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# Decision-based Methods for Early Phase Sustainable Product Design*

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*This paper presents a new method for evaluating product designs at their early stage of development according to different criteria and a case-study-based project. The goal is to select among imprecisely defined design alternatives in a multicriteria context, as is required for taking into account sustainability considerations. Imprecision—the most dominant type of uncertainty during the early stages of design—is defined as designer's preferences for a range of values in the design variables; it can be modelled by fuzzy numbers. The project involves the analysis of three design concepts of a vacuum cleaner (paper bag, plastic bin with filters and plastic bin with cyclone). Using the proposed multicriteria decision method different End-of-Life (EOL) strategies for the three concepts are investigated from the viewpoint of four criteria (one economic and three environmental). Sensitivity analyses are performed to identify the parameters influencing the robustness of the decisions. The case study will show that the 'right' decision (i.e. the selection of the best design alternative) depends on the trade-off between criteria performances.*

**Keywords:** life cycle design; strategic design; engineering design

## INTRODUCTION

*Environmental concerns in early stages of design*

METHODS FOR EVALUATING product designs from the point of view of sustainability should be, more than ever, an integrated part of engineering education. Sustainability considerations may be defined along three dimensions: environmental, economical and social. Improving product environmental impact at all life cycles is an important topic for the manufacturers of electrical and electronic equipment. EOL is one stage of the product life cycle having gained the attention of the market. Companies must understand how to improve their products so that the environmental impact will be lower at the EOL, while still being economically feasible. Knowledge of EOL treatment strategies early in product design is necessary to develop new products with the highest possible eco-efficiency [1].

The European Commission, [2] established general principles for waste policy. The available options are given by the following hierarchy:

- product remanufacturing;
- parts/components reclamation;
- material recycling;
- incineration with energy recovery;
- incineration without energy recovery;
- disposal to landfill.

Many approaches for the products' EOL stage consider either only the economical implications of the problem (minimize cost, maximize profit, etc) or are based on a predefined hierarchy of the possible EOL treatments, hierarchy that considers mainly impact on the environment. Are these the right approaches? The notion of rightness is very subjective in this case as the EOL issue can be addressed from various points of view. A company specialized on EOL treatment prioritizes the economic consideration without neglecting environmental aspects, while a local authority would probably be more interested in environmental considerations, depending on the policy adopted at that specific region. It is impossible to judge which approach is better. It is possible to justify a certain hierarchy, as can be found in [3] from a unique point of view (called criterion in this paper), but it becomes much more difficult when more than one criterion is considered.

A more general approach is necessary to help the decision-makers (designers, EOL treatment companies, local authorities, etc.) customize their priorities and model the decision process such that the results are in accordance with their particular vision of the problem. The multicriteria decision aid framework can offer an alternative to existing approaches. The importance of teaching decision-making methods in engineering was also emphasized in [4].

It has been argued that the EOL options hierarchy does not, in fact, provide a guide to the least environmentally detrimental option for EOL treatment [5]. If the aim of the hierarchy is to recommend the most favourable EOL treatment option from an environmental perspective, in many situations, it does not. The problem is that the hierarchy

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Fig. 1. AEOLOS methodology.

of favoured options may, in general terms, represent the favoured approaches. Which are the environmentally favourable criteria at the basis of this hierarchy:

- in terms of waste reduction?
- in terms of sustainment of resources already utilized?
- in terms of conservation of natural resources?
- in terms of EOL processing that is least energy consuming?
- in terms of least environmental impact?

A recent approach for dealing with the *end-of-life* of Waste of Electrical and Electronic Equipment (WEEE) was proposed in the framework of the *AEOLOS* project [6]. The objective of this project is to provide the end-users involved in the treatment of EOL products with an integrated methodology and tool set that supports them in defining relevant EOL scenarios and compares them based on their performances with respect to selected environmental, social and economic indicators. Even if the methodology and tool set were intended to be used for waste from electrical and electronic equipment, the AEOLOS methodology and tool set were developed in such a way to deal with any type of EOL products. The stepwise structure of the AEOLOS methodology and tool set allows end-users to progress easily in their decision-making process concerning the choice of the most appropriate EOL scenario.

The AEOLOS methodology was structured in such a way to prepare all necessary data about alternatives, criteria and performances before the multicriteria decision aid (MCDA) method is applied in step 3 (EOL scenario analysis).

The methodology was developed, as already mentioned, to work with the existing WEEE, so the decision process takes place far away from the design stage. The idea of using a similar methodology during the design process ( above), somewhere towards the end of conceptual design—beginning of detailed design, is appealing. This is the moment when feasible design concepts or alternatives are generated and a certain assembly structure is associated to these concepts. Some decision tools presented below will enable future designers, working in an engineering team, to evaluate their products during the design phase from the EOL as well as other points of view. For each EOL option, two dimensions are considered: economical and ecological.

The economic dimension includes the costs of one of the EOL options and the revenues resulting from the processing of the element (product/ subassembly/ component). The criterion that measures performance with respect to this dimension, called *profit,* is the difference between the revenues obtained when applying one of the EOL options and the costs incurred to perform it. Of course, this value is described by a real number, meaning that negative values are possible for nodes in the disassembly tree, but restrictions can be made on the whole scenario values.

The ecological dimension is characterized by

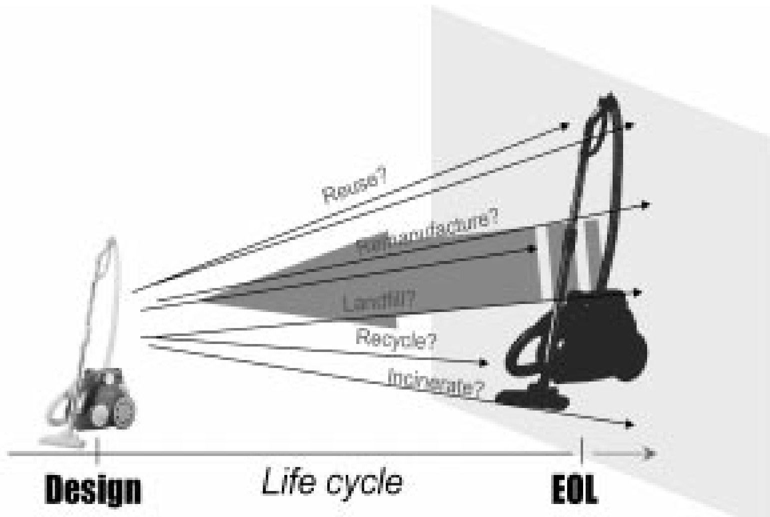



Fig. 2. The idea of the proposed approach to EOL evaluation.

three criteria, which are obtained from the endpoints of the LCA method used in Eco-indicator 99 [7]. These endpoints correspond to three impact categories:

1. Human health (HH);
2. Ecosystem quality (EQ);
3. Resources (RD).

These values are calculated starting from the Life Cycle Inventory (LCI) results and they are computed without involving any weighting process. The values used for the environmental criteria can be obtained using any of the software that includes the Eco-indicator 99 methodology. The numerical values that will be used are those obtained after the damage assessment step. The weighting will be performed later, during the evaluation processes.

One thing that should be underlined again is the fact that we are at the design phase and we want to include EOL considerations during the design evaluation process. The EOL happens after a period of time that can vary from months to years, depending on a series of factors like the type of product, the working conditions, the development level of the community where the product is used (in a less developed country products tend to have a longer life, driven by their utility, than in a better developed country where other factors like fashion influence their life time), etc.

Modelling costs and revenues for EOL at the design phase are a complex problem due to the different kind of uncertainties that are involved. Future uncertainties can be modelled by probability theory [8], while subjective uncertainty (more related to designer's preferences, called 'imprecision') can be modelled using fuzzy set theory introduced by Zadeh [9]. When there are no statistical data, presumptions about future costs and revenues should be done, using approximate values.

*Imprecision in design*

At the design stage, and especially at the beginning of design, a sine qua non condition is the modelling of uncertainty. Fuzzy sets could play an important role for modelling the different facets of uncertainty (e.g. imprecision [10, 11]), and fuzzy numbers constitute an appropriate tool for the representation of design parameters and performances.

Uncertainty due to vagueness, called imprecision by Wood [11], is the most dominant during the conceptual design phase. This is why it drew the attention of many researchers in the field of design and decision-making. Designers may have preferences over a range of values a variable can take, either based on their experience or on specific reasoning that makes them establish a hierarchy of preferences. For example, the size of the dustbin of a vacuum cleaner might be approximately based on the volume of dust to be stored, based on the designer's past experiences. It can be expressed as approximately 100 units $\times$ approximately 150 $\times$ approximately 100. These are representations that can be handled by fuzzy set theory.

Fuzzy set theory is a generalization of the classical set theory. In classical set theory, a subset $A$ is defined by its characteristic function which takes values in the $\{0, 1\}$ subset. So, an object is either a member of a subset $A$ or not a member of the subset. There are only two states. This is referred to as a crisp set. Zadeh [12] extended for the first time, in his article Fuzzy Sets, the domain of the characteristic function to the closed interval [0, 1]. Thus, it is possible to represent an object that has a degree of membership in a set, and whose value is taken in the interval [0, 1]. This forms the basis of fuzzy sets theory. Therefore, we are able to directly represent ambiguity or imprecision. Zimmerman notes that 'imprecision' as used in fuzzy sets theory is meant as a sense of vagueness rather than lack of knowledge about the value of a parameter [13].

Fuzzy numbers model imprecise quantities and they are mappings from the real line $\Re$ to the unit interval that satisfies a series of properties such as normality, piecewise continuity and convexity, properties that can be relaxed if necessary.

*Definition 1: normalized fuzzy number*

A normalized fuzzy number is a convex fuzzy subset $\boldsymbol{A}$ characterized by its membership function $\mu_{\boldsymbol{A}}: U \rightarrow [0, 1]$, such that:

- $\boldsymbol{A} = \{(x, \mu_{\boldsymbol{A}}(x)) | x \in U\}$
- $\inf_{x \in A}\{\mu_1 A(x)\} = 0$
- $\sup_{x \in A}\{\mu_1 A(x)\} = 1$

$\forall x_1, x_2 \in U, \forall x_3 \in [x_1, x_2] \cap U, \mu_{\boldsymbol{A}}(x_3) \geq \min\{\mu_{\boldsymbol{A}}(x_1), \mu_{\boldsymbol{A}}(x_2)\}$ (convexity), where $U$ is the universal set, $\boldsymbol{A}$ being a fuzzy subset of $U$.

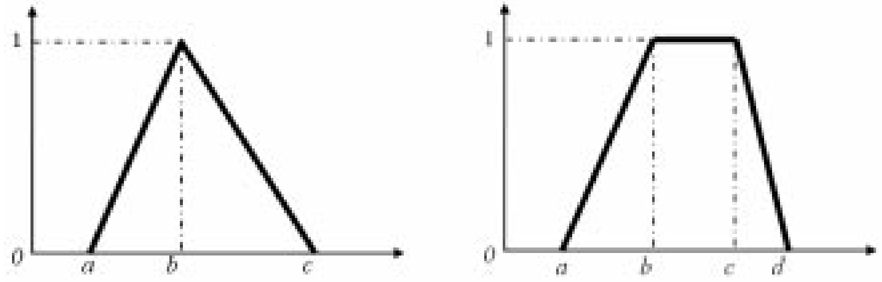



Fig. 3. Triangular and trapezoidal fuzzy numbers

In practice, two particular cases of fuzzy numbers have been used: the triangular and the trapezoidal fuzzy numbers (Fig. 3). Their particularity consists in the fact that the membership function is composed of a left and a right function, which are linear. This makes possible to represent them using only three $\langle a, b, c\rangle$, respectively four values $\langle a, b, c, d\rangle$. Triangular fuzzy numbers are special cases of the trapezoidal numbers, obtained by making $b = c$.

## MULTICRITERIA DECISION AID FOR CONCEPTUAL DESIGN

The scope of MCDA methods is to give to the decision-maker tools to advance through solving a decision problem, where several points of view, most often contradictory, have to be taken into account. A main observation, when addressing such problems, is that usually there is no decision (or alternative, or judgement) which is simultaneously best from all points of view, so the term optimization has no meaning here.

Fuzzy outranking methods is a special class of fuzzy MCDA methods that can successfully model the decision problem, helping the decision-maker (DM) in taking the right decision, according to his/her reference criteria. They consist of three main steps:

- building a fuzzy outranking relation for each criterion;
- aggregating the monocriterion fuzzy outranking relations to obtain the global fuzzy outranking relation;
- exploiting the global fuzzy outranking relation.

*Building the monocriterion fuzzy outranking relation*

In the case of a crisp fuzzy outranking relation $S$, the statement '$\boldsymbol{A}$ outranks $\boldsymbol{B}$ ' means that the DM has enough reasons to admit that alternative $\boldsymbol{A}$ is at least as good as alternative $\boldsymbol{B}$. A fuzzy outranking relation indicates for each pair of alternatives $(\boldsymbol{A},\boldsymbol{B})$ the degree of outranking of $\boldsymbol{A}$ over $\boldsymbol{B}$, denoted by $S(\boldsymbol{A},\boldsymbol{B})$, where $S(\boldsymbol{A},\boldsymbol{B}) \in [0,1]$. Fuzzy outranking relations must satisfy a number of properties, as described in [14].

In [14] the following outranking relation was developed, starting from $\alpha$ -cuts (Fig. 4), the interval values $a^{\alpha_i}$ an $b^{\alpha_i}$ corresponding to a preference ($\geq \alpha_i$), which overcomes the disadvantages of linearly approximating nonlinear membership functions and using as input intervals ($\alpha$-cuts), whose arithmetic is simple and accurate:

$$S(\boldsymbol{A},\boldsymbol{B}) = \sum_{i=1}^{N} \left(\beta \cdot \left(i - \frac{N+1}{2}\right) + \frac{1}{N}\right) \cdot [(1-\kappa)\cdot s_l^{\alpha_i}(a^{\alpha_i}, b^{\alpha_i}) + \kappa \cdot s_{ra}^{\alpha_i}(a^{\alpha_i}, b^{\alpha_i})] \tag{1}$$

$N$ is the number of $\alpha$-cuts, $j$ denotes the $j^{\text{th}}$ criterion, while $\kappa$ and $\beta$ are the degree of **optimism** (which side of the fuzzy number is more important, right or left) and **aggressiveness** (which $\alpha$-cuts are more important, upper or lower ones) of the DM, and whose detailed description can be found in [14]. Equation 2 gives the *left $\alpha_i$-cut index* (a *right $\alpha_i$-cut index* is defined in similar way) which represents the relative intersection of the considered intervals:

$$s_{l_j}^{\alpha_i}(a^{\alpha_i}, b^{\alpha_i}) = \begin{cases} 0, & a_2^{\alpha_i} < b_1^{\alpha_i} \\ \dfrac{a_2^{\alpha_i} - b_1^{\alpha_i}}{a_2^{\alpha_i} - a_1^{\alpha_i}}, & a_1^{\alpha_i} < b_1^{\alpha_i} \leq a_2^{\alpha_i} \\ 1, & a_1^{\alpha_i} \geq b_1^{\alpha_i} \end{cases} \tag{2}$$

Introducing $\kappa$ and $\beta$ offers a flexible solution to the fuzzy numbers comparison problem, giving the DM the choice of defining his/her point of view.

*Aggregation*

We look for a suitable aggregation operator, which is used to aggregate, for each pair of alternatives, the monocriterion fuzzy outranking relations $S_j$ to determine the global fuzzy outranking

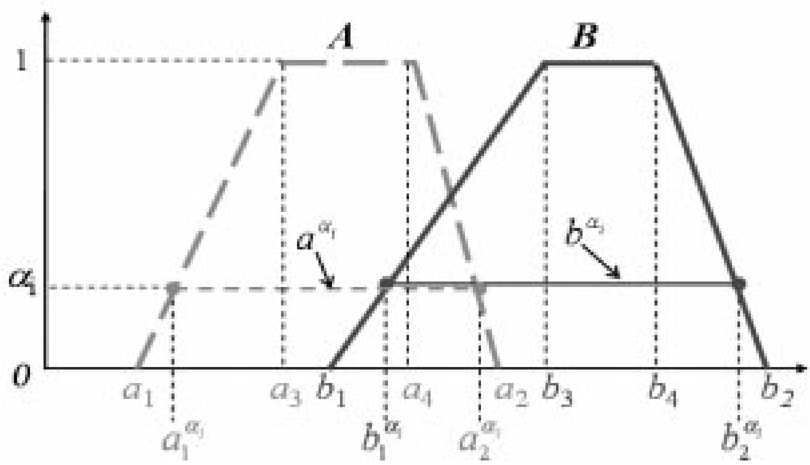



Fig. 4. Fuzzy numbers and $\alpha$-cuts representation.

relation $S$, based on which the final result is prescribed. Weighting coefficients are taken into account to enable modulation of the relative impacts of criteria in the calculation of the overall $S$:

$$S(A,B) = \sum_{j=1}^{n} S_{(j)}(A,B)[\mu_{\{(j),\ldots,(n)\}} - \mu_{\{(j+1),\ldots,(n)\}}] \quad (3)$$

where $n$ is the number of criteria considered in the decision problem.

In equation (3), the Choquet integral [15] is used for aggregation. This aggregator has the power of considering interaction (synergies or overlapping) between criteria. For any subset of criteria $L$, $\mu_L$ can be viewed as the weight of importance or strength of the combination $L$ for a particular decision problem under consideration. Thus, in addition to the usual weights of criteria taken individually, weights on any combination of criteria are also defined. In [16] it was proved that the resulted global fuzzy relation $S$ is an outranking relation. For our case study, only individual weights of importance $\omega_j$, are considered and relation (3) becomes:

$$S(A,B) = \sum_{j=1}^{n} S_j(A,B) \cdot \omega_j, \text{where} \sum_{j=1}^{n} \omega_j = 1 \quad (4)$$

*Exploitation*

In this stage of the MCDA problem, the global relations $S$ are used for: **choosing** the best alternative, **ranking** or **sorting** the set of alternatives. Choice functions are defined and used for choosing the best alternative(s). Rankings are also obtained using an algorithm that iteratively removes the chosen alternatives, until the set of alternatives $X$ becomes empty.

We use here the choice function $C_1$ introduced by Roubens [17], which can be interpreted as a degree of **weak domination** of alternative $x$ over all other alternatives $y$ in $X$. The chosen set of alternatives is given by equation (5).

$$C_1(X,S) = \left\{ x \in X | C_1(x) = \max_{x \in X} \min_{y \in X \setminus \{x\}} S(x,y) \right\} \quad (5)$$

Opposite to the idea of measuring the strength of the alternatives, 'complementary' functions, measuring the weakness of the alternatives can be used. In other words, choice functions, which select the less good alternative(s) in a given set can be used in order to obtain a ranking from the worst to the best.

## EOL DECISION MODEL

Previous research has been done mostly by considering a single criterion (economic or environmental). Optimization techniques were used in order to find the best EOL option for an element. From the point of view of the present approach, they are not applicable, being limited to single criterion approaches. As discussed earlier, decisions to assign a specific EOL option should not be taken only considering costs and revenues. There are other criteria. The four proposed—profit, human health, ecosystem quality and resources—have all different measuring units, making impossible the combination of their values. For this reason, optimization techniques are not suitable, unless the absolute values for each criterion are somehow transformed in relative values, based on a common scale, as, for example, building utility functions on a scale from 0 to 1. Fuzzy outranking methods do not need such transformations, making possible the use of performance values as they are, without losing their original meaning and avoiding the 'mixing of apples with oranges'.

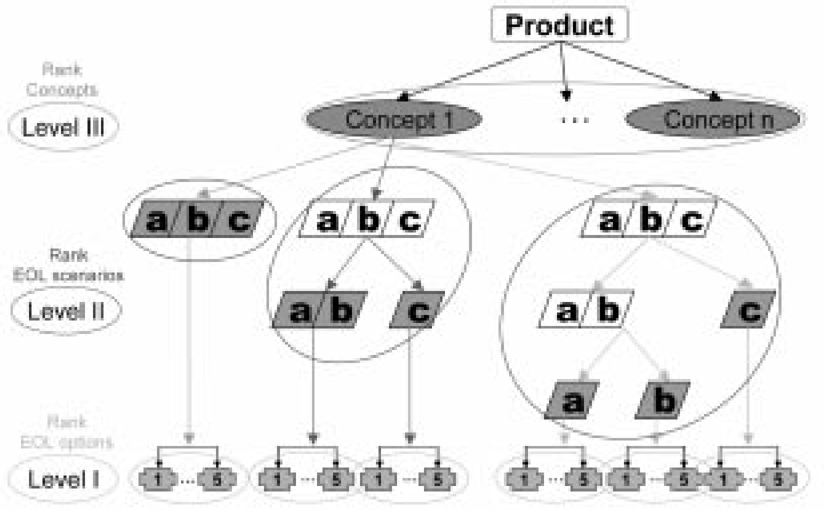



Fig. 5. The triad decision model.

The proposed model consists of a three-level evaluation: component (subassembly) level—where EOL options are compared; concept level—where EOL scenarios are compared and product level—where different concepts for the same product are compared (Fig. 5). The decision process takes place in three steps, starting from the bottom of the pyramid and ending at the top level, denoted by the product. Each step is based on the results of the previous one and therefore, it is conditioned by fulfilment of the inferior level.

We call EOL scenario a disassembly path from the disassembly tree, whose leaves have associated an EOL option (feasible options are chosen for each element from the proposed list).

*Level I*

This is the first step of the decision model, its results being used as input to the next level. The leaves of each EOL scenario (considered as given) of each concept are considered here. From the list of EOL options that may be available, only the feasible ones are considered, according to the material composition of the leaf. Not all the leaves have all the EOL options available and their number may vary from one leaf to another. For example, a part made of steel will not be incinerated, but it can be recycled or landfilled; an element made of steel and plastic cannot be recycled directly, and separation techniques must be used first, etc.

The feasible EOL options of a leaf are the alternatives, which have to be compared against the four criteria. Using the fuzzy outranking method described above, the EOL options are ranked. The first ranked EOL option denotes how the respective leaf will be treated at its EOL. Each leaf *i* of an EOL scenario *j* of concept *k* will be characterized by the four values: $P_{ijk}$, $HH_{ijk}$, $EQ_{ijk}$ and $RD_{ijk}$.

*Level II*

In the second level, the EOL scenarios are considered as given (some rules will be given below). For an EOL scenario, the values obtained for all the leaves are summed, and this is done individually for each criterion. For example, if we consider the profit and the three environmental criteria: impact on human health, ecosystem quality and resources, the EOL profile of concept k will look as in Fig. 6; it is defined by the four values (precise or imprecise) $P_{ijk}$, $HH_{ijk}$, $EQ_{ijk}$ and $RD_{ijk}$. These values represent the EOL profile of the corresponding concept. In this level, the EOL scenarios of concept *k* represent the alternatives to be compared against the four criteria. They are ranked using the fuzzy outranking method; the first ranked EOL scenario is used as input to the next level.

*Level III*

An EOL scenario contains quantitative information related to the economic and environmental

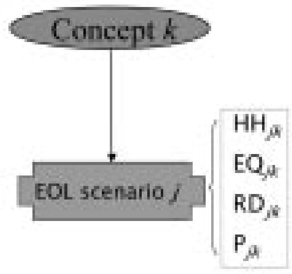



Fig. 6. EOL scenario profile

aspects considered during the first two levels of the decision pyramid. In other words, if the product would be treated according to that specific EOL scenario, the profit from implementing it and the environmental impact due to this way of treating it are known with some approximation. The level of precision of these values is given by the input values used when describing the product which is dependent on the design stage and available data.

The resulting EOL profile can be added to the values obtained from the other life cycle stages (material production, manufacturing, packaging, transportation, use, etc.); when a complete profile of the concept is obtained, the comparison of the given concepts is recommended to be done.

The alternatives in this level are the design concepts. They are ranked against the four criteria considered and the best concept(s) will be considered for further development. During this level, other criteria may be added too.

## A CASE STUDY BASE PROJECT

*Description of the case study*

This case study uses three vacuum cleaners that have been sold during the same period of time. They have about the same suction power, so basically they satisfy the same functional need. Their power is 1600W, and we consider an average vacuum cleaning time of 40min, twice per month. They have an eight-years lifetime. Also, we assume the use of two paper bags/year, 2l of water/use for cleaning the plastic bin of the second concept and 5l of water to clean the plastic bin and the sieves of the last concept. The main difference is given by the principle used to collect and store the dust:

- classical paper bag: the clean air flows into the machine and out through the pores of the bag (Fig. 7 left);
- plastic dust bin with filter: the clean air flows through the bin and out through the filters (Fig. 7 center);
- plastic bin with cyclone technology (no filter needed): Dirty air enters the outer cyclone, spins out the larger dust and dirt particles then the air passes to the inner cyclone to remove the smaller particles (Fig. 7 right).

The vacuum cleaners are household appliances

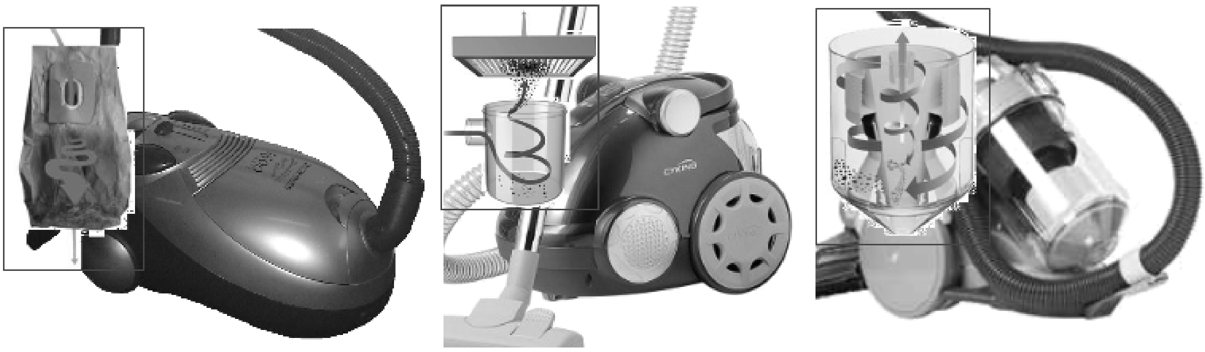


Fig. 7. Three vacuum cleaners concepts.

that usually are not remanufactured or sold on the second-hand market, thus the EOL options considered are:

1. recycling of pure or compatible fractions;
2. recycling with separation techniques;
3. incineration with energy recovery;
4. incineration without energy recovery;
5. landfill.

Let us consider the design phase of a vacuum cleaner. The concept's dimensions are defined with a certain degree of imprecision, so the volume can be computed under the form of an imprecise value. Materials are chosen and consequently their properties are known, making it possible to determine the weights of the material fractions. Furthermore, the assembly structure is known. Concretely, let's consider the three vacuum cleaners with their bill of materials. As we focus on decision-making methods to be used mainly at the end of the conceptual design stage, in this project we do not simulate the entire process of design concept development. We consider existing products, but the crisp weights of the material fractions were artificially transformed into imprecise values through a process that we call *fuzzification*. The fuzzification algorithm can be controlled by a parameter $s$ but it is not explained here. The following example illustrates such a transformation.

The dust bag sealing of the "paper bag" concept has a weight $w = 40$ g. The following *imprecise* values are obtained for different values of the *spread* parameter $s$:

$s = 0$ $\quad w_0 = (w, w, w, w) = (40, 40, 40, 40)$
$s = 50$ $\quad w_{50} = (0.75w, 0.9w, 1.1w, 1.25w) = (30, 36, 44, 50)$
$s = 100$ $\quad w_{100} = (0.5w, 0.8w, 1.2w, 1.5w) = (20, 32, 48, 60)$

For this case study, a number of approximately 25 disassembly paths have to be selected from the complete disassembly tree, e.g. according to the following reasoning:

- the full disassembly path and the one with no disassembly at all are considered, as extreme cases;
- leaves having relatively important quantities of materials, with possible environmental or/and economical gain, were identified in the disassembly tree; this disassembly operation is performed if when removing them, benefits can be expected, both economically and/or environmentally;
- starting from the top, we remove only the necessary elements, until the first leaf whose weight is

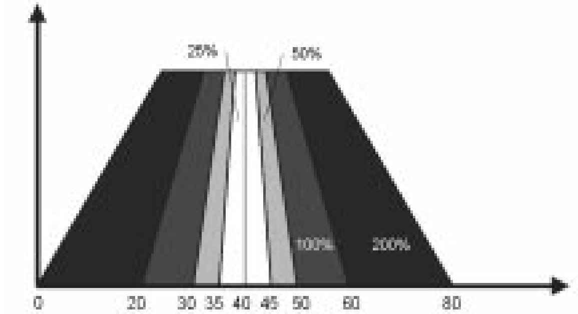



Fig. 8. Fuzzification of the 40g weight by 25%, 50%, 100% and 200%

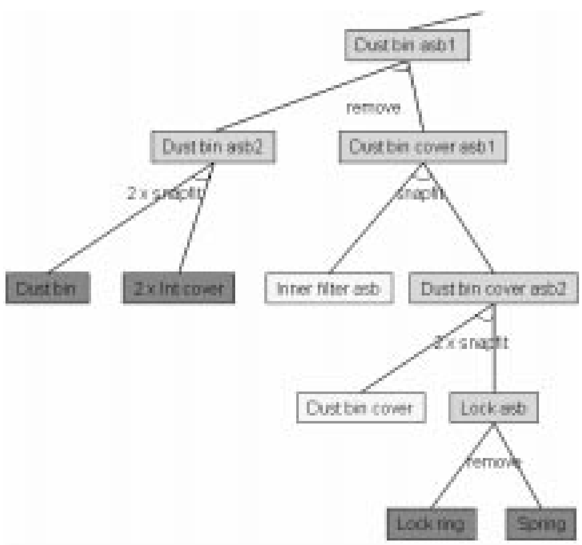



Fig. 9. Disassembly AND/OR tree of the plastic bin concept (partial view).

significant can be separated; this path is recorded;
- next path is recorded when the next leaf with a significant weight is reached;
- disassembly paths are recorded until the last element with significant weights is removed;
- other combinations of partial disassembly of subassemblies are considered, in order to better cover other disassembly possibilities, but avoiding an exhaustive generation of disassembly paths.

Before the decision process described above starts, all the parameters—decision attitude ($\kappa$ and $\beta$), Eco-indicator 99 attitude, choice function and criteria weights—must be decided. The fuzzification parameter is a special one, because it was artificially introduced and will not appear in real cases. A default set of parameters is decided as follows:

- *decision attitude:* moderate, where $\kappa = 0.5$ and $\beta = 0.5$; these values are recommended and they were explained previously;
- *Eco-indicator 99 attitude:* Hierarchist, which is the default version of the method;
- criteria *weights:* $\omega_{\mathrm{C}} = 0.4$, $\omega_{\mathrm{HH}} = 0.24$, $\omega_{\mathrm{EQ}} = 0.24$, $\omega_{\mathrm{RD}} = 0.12$; the unit was almost equally distributed between the economic and environmental criteria categories, with a slightly higher importance for the environmental category (a more environment oriented DM); the ratio between the weights of the three environmental criteria is maintained constant at 2:2:1; this is the ratio used for the default set of weights of importance for the three categories (HH, EQ, RD) during the aggregation step of the Eco-indicator 99 method;
- *choice function:* $C_1$ (weak domination of the considered alternative over the others) ; for a partial ranking based on the concepts of *strength* and *weakness*, the functions $C_1$ and $C_5$ (weak domination of the others over the considered alternative) respectively are used;
- *fuzzification:* $s = 50\%$, which gives a "decent" degree of imprecision.

This is the suggested configuration for a DM whose knowledge in the areas involved by these parameters would not allow a deeper understanding of their meaning. In this case-study-based project, this is the basic set, which is used as a starting point for the different sensitivity analyses that will be carried out. During the sensitivity analysis, we vary, one by one, the criteria weights and the other parameters enumerated above, while keeping the rest of them at their default values described above.

*Sensitivity analysis for the criteria's weights of importance*

The weights given to the criteria used for the EOL evaluation are the most sensitive variables influencing the final results. That is why strong variations are expected when their values vary from one extreme case to the other. Because criteria weights are normalized, it is not possible to vary one of them while keeping the others constant. Consequently, the profit criterion's weight was varied from 0 to 1, while the complement was distributed among the three environmental criteria, as described earlier.

As expected, the way criteria weights are chosen has a strong influence on the final ranking of the EOL scenarios. The chart in Fig. 10 below (paper bag concept) shows that one EOL scenario may change its place from the first ranked to the end of the ranking when profit's weight goes from 1 to 0 (EOL scenario no.1, which has no disassembly), and vice versa (EOL scenario 2, which has the

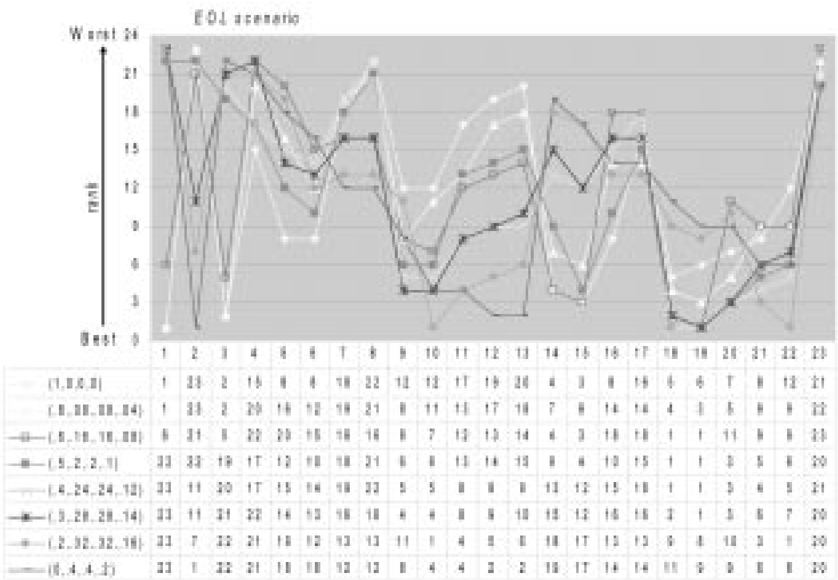



Fig. 10. Influence of the variation of criteria weights (P, EQ, HH, RD) on the ranking of EOL scenarios for the 'paper bag' concept.

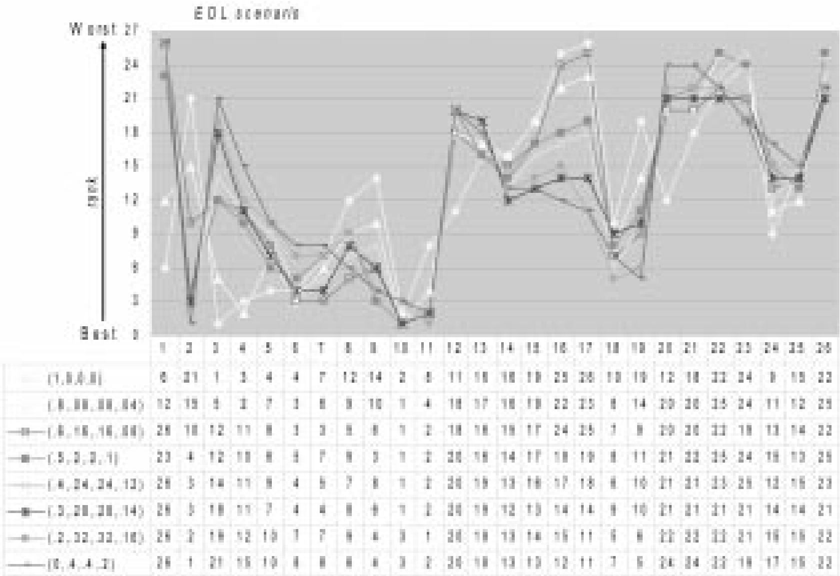



Fig. 11. Influence of the variation of criteria weights (P, EQ, HH, RD) on the ranking of EOL scenariosfor the 'plastic bin' concept.

maximum number of disassembly operations). When the importance of the two categories of criteria is more or less the same, other EOL scenarios are ranked first (EOL scenario 18 and 19). Similar comments can be done for the other two concepts.

Table 1 synthesizes the best-ranked EOL scenarios, for the three concepts. Three situations are considered: when profit criterion is very important (profit's weight close to 1), when the ecological dimension is the most important (profit's weight close to 0) and last, when varying profit's importance around the default value 0.4 (0.4 is the value that is used later for the design concept comparison). Thus, for the first concept, the EOL scenario no.19 is ranked first when the profit's weight varies in the interval [0.3, 0.6] and for the second concept, the EOL scenario no.10 is ranked first when profit's weight varies in [0.3, 0.8]. For the last concept, the weight's variation around the default values (0.4, 0.24, 0.24, 0.12) has a stronger influence on the final EOL scenario's ranking. The EOL scenario no.10, which is ranked first, moves to third and fourth position for the criteria weights combination (0.3, 0.28, 0.28, 0.14) and (0.5, 0.2, 0.2, 0.1) respectively. So, if for the first two concepts the DM could have given the criteria weights in the above-mentioned intervals without consequences on the first ranked EOL scenario, things are different for the last concept. An error of +/− 0.1 for the profit's weight would bring another EOL scenario into first place. If this situation is encountered, the DM should either be sure of his/her preferences for the criteria's weights before going further to the third level of the decision pyramid, or consider more than one EOL scenario alternative for the next level (e.g., EOL scenarios 2 and 19, which are ranked first for the set of weights (0.3, 0.28, 0.28, 0.14) and (0.5, 0.2, 0.2, 0.1) respectively).

An EOL scenario was defined as a disassembly path, having associated a number of nodes and leaves. The leaves of the same EOL scenario may have associated different EOL options for different parameters of the decision model, as a result of the ranking in the first level. When varying the different parameters of the decision model, the chosen EOL options for the EOL scenario may change, but these changes are not visible in the type of chart used for the sensitivity analysis. To see the effect of the changes in level I, we introduce another graphical representation, the mass distri-

Table 1. EOL scenarios ranked among the first when varying criteria's weights

| Profit's weight | Concept | Best choice EOL scenario(s) |
|---|---|---|
| Low importance | *Paper dust bag* | 2, 10 |
| | *Plastic dust bin* | 2, 11 |
| | *Cyclone* | 2 |
| High importance | *Paper dust bag* | 1, 3 |
| | *Plastic dust bin* | 3, 10 |
| | *Cyclone* | 3, 14 |
| ± 0.4 | *Paper dust bag* | 18, 19 |
| | *Plastic dust bin* | 10, (11) |
| | *Cyclone* | 10, (2, 19) |

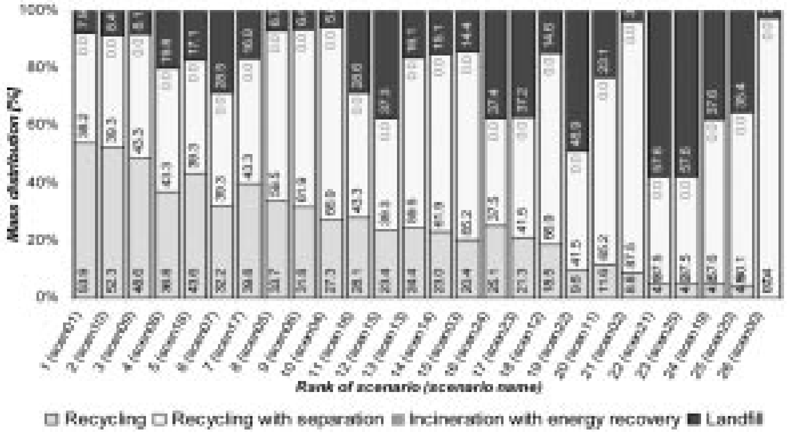



Fig. 12. The distribution of the material mass among the EOL destinations for the 'plastic bin' concept for the set of criteria weights (0, 0.4, 0.4, 0.2).

bution among the available EOL options. This is a bar chart that, for each EOL scenario, shows the percentage of the whole material mass that, according to the respective EOL scenario, goes to each of the available EOL destinations. A difficulty arises here due to the fuzzy nature of the values expressing the material masses, which introduces some complexities for the computation of the mass percentages (how to compute the percentage of fuzzy numbers with respect to another one). One possible solution to the problem is the use of defuzzification techniques of the fuzzy numbers. The crisp values obtained can be used to create the proposed charts. For this case study, in which the fuzzy weights were obtained with a fuzzification process, the original crisp values will be used. In a real problem, this is not possible, since there are no original crisp values, and the defuzzification techniques must be used.

Figures 12–14 plot the distribution of materials among the EOL options for each EOL scenario of the plastic bin concept, for three situations:

1. when only the ecological dimension is considered (criteria weights combination (0,0.4,0.4, 0.2));
2. when there is a trade-off between the two dimensions (criteria weights combination (0.4, 0.24, 0.24, 0.12));
3. when only the economic dimension is considered (criteria weights combination is (1,0,0,0)).

- A first and very important conclusion when looking at the three charts is that the EOL scenarios which are ranked among the first, no matter the criteria weights combination, would send the three concepts to recycling (pure fraction recycling (bottom area of the bars) and recycling after shredding and separation (middle area of the bars)) to a very large extent. In other words, for these three examples, recycling was largely preferred to incineration and landfill;
- When only environmental criteria are considered, for the EOL scenarios ranked first, the quantity of materials, which goes to recycling of pure or compatible fractions (bottom area of the bars), is more important than those going to recycling with shredding and separation, incineration or landfill. This quantity might have been more important, but in our analysis only

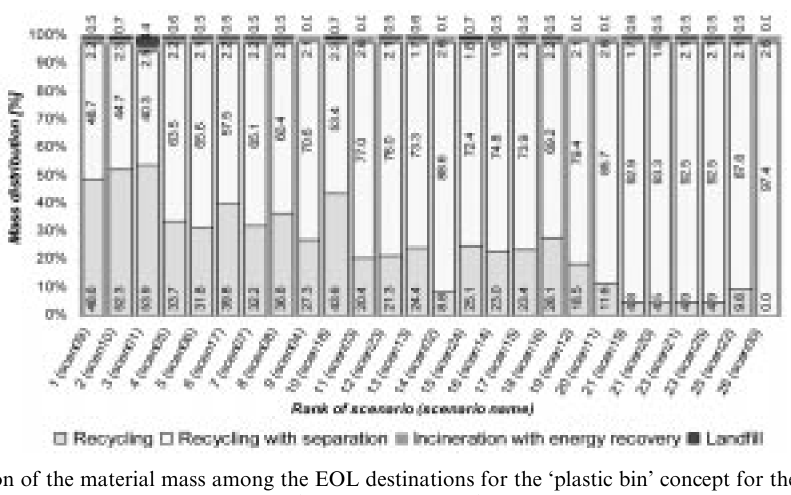



Fig. 13. The distribution of the material mass among the EOL destinations for the 'plastic bin' concept for the set of criteria weights (0.4, 0.24, 0.24, 0.12).

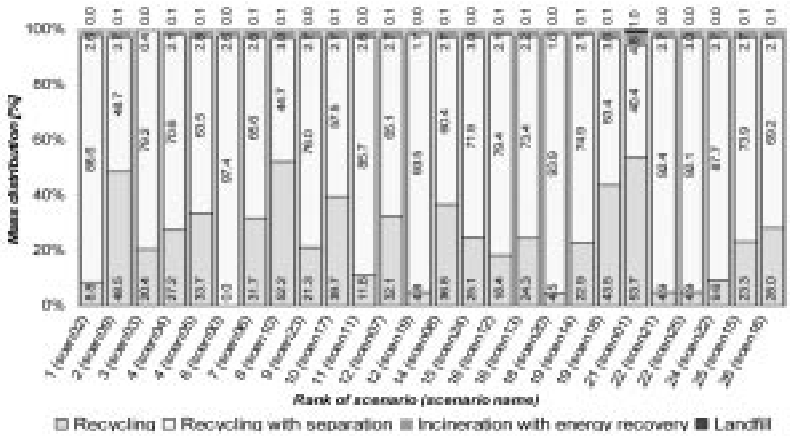



Fig. 14. The distribution of the material mass among the EOL destinations for the 'plastic bin' concept for the set of criteria weights (1, 0, 0, 0).

non-destructive disassembly operations were considered, for which standard disassembly times are available (e.g. the motor has to go to the shredder because it cannot be disassembled without breaking it). The tendency is that the lower the rank of the EOL scenario, the less recycling of pure material we have (the last place is taken by the EOL scenario no.0, which has no disassembly operations, while in first place we find the EOL scenario no.1 with a maximum of disassembly).

- When only the economic criterion is considered, the EOL scenarios with less disassembly are ranked first, but this is not a general rule (for the 'plastic bin' concept, the EOL scenario no.9 is ranked second, but it contains quite a lot of disassembly).
- When there is a trade-off between the two dimensions, the EOL scenarios ranked first would send to recycling of pure or compatible fractions an important quantity of material, but not the maximum possible. The EOL scenarios with no disassembly at all are ranked among the last.
- Very interesting remarks refer to the situation where only the environmental dimension is considered. For all three concepts and for many EOL scenarios we can see that there is a considerable quantity of material that would be landfilled (Fig. 12, top area of the bars). Moreover, landfill is preferred to incineration with energy recovery (there is almost no incineration among the EOL treatments chosen). Also, there are situations in which EOL scenarios whose quantity of material sent to landfill is much higher than others, but which are ranked better than those with less material landfilled (in Fig. 12, EOL scenario no.8 with 19.8% landfill is ranked fourth,while EOL scenario no.5 with 6.7% landfill is ranked eighth).
- For these three examples, when the economic dimension is considered only (criterion *P*), landfill does not take place; instead a small part of the materials goes to incineration.

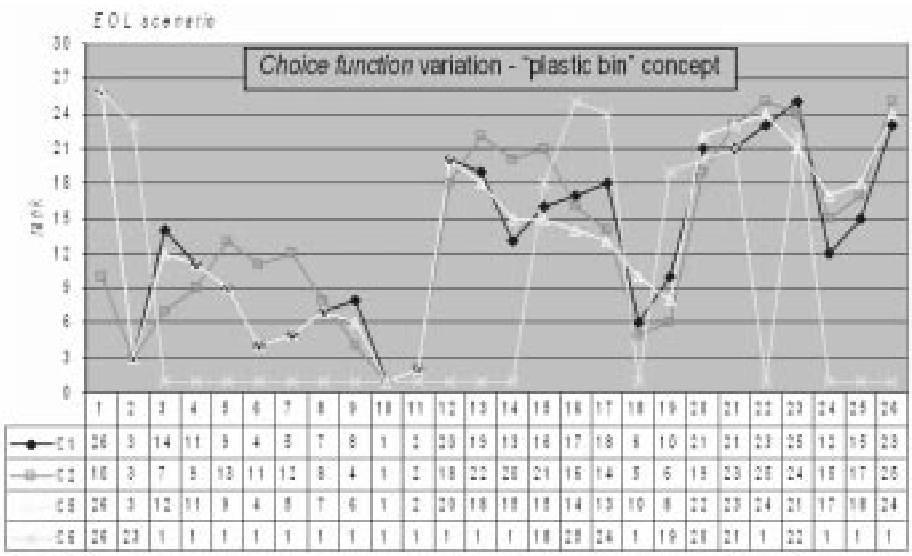



Fig. 15. Influence of the variation of the choice function for the ranking of EOL scenarios for the 'plastic bin' concept.

Some of the results, especially those given in Fig. 12 above, may be seem questionable at first glance. Is landfill sometimes better than recycling or incineration with energy recovery? And if yes, when can this happen? Going deeper into our analysis of EOL scenarios, one main factor that could lead to these results refers to how the importance given to the environmental dimension is distributed among the three criteria (HH, EQ and RD). As mentioned earlier, the values used for the performances with respect to these criteria are those obtained after the damage assessment step, which are absolute values, and any relative comparison between them is meaningless. The benefits of the recycling and incineration with energy recovery are mostly (not always) related to the damage category 'Resources', so implicitly to the performance with respect to the criterion RD. Since we wanted to keep the ratio between the environmental criteria as recommended in the default version of the Eco-indicator 99 method, criterion RD receives a fifth part of the total weight allocated to the environmental dimension, while the other two criteria, HH and EQ receive two-fifths each. At the same time, the data used for the landfill concern the Swiss situation and technology, which is somehow a favourable situation. A simple test, consisting in giving the weight of 1 to the criterion RD would reduce the amount of material sent to landfill, while giving the same value for any of the other two criteria would not change a lot the situation in those figures.

*Sensitivity analysis for chosen functions*

The selection of appropriate choice functions is a difficult task, since their development is beyond engineering expertise and their meaning may seem rather abstract. The concepts they are built on were introduced earlier (for more details and a full example see [18]). As can be seen from Fig. 15 above, strong variations in rankings are observed. Finding an EOL scenario that is ranked first by all four choice functions is almost impossible, but this is beyond our scope. There are two alternatives: either construct a complete preorder using one of the choice functions, or, based on two complete preorders, construct a partial ranking, in which incomparabilities may appear. Sometimes, a choice function may not be discriminatory enough (too many alternatives having the same rank, called indifferent, see Fig. 15, the choice function $C_6$) and the use of a second one may be necessary for the refinement of the ranking. In this example, the complete preorders given by the choice functions $C_1$ and $C_5$ are shown, together with a partial ranking resulting from their intersection (Table 2).

*Synthesis*

Table 3 synthesizes the EOL scenarios that are the most stable with respect to each variation.

Global selected EOL scenarios are those used as input for the next application; they are considered the best and most stable choices. EOL scenarios

Table 2. Complete preorders given by $C_1$ and $C_5$ and the partial preorders resulted from their intersection.

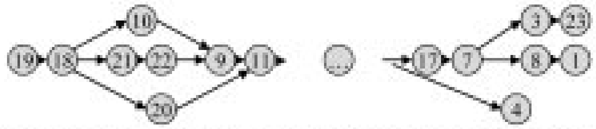
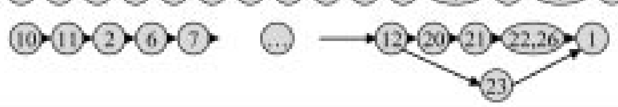
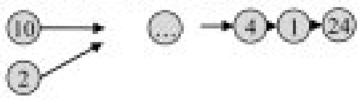
| Concept | Choice function | Ranking |
|---|---|---|
| *Paper dust bin* | $C_1$ | (18,19) → 20 → 21 → (9,10,22) → 11 → (12,13) → 2 → 15 → 14 → 6 → (5,16) → 4 → 17 → 7 → 3 → 23 → 8 → 1 |
| | $C_5$ | 19 → 18 → 10 → (21,22) → 9 → 20 → 2 → 11 → 12 → 13 → (14,15) → 16 → (5,6) → 17 → (7,8) → 1 → 3 → 23 → 4 |
| | $C_1$- $C_5$ |  |
| *Plastic dust bin* | $C_1$ | 10 → 11 → 2 → 6 → 7 → 18 → 8 → 9 → 5 → 19 → 4 → 24 → 14 → 3 → 25 → 15 → 16 → 17 → 13 → 12 → (20,21) → (22,26) → 23 → 1 |
| | $C_5$ | 10 → 11 → 2 → 6 → 7 → 9 → 8 → 19 → 5 → 18 → 4 → 3 → 17 → 16 → (14,15) → 24 → (13,25) → 12 → 23 → 20 → 21 → (22,26) → 1 |
| | $C_1$- $C_5$ |  |
| *Cyclone* | $C_1$ | 10 → 9 → 19 → 12 → 11 → (17,8) → 16 → 2 → 15 → 23 → 8 → (7,20) → 21 → 6 → 22 → 14 → 13 → 5 → 3 → 4 → 1 → 24 |
| | $C_5$ | 2 → 12 → 16 → 17 → (10,11) → 19 → 9 → 18 → 8 → 20 → 15 → 21 → 23 → 22 → 14 → 7 → 13 → 6 → 3 → 5 → 4 → 1 → 24 |
| | $C_1$- $C_5$ |  |

Table 3. Synthesis of the best and most stable EOL scenarios and the final selection.

| Concept | Parameter | Selected EOL scenario |
|---|---|---|
| *Paper dust bag* | $\kappa$ | 19, (18) |
| | $\beta$ | 19, (18) |
| | Choice function | 19, (18) |
| | Eco-indicator 99 attitude | 18, 19 |
| | Criteria weights | 18, 19 |
| | **Global selection** | **19** |
| *Plastic dust bin* | $\kappa$ | 10, (11) |
| | $\beta$ | 10, (11) |
| | Choice function | 10, (11) |
| | Eco-indicator 99 attitude | 10, (11) |
| | Criteria weights | 10, (11) |
| | **Global selection** | **10** |
| *Cyclone* | $\kappa$ | 10, (12, 19) |
| | $\beta$ | 10, (12) |
| | Choice function | 10, 2 |
| | Eco-indicator 99 attitude | 9, 10, (19) |
| | Criteria weights | 10, (2, 19) |
| | **Global selection** | **10** |

Table 4. Example of decision model parameters used for concept selection.

| Parameter | Range of values | Default value |
|---|---|---|
| $\kappa$ | [0, 1] | 0.5 |
| $\beta$ | [0, 1] | 0.5 |
| *Choice function* | $C_1$, $C_2$, $C_5$,$C_6$ | $C_1$ |
| *Eco-indicator 99 attitude* | Hierarchist, Egalitarian, Individualist | Hierarchist |
| *Criteria weights* | [0, 1], $\Sigma\omega_k = 1$ | $\omega_{\mathrm{P}} = 0.4$ $\omega_{\mathrm{EQ}} = 0.24$ $\omega_{\mathrm{HH}} = 0.24$ $\omega_{\mathrm{RD}} = 0.12$ |

written between the brackets are the second choices (ranked second).

*Selecting the best vacuum cleaner concept from the viewpoint of the EOL friendliness*

The second application of decision aid methods consists in helping the design team in evaluating the three proposed concepts from the point of view of EOL friendliness. The default parameters of the decision model are considered here, according to Table 4.

It is impossible to consider only the EOL environmental impact for this comparison due to a paradox that may arise: if the material weight of a concept increases, supposing that it will all be recycled, then from an environmental point of view its performance would increase, since it will replace a bigger amount of new material. The conclusion is obviously wrong, and this is because producing the material has its own environmental impact, which also increases with the quantity of virgin material produced. The environmental impact generated by the material production stage must be added to the EOL impact in order to avoid this paradox.

A question mark still exists whether we are taking the right decisions or not by not including the other life cycle stages. In this case study, we decided to add also the environmental impact of the part production processes and use stage for the final comparison. We assumed similar transportation conditions for all three concepts during their life cycle. By iterating the choice function $C_1$ we obtain the final ranking.

The concept using the cyclone working principle for collecting the dust is selected for further development. In this example, only economic and environmental criteria were considered. Concept comparison can be extended to a larger number of criteria, and the method can be used without any limitation.

*Implementing the project within the Design for X course*

The first, theoretical, part of the module introduces the students to a fuzzy multicriteria decision aid method, developed at the Laboratory for Computer-Aided Design and Production (LICP). Design variables are modelled by fuzzy numbers that represent a designer's preferences over a range of values. Consequently the evaluation performances, which are functions of design variables, are imprecise. After becoming familiar with the modelling of imprecision during the design stage, students are taught for the first time how to use an MCDA method for taking good decisions in an environment dominated by uncertainty, according to their evaluation criteria. The evaluation model offers a structured approach to determining the best EOL strategy for the design concept being analysed as early as possible. This is a precious piece of information to be added to the performances of the other stages of the life cycle.

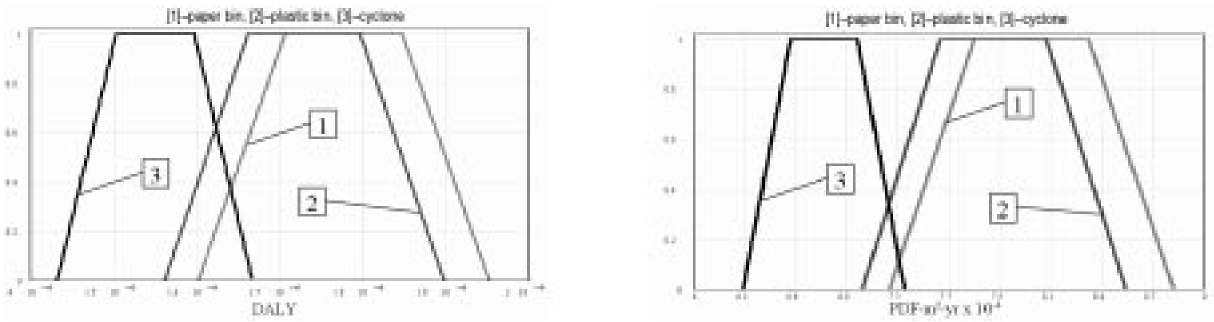



Fig. 16. The final performances for the three concepts with respect to the EQ and HH criteria.

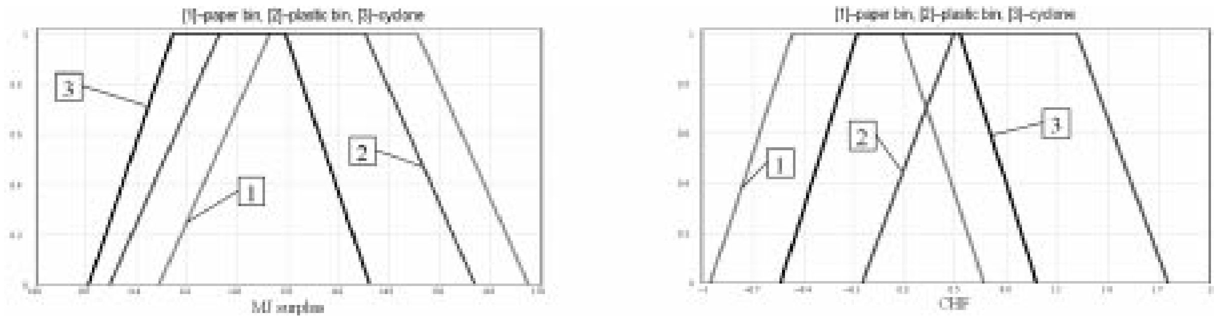



Fig. 17. The final performances for the three concepts with respect to the RD and P criteria.

The case-study-based project proposed in this module is structured as follows:

*Team working*

1. The class is divided in small teams of two or three students, depending on the number attending the course. Students from different departments (mechanical and materials mostly) make up the teams so that their complementary knowledge helps them to better understand and approach a project as it happens within a concurrent engineering team.

*Information at hand*

2. To each team one vacuum cleaner (playing the role of the design concept) is assigned. They have at their disposal the physical products and the necessary tools needed to disassemble them and study their functionalities, structure, materials, etc.
3. The bill of materials (BOM) is given for each of the three concepts, where the weights of the material fractions of the components are in the form of trapezoidal fuzzy numbers, obtained as described earlier.

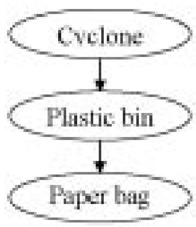



Fig. 18. The final ranking of the three design concepts.

4. Software developed at LICP (CoDEL) is available. It can handle the necessary computations with fuzzy numbers inside the disassembly trees. The database contains all the necessary data needed to determine the EOL process costs and revenues (including disassembly costs) and environmental impacts with respect to the three environmental criteria.

*Work done by the teams*

5. As a first step, the physical products will be analysed (disassembled), and the complete disassembly tree (AND/OR tree representation will be used) will be constructed.
6. Having done this, the students are advised to find ~25 disassembly scenarios, based on some empirical rules they have to think of (weight of components, revenues from materials, hazardous components, material clustering, etc.), such that a wide range of possibilities is covered (from no disassembly at all to full disassembly).
7. For the leaves of the disassembly scenarios, only the feasible EOL options have to be found and taken into consideration. At this point the decision process begins, with the following user interface.
8. After choosing the parameters shown in Table 4, the steps 1 to 3 in Fig. 19 above are processed in order to obtain a ranking of the EOL scenarios. Sensitivity analysis is performed by each group for the assigned vacuum cleaner by varying the values of the windows shown in Fig. 19. Some of the expected results were already discussed previously in this section.

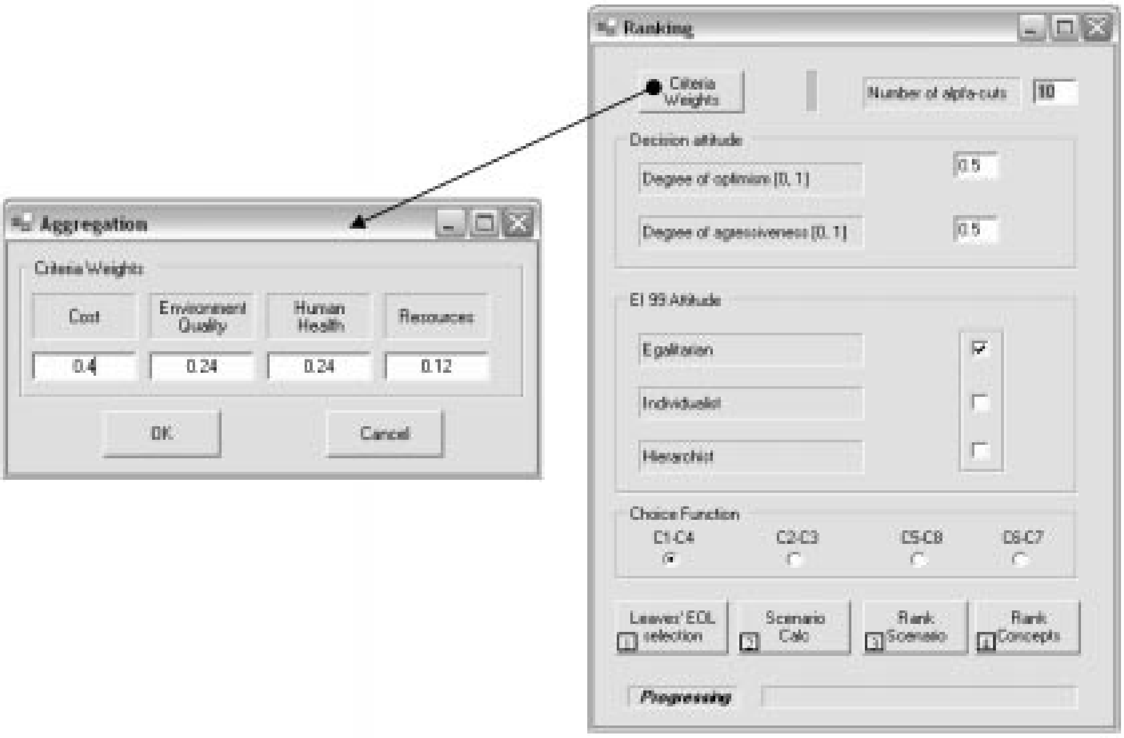



Fig. 19. User interface—the ranking window.

9. Based on the results of the sensitivity analysis, the teams will choose the EOL scenarios that are the most stable with respect to all parameters.
10. At this point, teams with different design concepts will exchange the results obtained individually, so that each of them will have access to the whole set of results of the three design concepts.
11. The three design concepts are compared and ranked during the last step. Students are asked to present the results in two different ways (see Fig. 20). On the left side of Fig. 20, the ranking of the concepts is done, from the best (top) to the worst (bottom). The other way to represent the results is shown on the right side of Fig. 20 below, where the defuzzification of the results shown in Fig. 16 above and Fig. 17 above was performed, followed by a transformation on a 0 to 1 scale.

## CONCLUSION

In order to take comprehensive decisions concerning the EOL of a product, the concurrent engineering team must be aware of the available EOL options and the future possible consequences of their decisions. Moreover, the present legislative context and competitive environment have stimulated, more than ever, research in the direction of improving the way producers design products with respect to their future EOL treatment. Each EOL scenario has its own consequences from an eco-

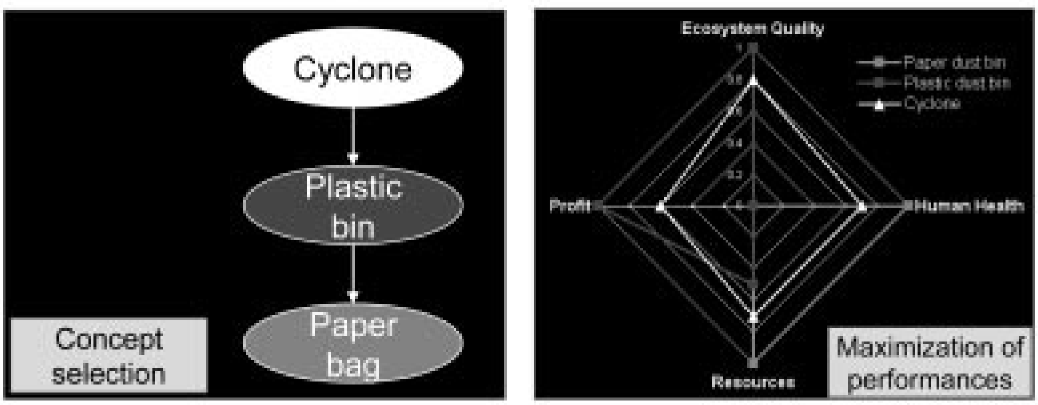



Fig. 20. Concepts comparison: ranking (left) and spider chart diagram (right).

nomical and environmental point of view. The criteria used to determine these consequences are often contradictory and not equally important. In the presence of multiple conflicting criteria, an optimal EOL scenario rarely exists. Hence, the decision-maker should seek the best compromise EOL scenario. We proposed a multicriteria decision aid method for the early stages of design (conceptual design) to be used for the exploration of various EOL scenarios and the choice of the best compromise one. The method is used then for the selection of the best compromise design alternative to be further developed. The method is employed during the concept evaluation and selection stage and can be integrated with classical design tools.

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