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## A new method for evaluating the best product end-of-life strategy during the early design phase

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The choice of an appropriate end-of-life (EOL) destination for discarded products is becoming an important issue for most manufactured products, given the current problems of environmental waste impact and landfill saturation. To address these issues, the design of a product must be optimised with a view to incorporating in that product an environmentally sustainable EOL scenario that respects economic and legislative constraints. The new EOL scenario evaluation method (ELSEM) that we propose in this paper takes these fundamental aspects into account, and provides a method for evaluating the various options for the EOL scenario of a product during early design phase. The ELSEM provides a simple and intuitive tool for designers to help them construct arguments for the EOL decision-making process. It is built using the fuzzy technique for order preference by similarity to ideal solution method, a multi-criteria decision process that is highly appropriate in the uncertain and subjective environment in which the designer works during the early stages of product development. Our method is illustrated with a case study involving a vehicle engine.

**Keywords:** design for environment; design for end-of-life; multi-criteria analysis; fuzzy sets; ecodesign

### 1. Introduction

The ability to produce environmentally friendly products is becoming a fundamental concern in our society. Demographic growth, combined with an increase in product demand, has led to serious pollution issues. In particular, an extremely large amount of retired products is generated each year and can no longer be controlled: landfills are now saturated, and many of them contain hazardous materials which may damage human health as well as the environment. In response to this concern, the EU has formulated new regulations based on the principle of extended producer responsibility (Walls 2006), which stipulates that the manufacturer is responsible for the various phases of the life cycle of their products, especially the end-of-life (EOL) phase. These regulations promote the reuse and recycling of waste of electronic and electric equipment and vehicles, prohibit the use of certain hazardous substances, and encourage designers to improve the design of their products with a view to resolving EOL recovery issues. This last objective has brought about the creation

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of new design methods called design for EOL (DfEOL), which facilitates the disassembly of products, indicates the kinds of materials and attachments that are appropriate, and specifies the best structures for product subassemblies as a function of their predicted EOL. The first step in this method is to predict the product's best EOL scenario, and this must be done before major design decisions are made which will be difficult to modify in advanced design stages (Spath *et al.* 1996).

Usually, companies fix their most suitable EOL strategy based on business directives and environmental targets (Brissaud and Zwolinski 2004, Choi *et al.* 2008). Once that decision is made, the designer must negotiate the performance and technical characteristics of the product with the rest of the design team. In order to do this, he first has to identify and evaluate the possible EOL scenarios for the product considered, that is to say, the appropriate EOL treatment for each of its elements. These scenarios generate different design situations and pose technical arguments for negotiating the detailed design stage specifications.

Unfortunately, designers usually do not have the skills required to evaluate these scenarios, as this is a task that demands advanced knowledge of the reverse supply chain and of EOL treatment. A number of methods have been developed to help the designers; however, many of them require precise and quantitative information which is not available during the product development phase, or is too complex and difficult to use without a considerable expenditure of time and money. The assessment of EOL scenarios should only be based on the small amount of information that is accessible in the early design phase.

The questions then become: which of the product's characteristics should we take into account, and how can we use them to easily and rapidly evaluate the various EOL scenarios of the product at the beginning of its development?

Our study uses a multi-criteria decision approach, which provides a systematic assessment of the alternatives based on a set of criteria (Sen and Yang 1995). This approach is highly appropriate for our case, since it allows us to consider both quantitative and qualitative assessments with a high level of flexibility (Powell 1996), and it has often been used to address environmental and waste management issues (Chan and Tong 2007, Vego *et al.* 2008). The fuzzy technique for order preference by similarity to ideal solution (TOPSIS) method has been chosen based on the literature review on multi-criteria decision methods.

We present our new EOL evaluation method in Sections 3 and 4, followed by an application of the method on various vehicle parts in Sections 5 and 6. But first, we describe existing methods in Section 2, and explain why they fail as efficient and easy-to-use tools for the designer.

## 2. Theoretical background

DfEOL is part of a new design approach called 'design for environment' (DfE). It endeavours to improve a company's global environmental performance by reducing the impact generated by each stage of the product life cycle, without compromising other important aspects, such as quality, functionality, and cost (Pigosso *et al.* 2010).

The DfE method developed by Lee *et al.* (2006), is an iterative method, where the first design is made respecting DfEOL general guidelines and taking into account the various regulations that may apply. The choice of the EOL scenario comes at the end of this process. If the choice respects the company's environmental objectives, the design is validated. Otherwise, a redesign must be considered. This approach facilitates EOL prediction, since the decision can be based on a concrete first design, but it may result in a considerable waste of time and energy.

Among the methods that require such detailed information, many are improvements in the design for disassembly, since they simply incorporate environmental constraints into the disassembly process: every disassembly operation leads to the removal of one component from

the product with a given EOL. Based on this principle, Lee *et al.* (2001) developed a method consisting of two steps: determination of the EOL of each of the components, considering the possible economic benefits of every EOL option and the generation of a disassembly sequence based on the multiple sequence alignment (MSA) algorithm. Hula *et al.* (2003) and Takeuchi and Saitou (2006) used genetic algorithms to identify an optimal disassembly sequence considering factors such as component characteristics, their links in the product, EOL regulations, market and infrastructure variables, costs, and environmental impacts. Takeuchi's methodology also gives an optimal product structure to maximise the recovery value. By taking into account many factors to determine product EOL, these methods give precise and relevant results, but they appear to be too time-consuming and require too much information to be used during the early design stage.

Other methods involve selecting a set of possible EOL scenarios and choosing the best ones, like the an EOL of product systems model, which uses a multi-criteria decision strategy (Kiritzis *et al.* 2003). Each scenario consists of a set of couples (product element, EOL of this element) ordered chronologically by disassembly operation order. The EOL option of each element, leading to the construction of an initial set of feasible scenarios are evaluated and chosen by the designer on the basis of his own judgement, as well as technological, market, and legislative constraints. A set of criteria which takes into account environmental, social, and economic aspects is then used to evaluate each remaining scenario and select the best one. Rao and Padmanabhan (2010) use an original approach which consists in evaluating the scenarios using the digraph and the matrix method. This method is flexible since the designer can choose the attributes (qualitative or quantitative) which will allow evaluating the scenarios and their relative importance. However, in the case the designer has little knowledge on products recovery process, choosing the initial set of scenarios, choosing the relevant attributes and determining their relative importance could be a difficult and time-consuming task. Mathieux *et al.* (2008) proposed a similar approach with his method: the designer must construct himself EOL scenarios, defined not only by the disassembly process, but also by sorting, crushing, and logistics operations. The method then provides a recoverability assessment of the chosen scenarios, using three indicators (weight recovery, economic recoverability, and environmental recoverability). The best scenario is the one which maximises these three indicators. Gehin *et al.* (2007) principally considered the environmental aspects, by assessing scenarios using an simplified life-cycle assessment. He created the life-cycle bricks model to enable the differentiation of scenarios by modifying EOL stages. Willems *et al.* (2004) applied a linear algorithm to calculate the least costly path the product could take. Finally, Kumar *et al.* (2007) developed an original approach to compare EOL scenarios, by arriving at the remaining value of the discarded product as perceived by the consumer as well as by the recycling company. Even though these methods have proved to be efficient, they are often too time-consuming, and require a specific expertise in recovery processes which some designers do not have. The reason for this is that constructing the initial set of the best EOL scenarios (which maximise the EOL benefit, the EOL environmental performance and which respect the regulations) taking into account the situation and characteristics of every part composing the product is a difficult and subjective task. Most of the time, the designers do not have the time to perform such a task with the only goal of improving the EOL phase of the product life cycle, since they also have to take into account all the other important aspects of the design (aesthetic, performance, safety, maintenance, reliability, etc.) (Luttrupp and Lagerstedt 2006). Moreover, most of these methods would need to be applied after the end of the detailed design phase, and must then be used with a DfE method similar to the one proposed by Lee *et al.* (2006), which, as we have seen, requires a lot of time and effort.

Another way to organise the DfEOL process is to choose the product EOL before embarking on the first detailed design. Brezet and Helmel's (1998) DfE guide uses this approach, which avoids the multiple redesign loops produced by Lee *et al.*'s DfE method. The procedure described in this guide includes: (i) definition of the ecodesign strategy, including constraints on

production, distribution and use impacts; (ii) selection of the best EOL based on this strategy; and (iii) guidelines and requirements for designing the product in accordance with this choice.

With Brezet and Helmel's DfE process, little information is available to evaluate the product EOL, since the evaluation has to be made at the very beginning of the design process. The characteristics implemented in the method should therefore be chosen carefully, in order to respect its applicability and relevance. In her end-of-life design advisor (ELDA) method, Rose *et al.* (2000) used six technical characteristics: wear-out life, technology cycle, level of integration, number of parts, design cycle, and reason for redesign. Based on many case analyses, she then applied the classification and regression trees algorithm and obtained a final decision tree. Xing *et al.* (2003) noted that some of these characteristics were redundant, and so simplified ELDA, creating the product EOL strategy planning method. He used only four characteristics (wear-out life, technology cycle, level of integration, and reason for redesign) and quantified the effect of physical deterioration and that of technological obsolescence. These two indicators result in a final EOL evaluation.

These latter methods are the best we have found for the purposes of this paper, since they can be used during the early design phase, and they are quick and require little effort. However, they are simplified to the point that certain key aspects, like regulations and economic benefit, are overlooked. Moreover, they give a single EOL for the entire product, whereas, in reality, when a worn-out product is disassembled, the various elements resulting from the disassembly sequence are given different EOLs. It is this precise EOL scenario the designer has to find to be able to determine the detailed design specifications. In responding to this problem, Rose specifies that her method can be used for a subassembly, as well as for the entire product (Rose 2001). However, considering the EOL of an element inside a product requires more information than considering the entire product's EOL, like its attachments or its location within the product structure, so much so that the same method cannot be used for both cases.

In our method, the EOL is evaluated at the beginning of the design phase, and is implemented on the product subassemblies instead of the entire product. This evaluation is made by using a multi-criteria decision approach.

Among all the possible multi-criteria decision methods that were applicable, we considered the most commonly used among them: weighted sum model (WSM), weighted product model (WPM) (Triantaphyllou *et al.* 1998), analytic hierarchy process (AHP) (Saaty 1990), ELimination Et Choix Traduisant la REalité (ELECTRE) (Hokkanen and Salminen 1997), and TOPSIS (Lai *et al.* 1994). In the study performed by Rao (2007), these different methods are applied in the case of the telephone EOL scenario selection and all of them give similar results. We thus applied them in our case (using the criteria hierarchy described later) on various modules. WSM and WPM were simple and intuitive to use, but gave unsatisfactory results. Moreover, some authors criticised them due to their invariant scale property (Zanakis *et al.* 1998). AHP and ELECTRE are based on pairwise comparison of criteria and alternatives. They gave good results but given the complexity of the hierarchy used, they required a large number of pairwise comparisons and an excessive amount of time. The use of such processes in the situation of a quick EOL scenario evaluation during the early design phase would then be inadequate. Moreover, ELECTRE does not give a global preference for the alternatives, but only a partial ranking. The TOPSIS method, which has been applied very often to environmental and waste management issues (Cheng *et al.* 2003, Gumus 2009), has many advantages: (i) it is logical and follows the rational nature of the human's selection process; (ii) for each alternative, it takes into account the distance to the best, as well as to the worst alternative; and (iii) it is simple to implement and can be easily programmed (Shih *et al.* 2007). Moreover, its application for our case gave good results. For these reasons, we selected TOPSIS for our multi-criteria EOL evaluation.

As the characteristics of the module are not precisely determined in the early design stage, we decided to apply TOPSIS using the fuzzy set theory, which has been shown to be widely

applicable to formulating decision problems where the information available is subjective or imprecise (Herrera and Herrera-Viedma 2000).

### 3. Overview of a new EOL scenario evaluation method

The EOL scenario evaluation method (ELSEM) is a new tool for EOL scenario assessment during the early design phase of the product development process. The goal of this method is to help the designer with examining the suitability of the various EOL treatments, and make it possible to: (i) identify the applicable EOL scenarios, given the environmental policy and business objectives of the company; (ii) find the suitable design options corresponding to the chosen scenario, and negotiate the technical characteristics of the product with the rest of the design team; (iii) in certain cases, negotiate the EOL strategy chosen by the company with company headquarters if it seems unrealistic. All these features make the ELSEM a valuable tool for assisting with EOL decision-making.

At the beginning of the design stage, the main functional components, their relationships, and their materials and weights are estimated (Brissaud and Zwolinski 2004), based on the available functional requirements (Prudhomme *et al.* 2003) and on the product under redesign or other similar products. Each of these components, which the designer is already able to identify, is called a 'module' in the rest of this paper.

To assess the various scenarios, the designer has to evaluate:

- the materials making up the product, including their recovery rate and the energy recovery rate of the entire product imposed by the applicable regulations;
- a set of 13 technical characteristics for each individual module.

This evaluation is made using linguistic terms that are intuitively easy to use, since they allow the assessment of imprecise and subjective information. The burden of quantifying characteristics that are not precisely determined during the conceptual design phase is then eliminated (Herrera and Herrera-Viedma 2000).

Once this implementation has been carried out, the ELSEM gives a ranking of each EOL option (reuse, remanufacturing, recycling with disassembly (Rwd), recycling without disassembly (Rwod), incineration, disposal) for each module. The designer can then select the most suitable EOL scenarios based on this information, the product structure, and the targets and EOL strategy fixed by the company.

The ELSEM uses a fuzzy, multi-criteria decision method, called fuzzy TOPSIS, which organises the decision problem into a hierarchy made up of a set of criteria and sub-criteria which take into account the economic, regulatory, and environmental aspects of the recovery of discarded products. Depending on the preferences of the designer and the company's objectives, the relative importance of these aspects can be adjusted.

The ELSEM is thus a useful instrument that guides and facilitates the negotiation between the members of the design team relative to environmental concerns and increases the awareness of designers regarding product EOL issues.

### 4. Evaluating the EOL of a product's modules at the early design stage

The ELSEM evaluates six EOL options for each module, using a multi-criteria decision approach. To construct the set of criteria, we determine the fundamental aspects of a product's recovery. The performances of the EOLs according to these criteria are based on certain technical characteristics

of the module. These parameters are chosen according to their influence on the product EOL and their availability during the early design phase.

#### 4.1. Definitions

The various EOLs that we chose to implement in our method are defined below, in order of preference in terms of environmental performance:

- $A_1$ : *Reuse (RU)*: The module is reused without performing any repair or renovation operation other than cleaning. It can be reused for the same initial application, or for another, secondary application. For instance, following the disposal of a car, its engine can be recovered and cleaned to be resold and installed in a new car. Using a tire for embankment construction would be another example of reuse.
- $A_2$ : *Remanufacturing (RM)*: A significant number of modules of the same type is disassembled at a recycling center. Depending on their condition, parts are then either disposed of or sorted, cleaned, and repaired. Using these refurbished parts and new ones, new modules are built and sold as ‘remanufactured products’. During the remanufacturing process, it is possible to improve module performance by upgrading the original parts.
- $A_3$ : *Rwd*: Materials are separated before being recycled. This process allows the reuse of a material for its original application, since there is no mixing of materials of the same type, but which are slightly different, as is the case for *Rwod*.
- $A_4$ : *Rwod*: The module is shredded or compacted without any previous disassembly operation, and the different kinds of materials are then recovered: materials containing iron are separated magnetically and others are separated with methods like wind sifting, vibration methods, hydro-cyclone separation, flotation techniques, etc. Following the recycling process, materials of significant economic value are sold. Choosing which parts should be recycled depends largely on the material’s current market value. However, there are certain precious and semi-precious materials that have a higher economic value and a high probability of being recycled.
- $A_5$ : *Incineration with energy recovery (IER)*: The module is incinerated using an energy recovery method and flue gas purification. This option is selected for modules containing materials with a high calorific value, generally plastics.
- $A_6$ : *Disposal (Disp)*: The module is sent to a landfill as solid waste. Most of the time, this scenario is not desirable from an environmental point of view. However, it is the most commonly applied EOL option.

#### 4.2. Construction of the multi-criteria problem hierarchy

The multi-criteria decision method requires the choice of relevant criteria that will constitute the principal aspects of a product that a company usually considers when making a decision, such as selecting the best EOL for a product. We chose the four criteria that have been systematically used in the existing EOL evaluation methods (Navin Chandra 1994, Rao and Padmanabhan 2010): environmental performance (which is linked to the image the company wants the consumer to see); income generated from sales; treatment cost; and compliance with regulations. Each of these criteria is decomposed into sub-criteria, some of which are decomposed into sub-sub-criteria. To choose among them, we looked at the literature on the reverse supply chain process (Brezet and Hemel 1998, Hammond *et al.* 1998, Johnson and Wang 1998, Knemeyer *et al.* 2002) and we respected the five principal properties isolated by Keeney and Gregory (2005) (completeness, operational ability, decomposability, non-redundancy, and minimum size), in order to take into account all the relevant impacts of the proposed options. Finally, the alternatives (that is to say,

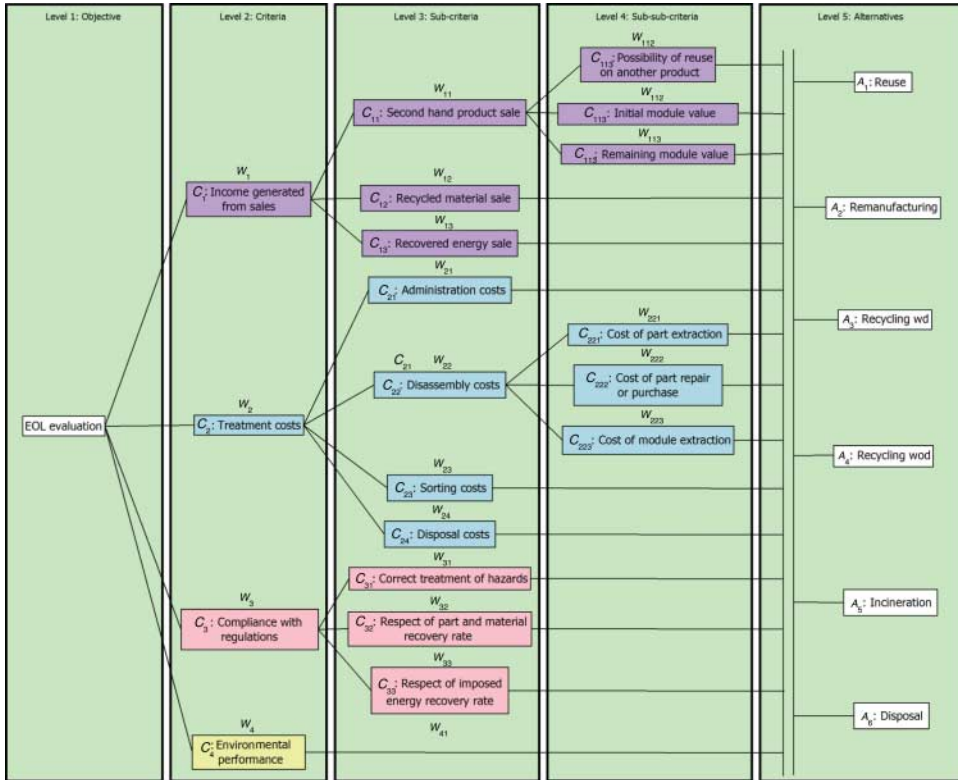


Figure 1. Problem hierarchy with five levels: objective, criteria, sub-criteria, sub-sub-criteria, and alternatives.

the EOL options) are evaluated on the basis of the set of sub-sub-criteria each of them affects. Proceeding in this way, we finally arrive at the hierarchical structure of the decision problem.

This multi-criteria decision problem can be illustrated by a hierarchical diagram, as shown in Figure 1, which represents five levels: the principal objective, the four criteria ( $C_j$ ) used to reach it and their relative weights ( $w_j$ ), the 10 sub-criteria ( $C_{jk}$ ) composing the criteria  $C_1$ ,  $C_2$ , and  $C_3$  and their relative weights ( $w_{jk}$ ), the six sub-sub-criteria ( $C_{jkl}$ ) composing each the sub-criteria  $C_{11}$  and  $C_{22}$  and their relative weights ( $w_{jkl}$ ), and the six alternatives ( $A_i$ ) that we want to evaluate according to each of the criteria. The four criteria and their corresponding sub-criteria and sub-sub-criteria are each represented by a distinct colour.

If needed, the hierarchy can be modified without any difficulties by adding or removing sub-criteria or sub-sub-criteria, the main concern will be on determining their relative weights. The fuzzy TOPSIS process described later in this paper allows doing so since it can be applied to any hierarchy with any number of different levels.

### 4.3. Influence parameters

The criteria hierarchy described above is used to assess every EOL option. However, this assessment will differ depending on the characteristics of the module under consideration or on the EOL regulations that may apply to the product under development. For instance, the assessment of the sorting cost for the Rwd depends on the quantity of materials within the module. Moreover, the cost of part repair for REM and Rwd depends on the EOL condition of the module. The quantity of material or the EOL condition are called ‘influence parameters’ and are used to calculate the



performances of REM, Rwd, and Rwod. This example shows that the influence parameters allow differentiating the modules studied and that each of them is relevant for evaluating only certain EOL options.

It is precisely these parameters that the designer will have to implement in the ELSEM to obtain the final results.

Based on the research conducted by Brezet and Hemel (1998), Rose *et al.* (1998), Parlikad *et al.* (2003) and Sy and Mascle (2011) and our own experience, we arrived at a set of 15 final parameters that influence the EOL decision, and are relevant to the purposes of our method. To take this decision, we respected two conditions.

- The number of parameters has to be minimal, in order for the method to be simple to use and quick.
- The selected parameters must be available, or at least available for evaluation, during the early design phase.

The final 15 influence parameters take the majority of product recovery aspects into account. The other features, like the manufacturer's intentions and other situational variables, the country where the product will be sold and labour and energy costs, for example, are not directly represented among the 15 parameters, but they are considered within the choice of weights of influence for each criterion, as we will see in greater detail below.

Moreover, we can see that the collection possibilities do not appear either. This is because they should not be considered in the same way as the others: envisaging whether or not the product will be taken back after reaching its EOL is a question the designer should answer before beginning the EOL selection process, and even before deciding whether or not to apply a DfEOL method. If there is no existing take-back system, and if it is unrealistic to put in place an inverse supply chain, it is unnecessary to use our method, since the product will wind up in a landfill or be incinerated anyway. Evaluating the possibility of creating a take-back system then becomes a full-fledged problem that we chose to not consider.

In fact, what we did when creating the method was to consider putting in place an inverse supply chain for the product studied, which made all EOL scenarios conceivable.

The final 15 parameters selected are described below.

- $P_1$ : *Adaptability*: The capability of assembling the EOL module on a product other than the one for which it was initially intended. If the module is still up to date following the EOL of its initial product (which is usually the case for components with high-standard specifications), it will then be possible to find another product to which it can be adapted.
- $P_2$ : *Durability*: Linked to the module's residual value after it is first used, and defined as the ratio between the module's wear-out life and the product's useful life, which has to be as high as possible, so that the module can still be functional after the product's EOL and be reused.
- $P_3$ : *Module market value*: The selling price of the product, immediately following its manufacture. Generally, the higher the module market value, the more developed the second market, but the greater the remanufacturing cost.
- $P_4$ : *EOL condition*: The state of the module at the EOL of the product. This reveals how clean it is, its esthetic state, and its level of functionality (number of parts still functioning). The EOL condition is associated with the module's reliability and the circumstances in which it was used during its lifetime, and indicates the possibilities for reuse and the potential remanufacturing costs.
- $P_5$ : *Quantity of high-value materials*: These can be resold at a high price after their recovery. Materials with a very high value, like gold, palladium, and silver, are considered as precious materials. Modules made with one or more of these are usually Rwd. Other materials that

can easily be resold are special metallic alloys (e.g. copper, aeronautic aluminum, iron), some plastics (e.g. PEE, PC, PM, ABS), and glass.

- *P<sub>6</sub>: Calorific capacity*: Depends on the calorific capacity of the materials of which the module is composed. When the value is high, it is preferable to incinerate the module, rather than dispose of it in a landfill, because this will permit the recovery of a substantial amount of energy. Metals do not produce any recoverable energy, whereas plastics can provide up to 40 MJ/kg. Generally, when calorific capacity is higher than 8 MJ/kg, the option of incineration is preferred over landfill disposal.
- *P<sub>7</sub>: Difficulty with the module's disassembly*: Takes into account the overall access to the module, as well as the number and type of attachments that have to be dismantled in order to dissociate them from the product. This is directly related to the module's disassembly cost.
- *P<sub>8</sub>: Level of integration*: Linked to the number of functions realised by the module's parts and subassemblies, and represents their complexity. The higher the number of functions performed by each part or subassembly of the module, the greater the level of integration will be. This characteristic is useful when determining the remanufacturing costs. So, if a subassembly performs many functions, it is complex and its cost is significant. As a result, if only a single function is deficient, repairing it will be preferable to replacing it. Yet, this option will still be much more costly than replacing a simple subassembly, which would only have performed the function in question.
- *P<sub>9</sub>: Quantity of parts*: Defined as the indissociable elements of the product that perform one or more functions, except the connection function. Generally, the quantity of parts is an indication of the module's disassembly cost, and is thus related to the cost of remanufacturing and Rwd.
- *P<sub>10</sub>: Difficulty of dismantling part attachments*: Refers to the cost of dismantling the connectors that link the various parts of the module. This parameter is involved in the module's part disassembly cost, which has to be taken into account if remanufacturing or Rwd is chosen as the module's EOL option.
- *P<sub>11</sub>: Amount of different materials*: A module with few materials can be easily recycled, since its treatment will require less separation effort. In addition, there is an important benefit: with an appropriate separation method, a significant amount of a particular material will be recovered and potentially resold.
- *P<sub>12</sub>: Amount of hazardous materials*: According to the Institute of Hazardous Materials Management (2010), 'a hazardous material is any item or agent (biological, chemical, physical) which has the potential to cause harm to humans, animals, or the environment, either by itself or through interaction with other factors'. Hazards are governed by laws and regulations which differ from one country to another. For instance, in Europe, the requirements that apply to hazardous waste and its definition (based on a list) are described by directive 91/689/EEC, created in 1991. Generally, regulations stipulate that hazardous modules must be disassembled and treated separately.
- *P<sub>13</sub>: Imposed rate of material and part recovery*: In several countries, regulations determine the required rate of material and part recovery for some products, and cover the recycling, reuse, and remanufacturing of products. Generally, they concern categories of products manufactured in large quantities and generating a significant amount of waste, like household appliances, vehicles, and telecommunications equipment. When the rate is high, as many modules and materials as possible in the product have to be considered. This then influences the choice of EOL scenario for each of them, and will favour the recycling, reuse, and remanufacturing scenarios.
- *P<sub>14</sub>: Imposed energy recovery rate*: Commonly associated with material and part recovery. This only concerns incineration with an energy recovery option.
- *P<sub>15</sub>: Module weight*: Influences recycling and incineration, since it greatly impacts the quantity of high-value materials and recovered energy.

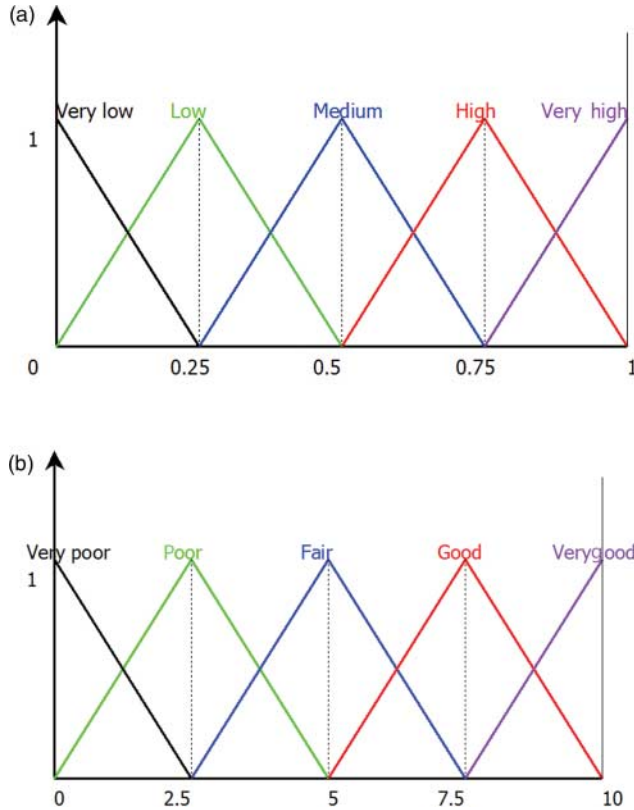


Figure 2. (a) Membership functions of EOL performances and influence parameters, apart from the module's weight. (b) Weight membership functions.

These 15 influence parameters are evaluated by the designer using a set of five possible linguistic variables. These allow the qualitative, imprecise, and subjective information to be ranked in a comprehensive and intuitive way, which is essential during the early design phase. The fuzzy ranking of each parameter  $P_n$  is denoted  $N_n$ .

$N_n$  ( $n = 1, \dots, 14$ ) can take the following linguistic values: very poor (VP), poor (P), fair (F), good (G), and very good (VG), represented by triangular membership functions distributed over the interval  $[0, 10]$ , as illustrated in Figure 2(a).

$N_{15}$  can take the following linguistic values: very low (VL), low (L), moderate (M), high (H), and very high (VH), represented by triangular membership functions distributed over the interval  $[0, 1]$ , as illustrated in Figure 2(b).

We can then express each of these linguistic terms as a triangular fuzzy number  $(a, b, c)$ , where  $a$ ,  $b$ , and  $c$  represent the three remarkable values of the function (for example, poor =  $(0, 2.5, 5)$ ).

#### 4.4. The fuzzy TOPSIS approach

##### 4.4.1. Problem formulation

Our problem consists of choosing among a set of six EOL alternatives  $A_i$  ( $i = 1, 2, \dots, 6$ ). These alternatives are evaluated by a set of four criteria  $C_j$  ( $i = 1, 2, \dots, 4$ ), which we will consider to be independent of each other. Certain criteria  $C_j$  can be broken down into  $p_j$  sub-criteria  $C_{jk}$  ( $k = 1, 2, \dots, p_j$ ). Certain sub-criteria are broken down again, into  $q_{jk}$  sub-sub-criteria

$C_{jkl}$  ( $l = 1, 2, \dots, q_{jk}$ ). The sub-criteria and sub-sub-criteria are also considered independent of each other. When a sub-criterion (respectively, criterion) is not decomposed, we will consider that the corresponding sub-sub-criterion (respectively, sub-criterion) is unique and identical to the sub-criterion (respectively, criterion). For instance,  $C_{121} = C_{12} =$  recycled material sale and  $q_{12} = 1$  or  $C_{41} = C_4 =$  environmental performance and  $p_4 = 1$ .

The decision matrix for the four principal criteria used to evaluate the six alternatives is designated as  $X = [x_{ij}]_{6 \times 4}$ , where  $x_{ij}$  represents the fuzzy performance of the EOL with respect to the criterion  $C_j$ .

- As  $p_j$  sub-criteria  $C_{jk}$  are used for the criterion  $C_j$ , we can define a sub-criteria decision matrix denoted as  $Y_{C_j} = [y_{ik}]_{6 \times p_j}$ , where  $y_{ik}$  represents the fuzzy performance of the EOL  $A_i$  with respect to the sub-criterion  $C_{jk}$ .
- As  $q_{jk}$  sub-sub-criteria  $C_{jkl}$  are used for the sub-criterion  $C_{jk}$ , we can define a sub-sub-criteria decision matrix denoted as  $Z_{C_{jk}} = [z_{il}]_{6 \times q_{jk}}$ , where  $z_{il}$  represents the fuzzy performance of the EOL  $A_i$  with respect to the sub-sub-criterion  $C_{jkl}$ .

The weights of criteria, sub-criteria, and sub-sub-criteria are given by the following weighting vectors, respectively:

$$W = (w_1, w_2, \dots, w_4),$$

$$W_j = (w_{j1}, w_{j2}, \dots, w_{jp_j}),$$

$$W_{jk} = (w_{jk1}, w_{jk2}, \dots, w_{jkq_{jk}}).$$

As seen above, the influence parameters  $P_n$  ( $n = 1, \dots, 14$ ) are assessed using triangular fuzzy numbers defined on the interval  $[0, 10]$ . Since the performances of each EOL option according to the set of criteria, sub-criteria, and sub-sub-criteria will be evaluated on the basis of this assessment, the numbers  $x_{ij}$ ,  $y_{ik}$ , and  $z_{il}$  are triangular fuzzy numbers defined on  $[0, 10]$  as well. Moreover, the various weights are also evaluated by triangular fuzzy numbers, according to the same ranking system used for  $N_{15}$  (triangle membership functions of the values that the weights can take are distributed over the interval  $[0, 1]$  and are illustrated in Figure 2(b)).

The various steps of the problem are summarised in Figure 3. The matrices  $R$  and  $V$  will be further defined in Page 16.

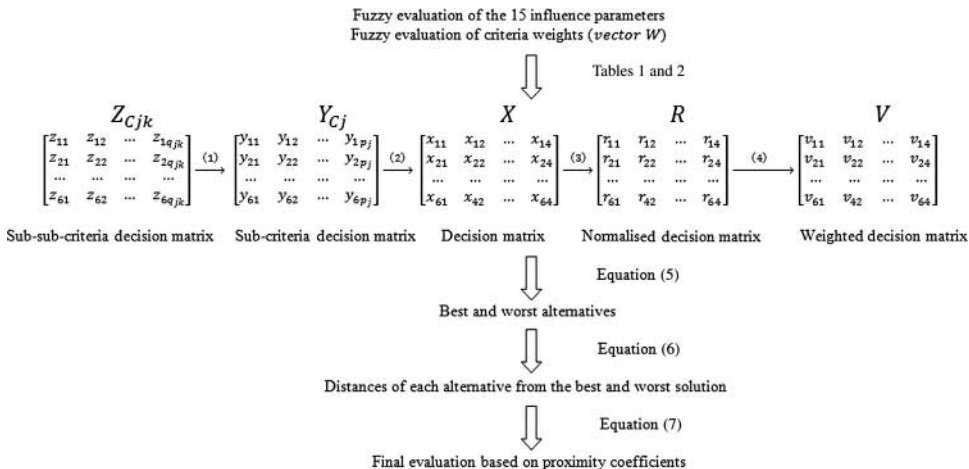


Figure 3. Summary of the ELSEM steps.

4.4.2. Evaluation of each EOL for each sub-sub-criterion on the basis of parameter evaluation

Table 1 shows the fuzzy performances of the six EOL options according to the 15 sub-sub-criteria. Each line corresponds to one sub-sub-criterion and each column corresponds to one EOL option. Moreover, the table is divided into four sections which allow classifying the sub-sub-criteria under the four principal criteria. Certain performances are variables since they depend on the characteristics of the module under consideration. This is why certain values of  $z_{il}$  are calculated using the  $N_i$  values. For instance, the performance of alternative  $A_2$  (remanufacturing) with respect to sub-sub-criterion  $C_{112}$  (initial module value) is equal to value  $N_3$  (of parameter  $P_3$ : module market value). The variables performances are coloured in grey on Table 1. The other performances are fixed since they are independent of the module under consideration. For example, the performance of the alternative  $A_5$  (incineration) with respect to sub-sub-criterion  $C_{211}$  is equal to VP (very poor, represented by the triangular number (0, 0, 2.5)) regardless of the module studied.

The weighting vectors of the sub-criteria and sub-sub-criteria in Table 2 (vectors  $W_j$  and  $W_{jk}$ ) have been chosen based on the literature review on the reverse supply chain process (Thierry *et al.* 1995, Brezet and Hemel 1998, Johnson and Wang 1998, Srivastava 2007), and on the assumption that the recovery process takes place in a developed country in Europe, where the regulations impose quite restrictive rules, the labour cost is high but many resources are available, and the concern for the environment is growing quickly. If the situation proves to be different, the ELSEM allows these weights to change. Some weights depend directly on the module's weight  $P_{15}$ , as, for instance, the income generated from the sale of the recycled materials or the cost of disposal. These weights are then equal to  $N_{15}$ . The weighting vectors that are singletons are not represented in Table 2, since we only consider the relative weights of the elements contained in each of the vectors.

The weights of the criteria (vector  $W$ ) must be fixed by the designer before the beginning of the EOL choice process. To evaluate these weights, he or she uses his own judgement and considers the company's priorities and intentions.

4.4.3. Construction of the decision matrices

If the sub-criterion  $C_{jk}$  is broken down into  $q_{jk}$  sub-sub-criteria, the decision vector  $(y_{1k}, y_{2k}, \dots, y_{6k})$  used to evaluate the six EOL options according to the sub-criterion  $C_{jk}$  is given by

$$\begin{pmatrix} y_{1k} \\ y_{2k} \\ \dots \\ y_{6k} \end{pmatrix} = \frac{z_{C_{jk}} W_{jk}^T}{\sum_{l=1}^{l=q_{jk}} w_{jkl}} \tag{1}$$

We thus obtain the sub-criteria decision matrix  $Y_{C_j}$ .

If the criterion  $C_j$  is broken down into  $p_j$  sub-criteria, the decision vector  $(x_{1j}, x_{2j}, \dots, x_{6j})$  used to evaluate the six EOL options according to the criterion  $C_j$  is given by

$$\begin{pmatrix} x_{1j} \\ x_{2j} \\ \dots \\ x_{6j} \end{pmatrix} = \frac{Y_{C_j} W_j^T}{\sum_{k=1}^{k=p_j} w_{jk}} \tag{2}$$

We thus obtain the criteria decision matrix  $X$ . This matrix has to be normalised, so that the scales of the various criteria are comparable. For this purpose, we decided to use the linear scale

Table 1. Performances of the various EOL alternatives, according to each sub-sub-criterion.

Income generated from sales ( $C_1$ )	$A_1$	$A_2$	$A_3$	$A_4$	$A_5$	$A_6$
Possibility of reuse on another product ( $C_{111}$ )	$N_1$	$N_1$	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)
Initial module value ( $C_{112}$ )	$N_3$	$N_3$	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)
Remaining module value ( $C_{113}$ )	$\frac{VG}{VG - VP} \sqrt{(N_4 - VP)(N_2 - VP)}$	G	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)
Recycled material sale ( $C_{121}$ )	(0,0,0)	(0,0,0)	$N_5$	$N_5 * \frac{F}{VG}$	(0,0,0)	(0,0,0)
Recovered energy sale ( $C_{131}$ )	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)	$N_6$	(0,0,0)
Treatment costs ( $C_2$ )	$A_1$	$A_2$	$A_3$	$A_4$	$A_5$	$A_6$
Administration costs ( $C_{211}$ )	VG	VG	F	F	VP	(0,0,0)
Costs of part extraction ( $C_{223}$ )	(0,0,0)	$\frac{N_8 + N_9 + N_{10}}{3}$	$\frac{N_8 + N_{11} + N_{10}}{3}$	(0,0,0)	(0,0,0)	(0,0,0)
Cost of module extraction ( $C_{221}$ )	$N_7$	$N_7$	$N_7$	(0,0,0)	(0,0,0)	(0,0,0)
Costs of part repair and/or purchase ( $C_{222}$ )	(0,0,0)	$N_4^{-1a}$	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)
Sorting costs ( $C_{231}$ )	(0,0,0)	(0,0,0)	(0,0,0) <sup>b</sup>	$N_{11}$	(0,0,0)	(0,0,0)
Disposal costs ( $C_{241}$ )	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)	(10,10,10)	(10,10,10)
Compliance with regulations ( $C_3$ )	$A_1$	$A_2$	$A_3$	$A_4$	$A_5$	$A_6$
Correct treatment of hazards $C_{311}$	G	G	G	G	$N_{12}^{-1}$	$N_{12}^{-1}$
Respect of part and material recovery rate $C_{321}$	$N_{13}$	$N_{13}$	$N_{13}$	$N_{13}$	(0,0,0)	(0,0,0)
Respect of energy recovery rate $C_{331}$	(0,0,0)	(0,0,0)	(0,0,0)	(0,0,0)	$N_{14}$	(0,0,0)
Environmental performance ( $C_4$ )	$A_1$	$A_2$	$A_3$	$A_4$	$A_5$	$A_6$
Environmental performance ( $C_{411}$ )	VG	G	F	P	$N_{12}^{-1} \times N_{15}^{-1} \times \frac{P}{VG^2}$	$N_{12}^{-1} \times N_{15}^{-1} \times \frac{VP}{VG^2}$

<sup>a</sup>The notation  $N_n^{-1}$  means that the higher the assessment of the parameter, the lower its performance. If  $N_n = VG$ , then  $N_n^{-1} = VP$ ; if  $N_n = G$ , then  $N_n^{-1} = P$ ; if  $N_n = F$ , then  $N_n^{-1} = F \dots$

<sup>b</sup>We consider that, for Rwd, sorting is included in the disassembly process.

Table 2. Remarkable weighting vectors of the criteria and sub-criteria.

Weighting vectors	Fuzzy criteria weights
$W_1$	(VH, $N_{15}$ , $N_{15}$ )
$W_{11}$	(H, L, VH)
$W_2$	(H, VH, VL, $N_{15}$ )
$W_{22}$	(M, L, VH)
$W_3$	(H, $N_{15}$ , $N_{15}$ )

transformation, as described in (Chen 2000). The normalised matrix is denoted  $R = [r_{ij}]_{6 \times 4}$ , with  $r_{ij}$  defined as follows.

If  $x_{ij} = (a_{ij}, b_{ij}, c_{ij})$ , then

$$r_{ij} = \left( \frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*} \right), \quad (3)$$

with  $C_j^* = \max_i c_{ij}$ .

Finally, in order to take into account the importance of each criterion, we define the weighted decision matrix as follows:

$$V = [v_{ij}]_{6 \times 4} = [r_{ij}w_{ij}]_{6 \times 4}. \quad (4)$$

#### 4.4.4. Distance of each EOL option from the best and worst alternatives

The principle of TOPSIS is to consider the six alternatives evaluated according to the four criteria as six points in a four-dimensional space. An alternative becomes more attractive as it moves towards the best solution and away from the worst solution (Cheng *et al.* 2003).

The best and worst alternatives are given by Öñüt and Soner (2008):

$$A^+ = (v_1^+, v_2^+, v_3^+, v_4^+), \quad \text{and} \quad A^- = (v_1^-, v_2^-, v_3^-, v_4^-), \quad (5)$$

$$\text{with } v_j^+ = \left\{ \begin{array}{l} (\max v_{ij} \text{ if } j \in B) \\ (\min v_{ij} \text{ if } j \in C) \end{array} \right\} \quad \text{with } v_j^- = \left\{ \begin{array}{l} (\max v_{ij} \text{ if } j \in B) \\ (\min v_{ij} \text{ if } j \in C) \end{array} \right\}.$$

$B$  is the set of criteria for which the EOL alternatives in agreement with it are given a good performance rating (income generated from sales, compliance with regulations, environmental performance).  $C$  is the set of criteria for which the EOL alternatives in agreement with it are given a poor performance rating (treatment cost). The best alternative (respectively, worst alternative) is the combination of the best performances (respectively, worst performances) calculated for each of the four principal criteria. For instance, the best performance for the criterion 'income generated from sales' corresponds to the performance of the EOL which rewards the largest income. On the other hand, the best performance for the criterion 'treatment cost' is the one of the cheapest EOL.

The distances of each alternative from the best and worst solutions are expressed, respectively, by

$$D_i^+ = \sum_{j=1}^{j=4} d(v_{ij}, v_j^+) \quad \text{and} \quad D_i^- = \sum_{j=1}^{j=4} d(v_{ij}, v_j^-). \quad (6)$$

To calculate the distance between two fuzzy numbers, we used the vertex method (Dong and Shah 1987), because of its efficiency and simplicity. According to this method, the distance

between two fuzzy numbers  $\alpha = (a_1, b_1, c_1)$  and  $\beta = (a_2, b_2, c_2)$  is:

$$d(\alpha, \beta) = \sqrt{\frac{1}{3}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]}.$$

#### 4.4.5. Evaluation of each alternative with the proximity coefficient

This coefficient, which quantifies the proximity of each EOL alternative from the best and the worst solutions, is defined as

$$CC_i = \frac{D_i^-}{D_i^+ + D_i^-}. \quad (7)$$

Finally, the best alternative is the one with the higher proximity coefficient.

## 5. Case study

To illustrate the use of the ELSEM, we carried out a case study on the design of a vehicle engine. We chose to treat a vehicle part, since the EOL treatment of vehicles has become an important issue in the past decade, following the creation of the European end-of-life vehicle (ELV) directive in 2000 (Ferraio and Amaral 2006).

We assume the designers are at the beginning of the design phase of a new engine. This design is made in the framework of the redesign of an entire car. The redesign must lead to the improvement of the performances as well as the aesthetic aspects of the car. Moreover, the project team leaders have decided to take advantage of this opportunity to decrease the economic and environmental costs of the modules EOL treatments. However, the designers must respect the company politics which will give the relative importance of each criterion.

A designer made a first drawing of the future engine represented in Figure 4. At this point, he does not know the detailed design of each individual part, however, he or she knows that the new engine design will be similar to conventional fuel engines. Concerning the elements which will change, he or she assumes with a high level of certitude the following assertions.

- (1) Few new materials will be implemented. The principal materials will remain steel and aluminum alloys, neither of which is a hazardous material. There is no need to use some precious materials.
- (2) The difficulty disassemble a module will be similar to that of previous engines. On a scale that varies from 1 to 10 (10 means very difficult), it is estimated to be between 6 and 8.
- (3) There will be few new parts. The new parts will realise several functions at the same time.
- (4) The fasteners used will principally be welds and screws as usual with similar engines

In order to decrease the costs of the engine EOL treatment, the designer has to adapt the detailed design parameters to the future engine EOL option. Consequently, he or she first must decide with the rest of the team which EOL option will be the most suitable for the new engine. To evaluate the different EOL options, he or she uses the ELSEM method. Given the company politics, he or she chooses the following weighting vector for the four principal criteria:  $W = (VH, VH, L, VL)$ . This means that income generated from sales are considered with very high importance, treatments costs with very high importance, compliance with regulations with low importance, and environmental performance with very low importance. He or she then evaluates the 15 influence parameters as described in Table 3. This table shows the name of each parameter, its assessment and the explanation of this assessment based on the information available at the beginning of the design phase.



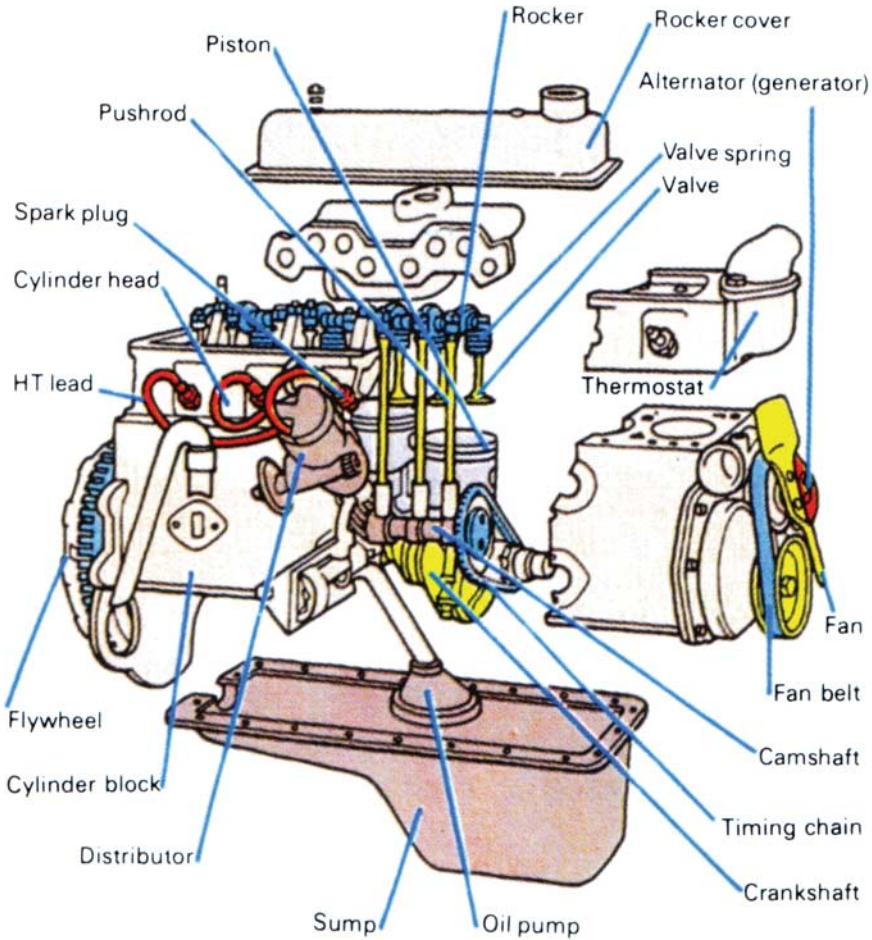


Figure 4. Schema of the future engine, realised during the early design phase Arthur’s machine clipart (2009).

Using this assessment and the various formulas described in Table 1, the ELSEM process begins with the calculation of the 11 sub-sub-criteria matrices. Based on these matrices and the values of the weighting vectors  $W_{11}$  and  $W_{22}$  (Table 2), four sub-criteria decision matrices are obtained. They show the performances of the six alternatives, according to the 11 sub-criteria, and are given by

$$Y_{C_1} = \begin{pmatrix} (3.0, 5.0, 6.0) & (0.0, 0.0, 0.0) & (0.0, 0.0, 0.0) \\ (6.0, 8.7, 10) & (0.0, 0.0, 0.0) & (0.0, 0.0, 0.0) \\ (0.0, 0.0, 0.0) & (0.0, 2.5, 5) & (0.0, 0.0, 0.0) \\ (0.0, 0.0, 0.0) & (0.0, 1.3, 3.7) & (0.0, 0.0, 0.0) \\ (0.0, 0.0, 0.0) & (0.0, 0.0, 0.0) & (0.0, 0.0, 2.5) \\ (0.0, 0.0, 0.0) & (0.0, 0.0, 0.0) & (0.0, 0.0, 0.0) \end{pmatrix}$$

$$Y_{C_2} = \begin{pmatrix} (7.5, 10, 10) & (1.3, 2.1, 3.3) & (0.0, 0.0, 0.0) & (0.0, 0.0, 0.0) \\ (7.5, 10, 10) & (5.0, 7.9, 10) & (0.0, 0.0, 0.0) & (0.0, 0.0, 0.0) \\ (2.5, 5.0, 7.5) & (5.0, 6.4, 7.8) & (0.0, 0.0, 0.0) & (0.0, 0.0, 0.0) \\ (0.0, 2.5, 5.0) & (0.0, 0.0, 0.0) & (5, 7.5, 10) & (0.0, 0.0, 0.0) \\ (0.0, 0.0, 2.5) & (0.0, 0.0, 0.0) & (0.0, 0.0, 0.0) & (0, 2.5, 5) \\ (0.0, 0.0, 0.0) & (0.0, 0.0, 0.0) & (0.0, 0.0, 0.0) & (0, 2.5, 5) \end{pmatrix}$$

Table 3. Assessment of the various sub-criteria for the engine.

Parameter $P_n$	$N_n$	Explanation
Adaptability	VG	The technology cycle of a common engine is usually longer than that of a car. Consequently, after the car EOL, it is possible to find another car model in which the engine could be reused. Moreover, as we consider the case as for the design of a new car, it will be possible to reassemble the future engine on the same car model which will still be in fashion after one car life cycle
Durability	F	The wear-out life of a common engine is approximately equal to its useful life – a car is often discarded because of the failure of its engine. As the new engine will be similar to common fuel engines, the same affirmation is used for the module studied
Module value	VG	Given the performance improvements realised on the new engine, this one will probably be sold at a greater price than common engines. Besides, this price was already relatively high
Module EOL condition	VP	At the car's EOL, an engine is usually in very poor condition and cannot be resold without any refurbishment. This is due to the fact that during its lifetime, it is exposed to soiling substances such as oil and fuel, it endures a significantly high level of strain and elevated temperatures. This will be the case for the new engine as well
High-value materials	P	As specified in assertion 1, the principal material used will be steel and aluminum and the new module will not contain any precious material
Calorific capacity	VP	Most of the module will be made of steel and aluminum, the calorific capacity of which is very poor
Difficulty of module disassembly	G	Assertion 2 indicates that the difficulty of module's disassembly will be between 6 and 8. The fuzzy number (5, 7.5, 10) associated with the linguistic variable 'G' allows to take the entire interval into account
Level of integration	G	According to assertion 3, the new parts will realise many functions at the same time. Moreover some usual parts of an engine already realise many functions like the camshaft
Quantity of parts	G	As shown in Figure 4, there will be a relatively high quantity of parts in the new engine
Difficulty of part attachment dismantling	G	Assertion 4 indicates that the principal fasteners used will be screws and welds. Removing these types of attachments is particularly time-consuming
Quantity of different materials	G	By looking at Figure 4, we can estimate that the quantity of materials will be significant: in addition to the parts made of steel and aluminum, there are plastic parts (spark plug) and rubber parts (fan belt). Moreover, certain special alloys will have to be used for the pistons and the combustion chambers subjected to high pressures and temperatures
Quantity of hazardous materials	F	Assuming the specifications of the new engine do not include the reduction of hazardous materials, its quantity will be the same as common fuel engines. This quantity is fair and it principally is due to the presence of oil
Imposed recycling rate	F	In Europe, this rate is defined by the ELV directive. Since 2006, the recovery rate of materials and parts must be at least 80%. This number will climb to 95% in 2015
Imposed energy recovery rate	VP	According to the ELV directive, the energy recovery rate must be at least 5%, and this number will climb to 10% in 2015
Module weight	H	The weight of the engine is considered high when compared with that of other modules

$$Y_{C_3} = \begin{vmatrix} (5, 7.5, 10) & (2.5, 5, 7.5) & (0, 0, 0) \\ (5, 7.5, 10) & (2.5, 5, 7.5) & (0, 0, 0) \\ (5, 7.5, 10) & (2.5, 5, 7.5) & (0, 0, 0) \\ (5, 7.5, 10) & (2.5, 5, 7.5) & (0, 0, 0) \\ (2.5, 5, 7.5) & (0, 0, 0) & (0, 0, 2.5) \\ (2.5, 5, 7.5) & (0, 0, 0) & (0, 0, 0) \end{vmatrix}$$

$$Y_{C_4} = \begin{pmatrix} (7.5, 10, 10) \\ (5.0, 7.5, 10) \\ (2.5, 5.0, 7.5) \\ (0.0, 2.5, 5.0) \\ (0.0, 0.0, 0.2) \\ (0, 0, 0.1) \end{pmatrix}$$

The next step of the process consists of constructing the decision matrix  $X$ , each column of which is the average of one of the sub-criteria decision matrices, weighted by the corresponding weighting vector  $W_1, W_2, W_3,$  or  $W_4$  (Table 2):

$$X = \begin{pmatrix} (1.3, 2.0, 2.0) & (2.7, 3.9, 4.1) & (2.5, 4.2, 5.8) & (7.5, 10, 10) \\ (2.6, 3.5, 3.3) & (4.3, 6.1, 6.1) & (2.5, 4.2, 5.8) & (5.0, 7.5, 10) \\ (0.0, 0.7, 1.7) & (2.9, 4.1, 4.7) & (2.5, 4.2, 5.8) & (2.5, 5.0, 7.5) \\ (0.0, 0.4, 1.3) & (0.0, 0.7, 2.3) & (2.5, 4.2, 5.8) & (0.0, 2.5, 5.0) \\ (0.0, 0.0, 0.8) & (0.0, 0.7, 2.3) & (0.8, 1.7, 3.3) & (0.0, 0.0, 0.2) \\ (0.0, 0.0, 0.0) & (0.0, 0.7, 1.5) & (0.8, 1.7, 2.5) & (0.0, 0.0, 0.1) \end{pmatrix}$$

The matrices  $R$  and  $V$  are easily achieved by, respectively, normalising and weighting the previous matrix  $X$  (the weighting vector of the various criteria is assumed to be  $W = (VH, VH, L, VL)$ ). Their values are as follows:

$$R = \begin{pmatrix} (0.4, 0.6, 0.6) & (0.4, 0.6, 0.7) & (0.4, 0.7, 1.0) & (0.7, 1.0, 1.0) \\ (0.8, 1.1, 1.0) & (0.7, 1.0, 1.0) & (0.4, 0.7, 1.0) & (0.5, 0.7, 1.0) \\ (0.0, 0.2, 0.5) & (0.5, 0.7, 0.8) & (0.4, 0.7, 1.0) & (0.2, 0.5, 0.7) \\ (0.0, 0.1, 0.4) & (0.0, 0.1, 0.4) & (0.4, 0.7, 1.0) & (0.0, 0.2, 0.5) \\ (0.0, 0.0, 0.3) & (0.0, 0.1, 0.4) & (0.1, 0.3, 0.6) & (0.0, 0.0, 0.0) \\ (0.0, 0.0, 0.0) & (0.0, 0.1, 0.2) & (0.1, 0.3, 0.4) & (0.0, 0.0, 0.0) \end{pmatrix}$$

$$V = \begin{pmatrix} (0.3, 0.6, 0.6) & (0.3, 0.6, 0.7) & (0.0, 0.2, 0.5) & (0.0, 0.0, 0.2) \\ (0.6, 1.0, 1.0) & (0.5, 1.0, 1.0) & (0.0, 0.2, 0.5) & (0.0, 0.0, 0.2) \\ (0.0, 0.2, 0.5) & (0.3, 0.7, 0.8) & (0.0, 0.2, 0.5) & (0.0, 0.0, 0.2) \\ (0.0, 0.1, 0.4) & (0.0, 0.1, 0.4) & (0.0, 0.2, 0.5) & (0.0, 0.0, 0.1) \\ (0.0, 0.0, 0.2) & (0.0, 0.1, 0.4) & (0.0, 0.1, 0.3) & (0.0, 0.0, 0.0) \\ (0.0, 0.0, 0.0) & (0.0, 0.1, 0.2) & (0.0, 0.1, 0.2) & (0.0, 0.0, 0.0) \end{pmatrix}$$

The best and worst alternatives are then deduced from the matrix  $V$ :

$$A^+ = ((0.6, 1.0, 1.0), (0.0, 0.1, 0.2), (0.0, 0.2, 0.5), (0.0, 0.0, 0.2)),$$

$$A^- = ((0.0, 0.0, 0.0), (0.5, 1.0, 1.0), (0.0, 0.1, 0.2), (0.0, 0.0, 0.0)).$$

By calculating the distances of each EOL alternative from  $A^+$  and  $A^-$ , for each of the criteria and for the entire set of criteria, we can finally calculate the  $CC_i$  for each criterion, shown in Figure 5, and the final  $CC_i$ , presented in Figure 6.

Figure 6 shows that the remanufacturing performance is better than that of other EOL criteria, with a proximity coefficient of 0.6. This result corresponds to the EOL option commonly applied in the industry. It can be easily understood by looking at Figure 5: the income generated by the sale of the remanufactured car engine has a  $CC$  equal to 1, a result which can be explained by the very good adaptability and module value. Moreover, remanufacturing is the best alternative in terms of compliance with regulations and environmental performance as well, which is the

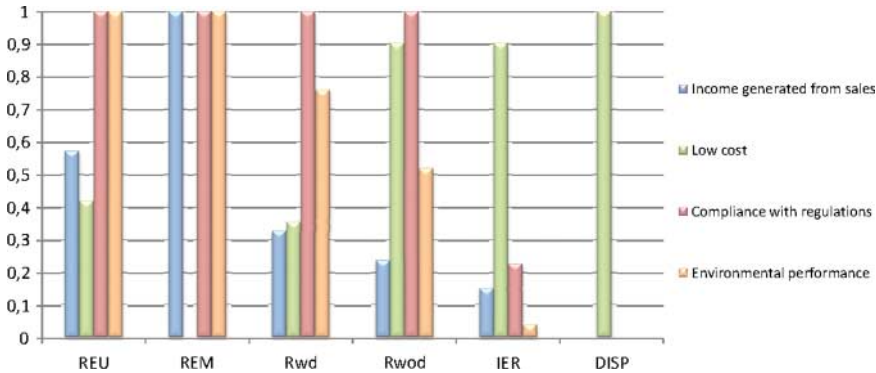


Figure 5. Proximity coefficients by criterion for the engine.

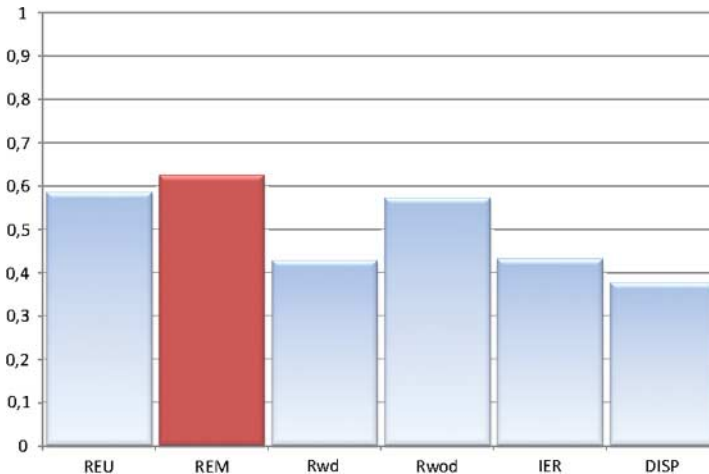


Figure 6. Final proximity coefficients for the engine.

case since they have a  $CC_2$  of 1. However, it is the worst alternative for the criterion ‘treatment cost’. Reuse and Rwd are less enviable than remanufacturing, with their  $CC_i$ s equal to 0.58 and 0.57, respectively, owing to the important benefits which could be generated by reusing the engine (significant income and low treatment cost) and the low cost of Rwd.

Finally, Rwd, incineration, and disposal are not advised because they will generate a small amount of income. Rwd will also be relatively costly since the engine has many parts. Moreover, the environmental performance and the level of compliance with regulations for both incineration and disposal are poor.

Based on this EOL evaluation, the EOL evaluation of other modules composing the future car, the available EOL resources, the feasibility of the design parameters associated with each option, etc., the members of the project team can decide which EOL option is the most appropriate for the new engine. According to the ELSEM, they should choose between REU, REM, and Rwd with a preference for REM.

Once this decision is made, the designer can begin the detailed design stage of the engine, optimising the design attributes depending on the chosen EOL option. For example, if remanufacturing is chosen, the designer will give the product a hierarchical and modular design structure to ensure easy accessibility for inspection, cleaning, and replacement of parts quickly worn-out.

Table 4. Proximity coefficients for various modules and comparison between the advice based on the ELSEM and industry practices.

	RU	RM	Rwd	Rwod	Incineration	Disposal	Best EOL given by the ELSEM	EOL frequently applied in the industry
Clutch	0.57	0.61	0.50	0.58	0.43	0.39	Remanufacturing	Remanufacturing
Exhaust pipe	0.54	0.58	0.78	0.75	0.43	0.38	Rwd	Rwd
Tire	0.56	0.60	0.46	0.57	0.70	0.40	Incineration	Incineration
Battery	0.59	0.62	0.56	0.63	0.47	0.38	Rwod	Rwod
Side mirror	0.55	0.61	0.61	0.65	0.45	0.39	Rwod	Rwod
Car door	0.77	0.58	0.47	0.58	0.49	0.38	Reuse	Reuse

Detachable joints such as snap and screws instead of welded or glued connections will be used to facilitate the dismantling. The parts which must be cleaned or maintained will be indicated for instance by using coloured lubricating points, etc. (Brezet and Hemel 1998).

## 6. Validation of the ELSEM on other car modules

In order to check the validity of the method, we applied it on another six car modules: clutch, exhaust pipe, tire, battery, side mirror, and car door. Table 4 represents the final  $CC_i$  values for each of these and compares the best EOL according to the ELSEM with that commonly applied in the industry. These results show an agreement between the results obtained through our method and through current industry practices for six out of the six modules.

To perform these analysis, we used the weighting vector value  $W = (VH, VH, L, VL)$  in order to reflect the preferences mostly applied in the industry. As a consequence, it was possible to compare the results given by the ELSEM and the common industry practices and realise the validation of the method. However, a company which would want to improve the environmental performance of its product could choose a greater value for the corresponding criterion weight, leading to different results.

## 7. Conclusion and future work

Consideration of EOL treatment during the design of a product has proved to allow the selection of environmentally friendly EOL options and has the potential to generate economic benefit. This paper introduces the ELSEM, a method designed to evaluate these options during the design stage. It is simple to use and quick, since the required information is easy to determine and assess with the help of linguistic variables. However, it is also flexible, because the designer can choose the weights he or she wants to give to each important aspect of the EOL choice, which permits consideration of the company's economic and environmental intentions. Moreover, the ELSEM does not require any particular knowledge of the recovery process on the part of the designer, and it can be implemented at the very beginning of the design phase. The ELSEM is thus more suitable than the DFEOL method, in which a precise EOL must be selected before the beginning of the detailed design stage, and it has a critical advantage over existing EOL evaluation methods, which require very precise product information that is only available at the end of the design phase. Finally, during the conceptual design phase, every module of the product is evaluated separately and has its individual recommendation, which is a more realistic approach than that of other methods, which only provide a unique EOL option for the entire product.

We summarise below the steps that the designer has to follow in order to use the ELSEM.

- Evaluation of the recovery rate and energy recovery rate ( $N_{13}$  and  $N_{14}$ ) imposed for the materials and parts making up the entire product.
- Selection of the criteria weights based on the company's intentions and other situational variables.
- Adjustment of sub-criteria and sub-sub-criteria weights, if required.
- Assessment, for each module, of the other 13 parameters, based on the requested product's specifications, and on the old product's characteristics in a case of redesign.
- Interpretation of results.

More than just helping designers evaluate each EOL scenario, ELSEM guides them in the decision-making process alongside the design team. With the help of this method, the negotiations will result in a final EOL selection for each module, as well as a determination of detailed technical characteristics for a future product with greater eco-efficiency. All this computation is easily supported in Excel or in any similar software which will provide an easy tool for the designer.

What is left to be achieved are the following objectives: (i) apply this method to other products to complete its validation and (ii) create a program to be used by designers directly, in order to implement the required information and obtain the desired results easily and intuitively.

Finally, this method will become more and more useful, because of the real development of new EOL treatment. Today, we know that the limited number of available EOL treatment and costs are the main drivers but it will change in the next future.

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