision as to choice of EOL strategy for WEEE is a difficult one, based as it is on a number of unlike criteria. A possible solution to this problem is AHP. It will not replace the decision-making process itself but it will generate information needed to make the decision and will present it in a structured way. The AHP is a method of solving problems that involve prioritisation of alternative solutions and is based on the evaluation of a set of criteria. Associated with the decision-making for WEEE, there are a number of criteria that a producer has to consider: damage to resources, damage to ecosystem, and economic efficiency. A hierarchical structure is formed by using the overall goal (choose strategy) as a root of the decision tree and making each major criterion a child. Each criterion in turn is detailed to provide additional descendants. At the lowest level of the tree are the end-of-life options (reuse, part reclamation, remanufacturing, recycling) assigned to every leaf node in the tree. The decision-maker makes pairwise comparisons at each level between criteria which have the same parent node and gives them relative weights. He/she will also judge all the EOL options against each other with respect to each of the criteria situated in the leaf nodes, and will give them relative weights. All these comparisons lead to priority vectors which are propagated through the hierarchy to arrive at a final priority vector for the set of end-of-life options. The decision maker is thus enabled to base his/her decision on various criteria to which he himself has assigned weightings.

1. Introduction

The decision-making process as it relates to determination of end-of-life option is based on several criteria, rather than an exclusive single criterion. Reality is complex; the decision situation involves consideration of variables which cannot be easily quantified into monetary units, and the decision-making process is likely to be influenced by multiple interconnected criteria [1].

Decision-making techniques have been long dominated by the cost-benefit analysis that uses the criterion of maximum total net benefit to choose the optimum solution [2]. The main limitation of such an approach is that all the effects of an activity are evaluated in monetary terms, so that when aspects that cannot be quantified into monetary units (like social and environmental issues) are dominant, the method is completely inappropriate [2].

The continuous focus on sustainable development in the past decade raised wide concerns towards integration of environmental, economic and social aspects into the decision-making process. The diversity of environmental and social impacts and the multitude of units they are expressed in, the natural resources depletion and the complexity involved in the economic valuation pose problems to monetisation of all these criteria [1]. That is why, for the complex environmental and economic decision-making processes, new techniques should be considered, like formulation of alternatives which meet various environmental, economic and social criteria, and give a compromising solution that meets both sustainability principles and economic efficiency [1].

Multi-criteria analysis methods are very helpful in taking into account the results of monetary valuation, ecological analysis, public concern as well as decision-makers' points of view in the decision-making process [1]. A multi-criteria analysis method that can be applied to environmental and economic decision-making where not all the criteria can be quantified in monetary units is the Analythical Hierarchy Process (AHP).

This document briefly presents the possible options a producer has for his/her end-of-life products and how he/she can judge them against each other using the AHP method in the decision-making process. The end-of-life options are compared with respect to environmental, economic and social criteria. Indicators representing these criteria are also presented in this document.

2. Environmental and Economic Decision-Making for End-of-Life of Products

The final stage of the life cycle of a product, retirement, is one that has been often ignored. The retirement stage begins when the customer no longer wants the product. What happens to a product after the end of its usage is of growing importance to the producer because of consumer demands and other growing pressures such as new legislation that mandates recovery and recycling of some products by their manufacturers.

During a product's retirement stage, there are a variety of things that could happen. There are multiple disposal options, but there are also options that do not include disposal such as *reuse/part reclamation*, product recovery (*remanufacturing*) or material recovery (*recycling*) [3]. There are also disposal options like *incineration with energy recovery* or simply *disposal to landfill*.

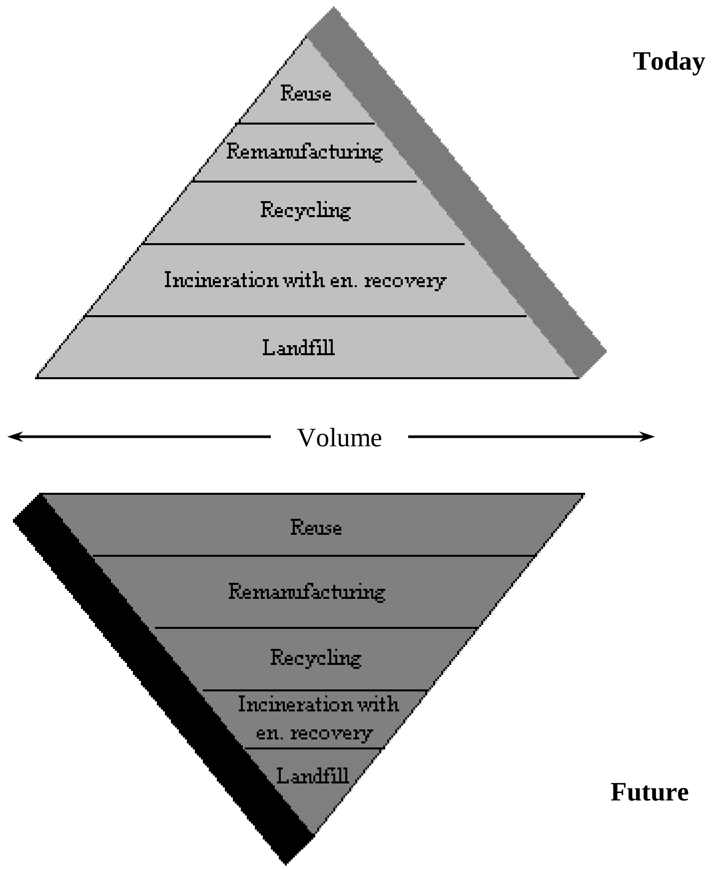

Figure 1. Hierarchy of end-of-life treatment options [4, modified]

Figure 1 presents a hierarchy of the end-of-life treatment options of the current situation and practice and the hierarchy recommended by the European Commission under its sustainable development initiative [5]. Once materials enter the waste stream first priority should be given to reusing or remanufacturing them or to recycle them for the purpose of manufacturing new products. Disposal without any material or energy recovery is to be regarded as an option of last resort.

The hierarchy aim is to recommend the most favourable end-of-life option from an environmental perspective but it does not always represent the best option in economic terms [4]. Actually even from an environmental point of view the hierarchy is contested by environmentalists and those involved in the recycling industry as the Commission doesn't specify on which criteria this hierarchy is based (is it waste reduction, conservation of resources, energy consumption, environmental impact?). Besides, sustainable development comprises environmental as well as economic and social considerations. Therefore, a multi-criteria analysis method (like AHP) should be used to provide a hierarchy of the possible end-of-life options considering all types of criteria: environmental, economic and social (externalities). The environmental, economic and social indicators chosen as criteria for decision-making for end-of-life products in the AHP are presented as follows.

2.1. Environmental Indicators

Every product has some impact on the environment, which may occur at any stage of the product's life cycle – including the end-of-life treatment options (reuse/part reclamation, remanufacturing, recycling, incineration, disposal to landfill). These impacts may range from slight to significant, they may be short-term or long-term; and they may occur at the global, regional or local level, or a combination of all three. The main effects of environmental flows from a product end-of-life treatment activity on environment could be concentrated into three main categories [6], [7]: (1) damage to resources; (2) damage to ecosystem; (3) damage to human health. A link can be established between environmental impacts and damages to environment, and indicators are calculated to show these impacts.

The ISO 14031 defines two basic types of environmental indicators that show environmental performance [8]:

- *operational performance indicators* – "information about the environmental performance of an organisation's operations" [8]. Examples include quantity of emissions to air or water, energy use, or quantity of raw material used.
- *management performance indicators* – "information about management efforts to influence the environmental performance of an organisation" [8]. An example is the degree of compliance with regulations.

A literature review was conducted and all types of environmental indicators studied. The following indicators that show environmental impact have been chosen for our model (see figure 2):

- *Damage to resources* (the environmental impacts that produce this effect occur both at a global and local level):
    - Non-renewable primary energy input
    - Materials consumption
    - Water consumption
- *Damage to ecosystem* (the environmental impacts that produce this effect occur both at a global and local level):
    - Greenhouse effect
    - Ozone layer depletion
    - Acidification
    - Water nutrient pollution
- *Damage to human health* (the environmental impacts that produce this effect occur mainly at a local level):
    - Hazardous substances emitted into air
    - Hazardous substances emitted into water
    - Emission of carcinogenic substances

When it comes to environmental issues, a lot of pressure on producers is generated by legislation. The forthcoming European Union Directive on Waste from Electrical and Electronic Equipment (WEEE Directive) sets targets for the rate of waste from electrical and electronic equipment (WEEE) collection, the rate of reuse and recycling of electrical and electronic goods [9]. As the model will be applied to WEEE, a new group of indicators was added, indicators that show compliance with the new regulations:

- *Compliance with regulation*:
  - o Percentage of waste that is reused/remanufactured/recycled/incinerated/landfilled
  - o Average percentage of product that is reused/remanufactured/recycled/incinerated/ landfilled

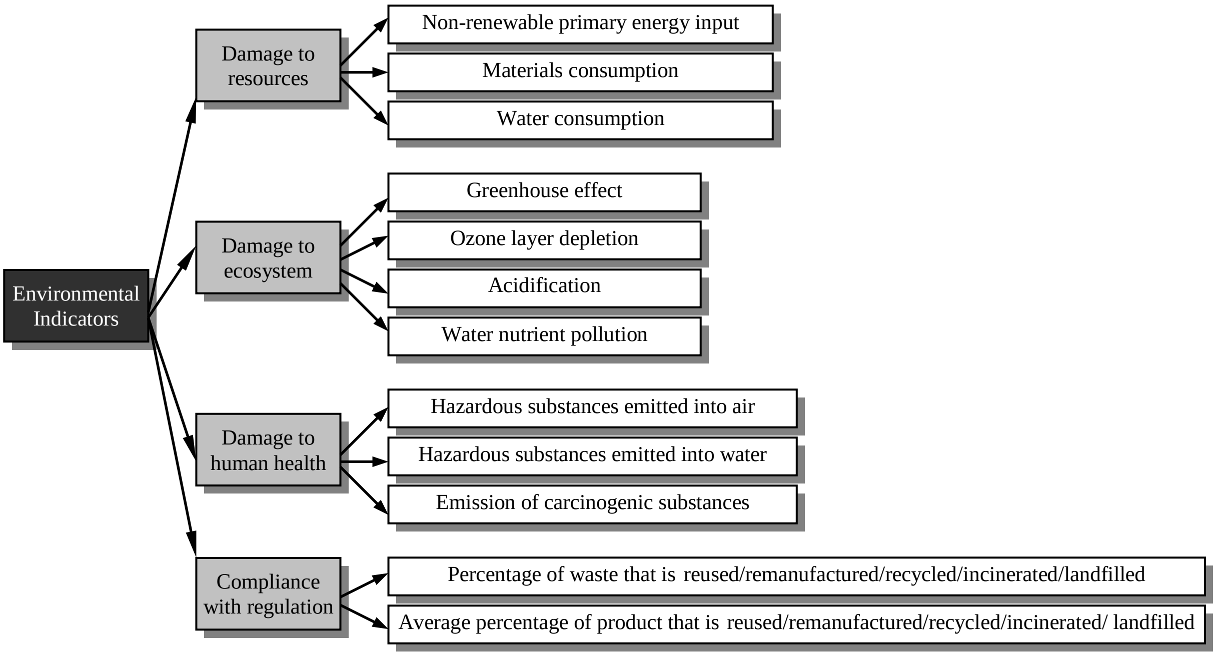

Figure 2. Environmental indicators

2.2. Economic and Social Indicators

The WEEE Directive states that financing of the costs for the collection, treatment, recovery and environmentally sound disposal of waste from electric and electronic equipment is to be provided for by producers [9]. This is an important reason for producers to be interested in the processing costs involved in different end-of-life options when making decisions as to the end-of-life option for their products, as whatever the nature of the business, all will use materials, employ labour and incur overhead costs [10].

Another issue in decision-making is corporate social responsibility. Sustainable development is built on three pillars: economic growth, ecological balance and social progress, all of which are integral to the achievement of sustainable development [11]. Simply stated, corporate social performance measures the relationship of business with its different stakeholder groups [12]. There is a core set of social issues that have broad utility across stakeholders and firms. Some key social elements might be: (1) *employment practices*: the provision of a safe working environment; financial and job security; freedom from discrimination on race, gender, colour or creed; and opportunity for professional development; (2) *community relations*: the contribution of a firm to community development, including: job creation; taxes paid/tax breaks received; philanthropy; and employee volunteerism; (3) *ethical sourcing*: engage in fair trading practices with suppliers, distributors, and partners; ensure that suppliers do not use child or forced labour, provide safe working conditions, and fair wages; (4) *social impact of product*: the contribution of products and services to: social welfare; equity; and the meeting of basic human needs, such as food, shelter, water, and health care [12].

The following indicators that show economic and social impact have been chosen for our model (see figure 3):

- Processing cost

- Number of jobs created
- Number of complaints from community
- Degree of resources applied to support community
- Degree of compliance with regulations

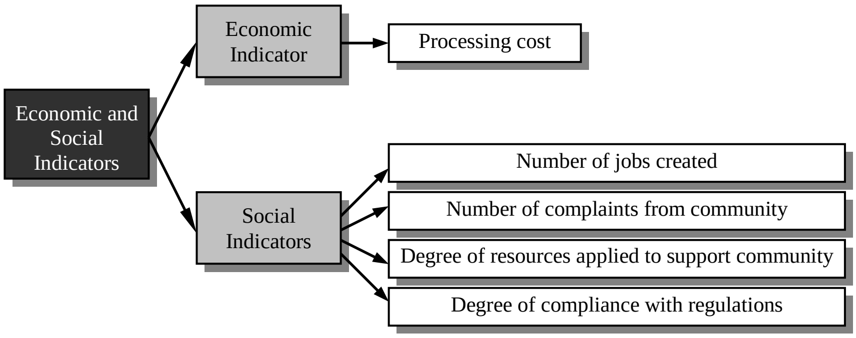

Figure 3. Economic and social indicators

3. The Analythical Hierarchy Process

Decision-making for end-of-life of products invariably involves multiple issues, multiple criteria. There is a need for a systematic approach to decision analysis that can integrate and incorporate the values of the decision-makers, public opinion and legislative constraints, and policy and management goals with technical information to examine the overall implications of each alternative [13]. The Analytic Hierarchy Process (AHP), which was developed as a methodology for multi-criteria modelling and decision-making [14], [15], provides a framework for facilitating such an approach.

AHP provides a hierarchical framework within which multi-attribute decision problems can be structured [14]. AHP is not designed to substitute for clear thinking by the decision-maker. It does, however, better organise their thoughts and make them more presentable to others. The real strength of AHP is that it treats the decision as a system, which is difficult for many decision-makers to do [16]. It is very difficult, nearly impossible for the decision-maker to consider all of the factors involved in a complex decision. Without decision support methodologies like AHP, managers might base their decisions on only a subset of criteria. The AHP makes complex decision processes more rational by synthesizing all available information about the decision in a system-wide and systematic manner and helps the manager prioritise the criteria in a manner that otherwise might not be possible [16].

The AHP is designed for subjective evaluation of a set of alternatives (end-of-life options in our case) based on multiple criteria, organised in a hierarchical structure. At the top level, the criteria are evaluated and at the lower levels, the alternatives are evaluated by each criterion. The decision maker assesses his/her evaluation separately for each level and sub-level. He/she creates a pairwise comparison matrix in which his/her evaluation for every pair of items is assessed [17].

The AHP procedure follows the following steps [17], [18]:

1. *Structuring the hierarchy of criteria and alternatives for evaluation*. Criteria are identified. A hierarchical structure is formed by using the overall goal as a root of the decision tree and making each major criterion a child node. Each criterion in turn is detailed to provide additional descendants. Once the decision tree is completely formed, all alternatives are assigned to every leaf node in the tree.

2. *Assessing the decision-maker evaluations by pairwise comparisons*. Relative importance (or preference) for each criterion is rated among those which have the same parent node. Rating is done using the scaled one-pair comparison method. Comparing criterion i and criterion j (where i is assumed to be at least as important as j), elements a_{ij} of the pairwise comparisons matrix are obtained as shown in table 1.

   Table 1. The pairwise comparison scale [13], [15], [18]

Intensity of importance	Definition
1	Objectives *i* and *j* are of equal importance
3	Objective *i* is weakly more important than *j*
5	Objective *i* is strongly more important than *j*
7	Objective *i* is very strongly more important than *j*
9	Objective *i* is extremely more important than *j*
2, 4, 6, 8	Intermediate values between the two adjacent judgements

A square matrix is formed when every two criteria are compared. The matrix has the property that element $a_{ji} = \frac{1}{a_{ij}}$. When a criterion has one of the above numbers assigned to it when compared to a second criterion, then the second criterion has the reciprocal value when compared to the first.

3. *Using the eigenvector method to yield priorities for criteria and for alternatives by criteria*. The relative importances are given as a normalised eigenvector of the pairwise comparison matrix, guaranteeing that the sum of relative importances of siblings always equals one. Relative importance for each alternative is rated in the same way as for criteria. All alternatives are judged against each criterion.
4. *Synthesizing the priorities of the alternatives by criteria into composite measures to arrive at a set of ratings for the alternatives*. Absolute importances for all criteria and alternatives are calculated. The absolute importance of the root node is set to 1. The absolute importance of all other nodes (criteria or alternatives) is calculated by multiplying a node's relative importance by its parent node's absolute importance. For each alternative, all of its absolute importances are summed. This value equals the total number of preference points (the score). Alternatives with greater scores are preferable to alternatives with less scores.

One major advantage of AHP is that the construction of the hierarchy diagram forces the decision-maker to structure the problem. Requiring the decision-maker to assign numerical values for the criteria and alternatives' relative importances forces the decision-maker to consider trade-offs in some detail [16]. Since managers typically rely on only a subset of information, AHP helps managers make ''more rational'' decisions by structuring the decision as they see it and then fully considering all available information on the criteria and alternatives [16].

4. AHP in Decision-Making for End-of-Life of Electrical and Electronic Products

The challenge in this study was to construct an AHP model that included relevant environmental, economic and social criteria and could be applied to decision-making for end-of-life of electrical and electronic goods. Initially we conducted a literature review to identify a set of indicators and the indicators presented in sections 2.1 and 2.2 were chosen. The goal of the study is choosing the end-of-life option which satisfies best all the environmental, economic and social criteria, the potential solutions being reuse/part reclamation, remanufacturing, recycling, incineration with energy recovery and landfill. The major criteria at the first level of the decision-tree are the environmental issues (damage to resources, damage to ecosystem, damage to human health and the compliance with regulations), the economic and the social issues. Damage to resources can be broken down to non-renewable primary energy input, materials consumption and water consumption; damage to ecosystem can be broken down to greenhouse effect, ozone layer depletion, acidification and water nutrient pollution; damage to human health can be broken down to hazardous substances emitted into air, hazardous substances emitted into water and emission of carcinogenic substances; compliance with regulations can be broken down to percentage of waste that is reused/remanufactured/recycled/ incinerated/landfilled and average percentage of product that is reused/remanufactured/recycled/ incinerated/ landfilled; economic and social impact can be broken down to processing cost, number of jobs created, number of complaints from community, degree of resources applied to support community and degree of compliance with regulations. This process of refining criteria is what forms the *decision tree*. Figure 4 shows the decision tree used by AHP to solve the end-of-life option problem.

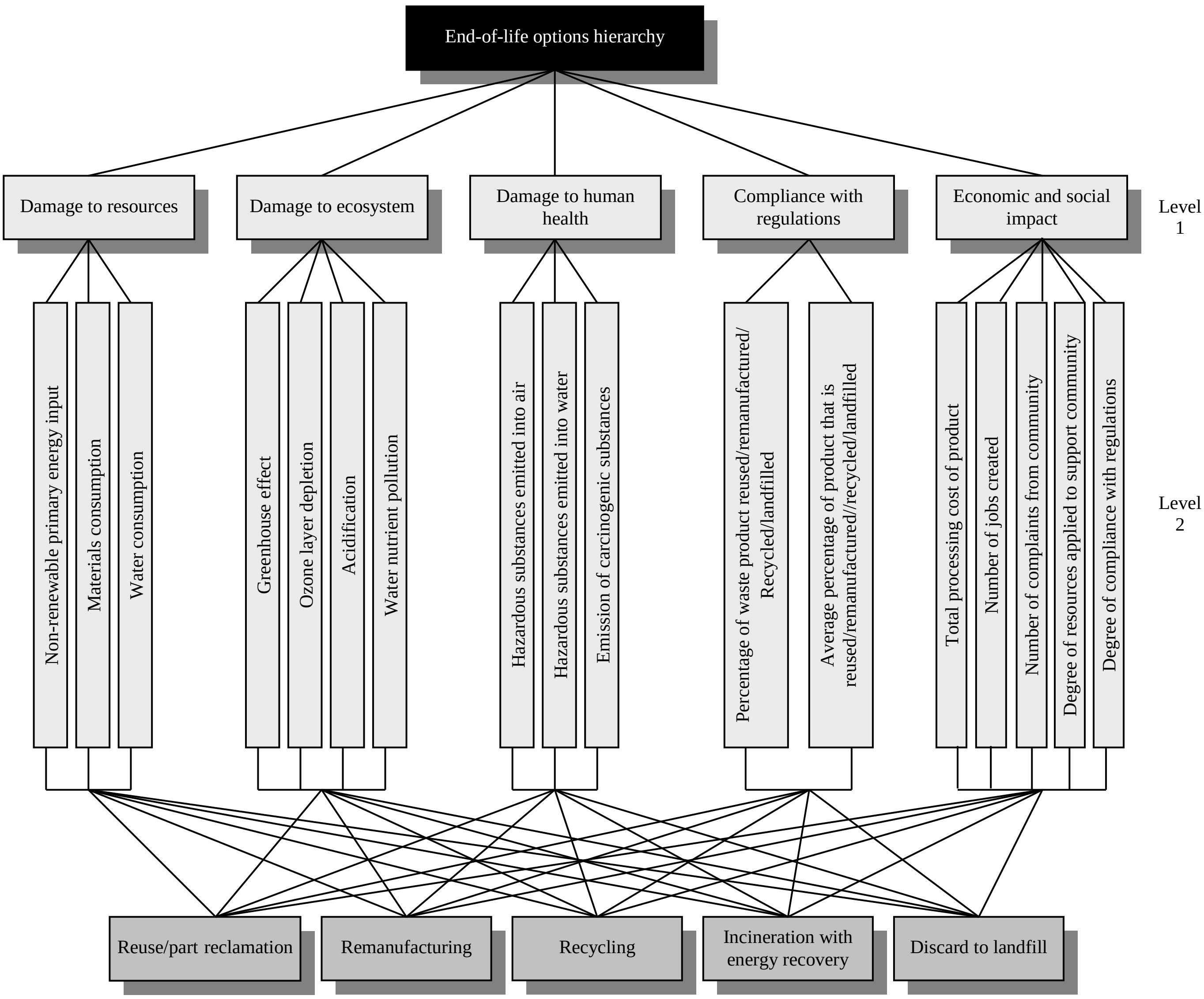

Figure 4. The hierarchical structure used by AHP in decision-making for end-of-life options for electrical and electronic products

Once the hierarchical structure is defined, *pairwise comparison judgements* may be made. Each criterion is compared to those that have the same parent node. Pairwise comparisons matrices are formed based on the scale presented in table 1. Table 2 shows a matrix of pairwise comparisons of the criteria at the first level in the decision tree with respect to the overall objective: obtaining the best end-of-life option.

The diagonal values of any pairwise comparisons matrix are always 1 as each criterion is compared with itself. As stated before, the lower triangular part of the matrix contains the reciprocal of the values in the upper triangular part $\left(a_{ji} = \frac{1}{a_{ij}} \right)$.

The next step is obtaining the *relative importances of criteria and alternatives* using the eigenvector method. Let us denote the pairwise comparisons matrix as $A=(a_{ij})$. If n criteria (C_1, C_2, …, C_n) at the same level are compared, then the relative weights are the normalised elements of the eigenvector $w=(w_1, w_2, \ldots, w_3)$ which verifies the equation:

$$(\lambda_{max} I\text{-}A)w = 0$$

where λ_{max} is the largest eigenvalue of A.

In practice, to determine the relative weights the sum of each column will be made. Then each number in the matrix will be divided by the sum of the column it appears in. By averaging across each row, the final relative weight is obtained for each criterion.

Table 2. Matrix of pairwise comparisons of the criteria at the first level in the decision tree with respect to the overall objective

	Damage to resources	Damage to ecosystem	Damage to human health	Compliance with regulations	Economic and social impact
Damage to resources	1	3	1/5	3	7
Damage to ecosystem	1/3	1	5	5	9
Damage to human health	5	1/5	1	1	3
Compliance with regulations	1/3	1/5	1	1	3
Economic and social impact	1/7	1/9	1/3	1/3	1

Let us denote the relative weights derived from pairwise comparisons of the criteria at the first level as:

w_i, where $\sum_{i=1}^{5} w_i = 1$

and $i = 1, 2, \ldots, 5$; i = criteria at level 1

The relative weights derived from pairwise comparisons of the criteria at level 2 corresponding to each criterion at level 1 are:

v_{ij}, where $\sum_{j=1}^{n} v_{ij} = 1$, $\forall\, i, i = 1, 2, \ldots, 5$

and i = criteria at level 1
$j = 1, 2, \ldots, n$
j = criteria at level 2 corresponding to criterion i at level 1
n = number of criteria at level 2 corresponding to criterion i at level 1

The relative weights derived from pairwise comparisons of the alternatives at the bottom level with respect to each criterion at level 2 are:

V_{kl}, where $\sum_{l=1}^{5} V_{kl} = 1$, $\forall\, k, k = 1, 2, \ldots, m$

and $l = 1, 2, \ldots, 5$; l = alternative
k = criteria at level 2
m = total number of criteria at level 2

After all the eigenvectors have been obtained, the *process of synthesis* can proceed. The absolute importances of criteria at level 2 corresponding to each criterion at level 1 will be obtained with the formula:

$U_{ij} = w_i v_{ij}$, $\forall\, i, i = 1, 2, \ldots, 5$
$\forall\, j, j = 1, 2, \ldots, n$
where i = criterion at level 1
j = criterion at level 2

n = number of criteria at level 2 corresponding to criterion i at level 1

Let us denote the absolute importances of criteria at level 2 calculated before as:

W_k, where $k = 1, 2, \ldots, 17$
k = criterion at level 2

Then the scores of the alternatives (end-of-life options) are:

$$S_l = \sum_{k=1}^{17} V_{kl} W_k, \quad \forall\, l,\ l = 1, 2, \ldots, 5$$

where l = alternative
k = criterion at level 2; $k = 1, 2, \ldots, 17$

The scores of the alternatives will give the hierarchy. The best end-of-life option (alternative) is the one with the highest score, max S_l.

5. Conclusions

Decision-making for end-of-life of products, especially electrical and electronic ones, is a difficult task. Many factors must be considered – environmental, economic, social – and so it becomes a multi-criteria decision problem. We have proposed one methodology, the AHP, that may help integrating all environmental, economic and social criteria in the decision-making process. The AHP is a simple and powerful tool that helps decision-makers structure and evaluate different alternatives. Incorporating environmental considerations, constraints stated by legislation and the voice of community in the decision-making process along with the economic judgements alters the decision for end-of-life of products. The main advantage of the AHP from the decision-maker point of view is that he/she is directly involved in the process. The decision-maker evaluates each pair of items he/she assesses. The result of the assessment is based only on the judgement of the decision-maker.

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