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ENVIRONMENTAL SELECTION OF MATERIALS FOR PRODUCT END-OF-LIFE

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ABSTRACT

This paper presents research conducted on the environmental selection of materials for product end-of-life. The literature review establishes the state of art in the field of environmental material selection. Several issues are studied: existing environmental material selection methods, parameters and validity of these parameters in terms of their influence on the product's life cycle. Subsequently, we describe the proposed method which allows the designer to select materials during preliminary design. This method is based on fuzzy logic data processing. The product end-of-life personalizes material assessment to select the best materials for the studied product. Fuzzy logic is the core of the proposed method: it allows easier processing of preliminary design data than traditional numeric methods. Then, we present a computer implementation of the method (software ECMSPEOL). The various operations performed by ECMSPEOL are detailed. Case study is presented to verify the method's validity. Results are summarized and discussed. Finally, we conclude this paper by proposing different avenues of potential research.

Keywords: eco design, design engineering, early design phases, rebirth, end-of-life

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1 INTRODUCTION

Science and technology have become indispensable and omnipresent in the products we use daily. These developments allowed the emergence of new modes of consumption of products: mass consumption, fervent consumption, addictive consumption, etc. This situation has multiplied tenfold the unwanted effects of industry on the environment: exhaustion of non-renewable resources, contamination of ground and air, etc. To illustrate: in 2007, more than 372 million electronic products, representing more than 2,25 million tons of waste, were declared to have reached their end of life (within the United States only). Only 18,4 % of this quantity was recycled (EPA, 2007 & 2010). This left more than 300 million products buried in United States waste dumps. New laws on the environment took effect in the mid-1970s. The constraints on the industry became increasingly tougher, obliging them at the same time to modify their habits. In this context, selection of materials was one of first concerns of legislators and by consequence of industrialists. The ban on use of a significant number of toxic and dangerous materials effectively decreased the environmental impact of products. Afterward, analysis of product life cycle stood out as the main tool for selection of materials. This tool is very reliable and effective to select the most environment-friendly materials by calculating the inventory of their life cycle. However, we notice that the methods of selection of materials do not take into account the context of use of the material. This context of use consists of: Product into which the material will be integrated; General environment of the product.

The research work presented in this article concerns the environmental selection of materials in their context of use. It is a systematic approach, where the material is considered not for itself, but in the context of use among the other materials. The question we try to answer is: **does consideration of the context of material use modify the environmental selection of a material?** Materials impact very strongly on the properties and ongoing qualities of a product during its entire service life and its **end of life (EOL)**. They thus present a real opportunity to improve the environmental characteristics of products. The compromise between the advantages and the technical, economical and environmental inconveniences of materials (Karana et al., 2008) becomes increasingly harder to achieve due to the multiplication of factors to be estimated. For example, the number of materials is in constant increase: Ljungberg estimates the number of marketed materials at 100 000 (Ljungberg, 2007).

2 BIBLIOGRAPHIC REVIEW

Literature on eco-design and material selection presented many books and articles, but in this paper a non-exhaustive literature review is done, only the most pertinent for our research are presented. The various methods for environmental selection of materials met in the literature can be divided into three categories: *Rules of selection; Life cycle assessment* and *Multicriteria methods*.

2.1 Rules of selection

Environmental rules of selection are numerous in the literature because they offer adaptability and thus allow the engineer to use them in most of the situations he encounters. We listed sixteen main rules:

- Rule n°1: minimize the toxicity of materials.
- Rule n°2: maximize the materials that require low energy consumption for their production.
- Rule n°3: maximize the materials that come from renewable resources.
- Rule n°4: maximize use of recycled materials.
- Rule n°5: minimize the quantity of materials used in products.
- Rule n°6: maximize use of recyclable materials.
- Rule n°7: maximize use of compatible materials for the recycling.
- Rule n°8: minimize the diversity of the present coloring agents in materials.
- Rule n°9: maximize use of paint and coating on materials for product EOL "Remanufacturing".
- Rule n°10: minimize use of paintings and coating on materials for product EOL "Recycling".
- Rule n°11: minimize use of composite material in a component.
- Rule n°12: maximize the marking of components for the identification of materials.
- Rule n°13: minimize the diversity of materials in the product.
- Rule n°14: optimize the material durability in terms of the end of life.
- Rule n°15: maximize the corrosion resistance of materials.
- Rule n°16: maximize the degradability of materials.

Certain rules have a direct effect on the completeness of the life cycle of the product (rules 1-5), the others have an influence at several precise stages of the life cycle (rules 6-16) .Table 1 summarizes the references and the application field of all the life cycle rules. This type of selection method is perfectly suited for materials selection in preliminary design. These rules of selection also allow the context of the materials selection to be taken into account. However, the engineer's freedom of choice in the process of evaluation is too large to allow a reliable and repeatable evaluation.

Table 1. Domain of validity of the selection rules (see reference list for numbers in square brackets)

Rule	References	Stages of the life cycle		
		Manufacturing	Using	EOL
1	[4-12]	X	X	X
2	[7-8, 10-12]	X		
3	[8, 11, 13]	X		
4	[4, 8, 12]	X		
5	[4, 8, 12]	X	X	X
6	[4-9, 11-14]			X
7	[4-9, 11-14]			X
8	[7, 10]			X
9	[9]			X
10	[7, 8]			X
11	[7, 8]			X
12	[4, 7-8, 10, 13]		X	X
13	[4, 7-8, 10, 12-13, 15]	X	X	X
14	[7, 9]			X
15	[4, 8-9]		X	X
16	[4-6, 8, 13]			X

2.2 Life Cycle Assessment (LCA)

Life Cycle Assessment is a method which was imperative in the '90s as the reference in the evaluation of products and their environmental impact. Stemming from the thought life cycle, it allows evaluation of the impact generated throughout the product life cycle and quantification of the environmental footprint for a product and its associated life cycle. Several databases were created to store the results of different LCAs to facilitate analysis of their distribution including; Eco-indicators 95 & 99 (Goedkoop, 1995 & 1999); Impact 2002+ (Jolliet et al., 2003) and Eco'Invent (Frischknecht et al., 2005). Life cycle assessment is a reliable and internationally recognized tool. This widespread recognition was partly due to standardization achieved through use of ISO. However, to achieve the exact quantification offered by LCA, it is important to have a significant amount of precise data, which only becomes available during detailed design (Pahl and Beitz, 2007) and, last year, a study was performed with the aim to identify the best among existing characterization models and provide recommendations to the LCA practitioner (Hauschild et al., 2012). The precision of the information required makes it incompatible with the preliminary design phase. But, also LCA, for an engineer, is not that effective tool for material selection (Reap et al., 2008).

2.3 Multicriteria methods

Multicriteria methods are a third type of methods found in the literature for environmental materials selection. There are several types including: graphic, analytic or optimization. They allow the environmental criterion of materials and technical or economic criteria to be taken into account. Environmental graphic methods are derived from the diagrams of Ashby (2012). They provide quick accessibility to the result. The precision of the evaluation is however weaker than the other method types presented below. The ranking must be generated by the user in this type of method. Weaver et al., (1996) and Holloway (1998) present an application of this method. Environmental analytical methods are widely used. These methods allow materials to be classified according to the parameters chosen by the engineer. Huang et al. (2006) uses a method derived from TOPSIS (Shanian and Savadogo, 2006) for material selection. Chan and Tong (2007) used the relational Grey analysis. Ribeiro et al. (2008) and Guidice et al. (2005) present methods using the results of eco-indicators'99.

2.4 Problem in preliminary design

As confirmed by Pahl and Beitz (2007), preliminary design has no formalized method of material selection. The engineer can only use the rules of selection. Yet these have several flaws: the efficiency of the environmental selection of materials depends mainly on the design engineer or on design teams that use them. And they are not based on a well defined and reliable process of selection. These factors can cause fatal changes in material selection. The problem of selection of materials from an environmental point of view during preliminary design receives little consideration in the literature, contrary to technical selection, which is treated by some authors. For this reason, Thurston advocates using fuzzy logic (Thurston and Locascio, 1994). Technical methods of material selection incorporating fuzzy logic are presented in the literature. Wang presents a method of material selection for a cutting tool (Wang and Chang, 1995). The selection is based on the evaluation of seven properties of materials: machinability, resistance to water exposure, resistance to softening at high temperature, hardness, security during the tempering, stability of material properties, and the cost of materials. The method requires a level-weighting for every property by the engineer. After inputting information quantifying the values of certain material properties, the method generates a ranking of the various materials. Chen (1997) suggested a lighter method to reduce the number of calculations. He illustrated this method for the selection of materials for cutting tool. Recently, Khabbaz et al. (2009) presented a method of material selection based on qualitative and quantitative properties. His method requires the definition of inferences rules, what obliges the design engineer to consider functions of membership with the possible minimum of fuzzy subsets to avoid excessive complication when defining inference rules. We also note the work of Liao (1996) who presented a framework of evaluation by fuzzy logic to help decision-making in material selection. The general method is based on an extension of the principle of fuzzy logic (Zadeh, 1975), which allows simplifying the material selection but requires more significant automation of data processing.

3 METHODOLOGICAL APPROACH FOR MATERIALS SELECTION

3.1 Framework of the method

The proposed method allows selection of environmentally friendly materials for product EOL during preliminary design. Parameters presented in the literature are reviewed to choose materials in relation to the various alternatives for EOL. The evaluation is thus personalized for every end of life. The EOL alternatives that are taken into account are those of: ELDA (Rose et al., 2000), EOL1: re-use, EOL2: service, EOL3: Remanufacture, EOL4 Recycle with disassembly, EOL5 Recycle without disassembly, and EOL6: Disposal. Other methods were set aside for the following reasons: PEOLSP is a simplification of ELDA and allows only the planning of three alternatives; EOL: recovery, remanufacturing and re-use (Xing et al., 2003). Hulla based his method on genetic algorithms to choose the best product EOL (Hula et al., 2003). Genetic algorithms are able to assure a near-optimal choice but their implementation demands more resources and a large quantity of data for learning purposes. This affects the workability of the selection method. The method we have chosen to develop is based on the context consideration for materials using:

1. The product that incorporates the selected materials;
2. The environment of the materials use and thus the product use.

Indeed, the product has an influence on the materials selected, it has a defined architecture, very precise properties and materials can be already attributed to some of these components. The environment of the product also possesses several properties which can modify the characteristics of the product and materials: aggressiveness, neutrality, severity, etc. The method must be able to use the available data during preliminary design: which can be vague and indistinct (Ashby, 2012). We therefore chose to treat the data using fuzzy logic as Thurston recommended for the evaluation of materials during preliminary design (Thurston and Locascio, 1994). The method proposed in this paper is one of the environmental selections. For the technical or economical purpose, the design engineer can indicate if a component must be necessarily manufactured with a selected material. For example, spring materials must be made of steel for many products to store enough energy and to maintain their functionality, but for some products plastic springs would be possible. The engineer is free to choose the best materials while satisfying his constraints.

3.2 Fuzzy Logic

Choice of fuzzy logic is justified by rule-based approach using precise, imprecise or vague language to qualify a rule application, for instance materials uniformity in a component (Figure 2). Zadeh (1965) defined a fuzzy subset $\tilde{A}$ of X by a function of membership $f_{\tilde{A}}$ which connects every element x of X with a real number in the interval [0,1]. The value of the function $f_{\tilde{A}}$ represents the membership of x in $\tilde{A}$. The membership functions of the fuzzy subsets can have several forms: triangular, square, rectangular, trapezoidal, comb. The proposed method in this paper is based on the frame of fuzzy evaluation multicriterion of Liao (1996). The frame of evaluation is based on the principle of extension which was presented by Zadeh (1965) and completed by the theory of fuzzy arithmetic of Kaufmann and Gupta (1985). The evaluation of materials developed in this paper requires progress through the following three stages represented in Figure 1: Calculation of the index of EOL-ability of every property j for every material i: Sij, Calculation of the index of global EOL-ability of every material: Si, and Defuzzification of the index of EOL-ability Si.

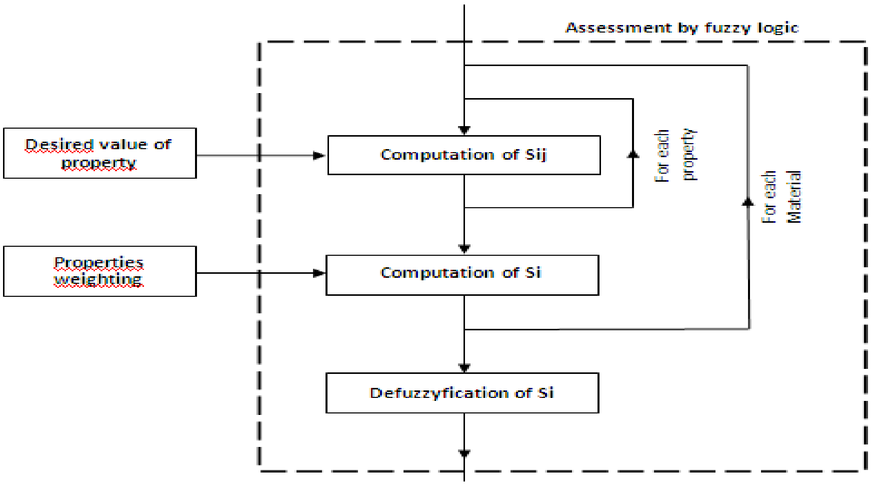

Figure 1. Chronology of the various stages for evaluation of EOL-ability materials

Detailed description of the various calculation operations is presented in the following paragraph. Let:

- $\tilde{S}_{ij}$ the index of the property j of materials i;
- $\widetilde{AP}_{ij}$ the value of the property j of material i adjusted with regard to the optimal value;
- $\tilde{D}_j = (da_j, db_j, dc_j, dd_j)$, the optimal value of the property;
- $\tilde{P}_{ij} = (pa_{ij}, pb_{ij}, pc_{ij}, pd_{ij})$, the value of the property j of the material i,
- $\tilde{S}_i$, the global index of EOL-ability of the material i;
- $\tilde{w}_j$, weight of the property j, with 1 < j < n and n the estimated number of material properties.
- $\oplus \ominus \otimes \oslash$ are respectively symbol used for addition, subtraction, multiplication and division.

3.2.1 Calculation of the index of EOL-ability of the properties

If the optimal value corresponds to the highest (strongest) possible value of the materials property:

$$\tilde{S}_{ij} = (\widetilde{AP}_{ij} \ominus \tilde{D}_j) \oslash \tilde{D}_j \quad (1)$$

$$\widetilde{AP}_{ij} = nd_j \oplus (pa_{ij}, pb_{ij}, pc_{ij}, pd_{ij}) \quad (2)$$

$$nd_j = |min(pa_{ij}) - dd_j| \quad (3)$$

If the optimal value corresponds to the weakest possible value of the materials property:

$$\tilde{S}_{ij} = (\tilde{D}_j \ominus \widetilde{AP}_{ij}) \oslash \tilde{D}_j \quad (4)$$

$$\widetilde{AP}_{ij} = (pa_{ij}, pb_{ij}, pc_{ij}, pd_{ij}) \ominus nd_j \quad (5)$$

$$nd_j = |da_j - max(pd_{ij})| \quad (6)$$

3.2.2 Calculation of the index of global EOL-ability Si

The EOL-ability index of material i is equal to:

$$\tilde{S}_i = \frac{1}{n} \cdot \otimes\left[\left(\tilde{S}_{i1} \otimes \widetilde{w}_1\right) \oplus \left(\tilde{S}_{i2} \otimes \widetilde{w}_2\right) \oplus (\dots) \oplus \left(\tilde{S}_{in} \otimes \widetilde{w}_n\right)\right] \quad (7)$$

For $\tilde{S}_i$ the form is: $\tilde{S}_i = (sa_i, sb_i, sc_i, sd_i)$

3.2.3 Defuzzification of the global index of EOL-ability Si

According to Liao, the final mark of a material is directly calculable by the following equation:

$$I_T^{\mu}\left(\tilde{S}_i\right) = \frac{1}{2}\left[\mu(sc_i + sd_i) + (1-\mu)(sa_i + sb_i)\right] \quad (8)$$

- $I_T^{\mu}\left(\tilde{S}_i\right)$, the final mark of EOL-ability of the material;
- μ, the coefficient of optimism, included in the interval [0, 1].

Table 2. Various properties and their characteristics

Properties	Relative selection rules	Validity domain						Fuzzy number	Data sources
		EOL 1	EOL 2	EOL 3	EOL 4	EOL 5	EOL 6		
Corrosion Resistance	15	X	X	X				Triangle	Handbook
Recyclability	6				X	X		Singletown	Gouvernment Data
Degradability	16						X	Triangle	Handbook
Materials uniformity in component	8-11			X	X	X		Triangle	Designer assessment
Diversity of materials	13				X	X		Singletown	Product study
Materials marking	12	X	X	X	X			Triangle	Designer assessment
Recycling compatibility	7				X	X		Triangle	Paper
Sorting capacity	7					X		Triangle	Gouvernment Data
Durability	14	X	X	X				Triangle	Designer assessment

4 NEW PROPOSED METHOD

The new method is based on the framework presented in the previous section. Here we describe the parameters that are taken into account, their origins and the relations between the design engineer, the method and the materials. Nine properties are taken into account to estimate and select materials: corrosion resistance, recyclability, degradability, uniformity of the material in the component, diversity of materials in the product, the marking of materials on components, compatibility of recycling, capacity of sorting and durability. These various properties are based on rules of environmental selection. Table 2 presents the various properties and their characteristics.

As the 9 properties are studied, one can distinguish two types of data: properties which have known constant values for any product and the properties which must be estimated by the engineer because they depend on materials, on product and on environment. The first type requires storing the values of the various materials to avoid having to find them each time environmental selection of materials is required. The second type requires the expertise and analysis of the design engineer or the software to choose the value of the material property (uniformity of the material, diversity, marking of components, durability). To assure a good repeatability of evaluations it is necessary to guide the engineer in this evaluation. Every property can be defined by means of a table of fuzzy evaluation. For example, Table 3 shows values for the property of materials uniformity in the component. The membership function of this property is illustrated in Figure 2. The evaluation of materials is done by following the operations described in paragraph 3.2. After ranking of materials, the engineer can choose as he wishes. Our method supplies information to the engineer about materials with regard to their environmental impact at the end of life. The adaptation of the method to the technical and economic constraints of the designer is real.

The method presented here was implemented in a software package programmed in C ++: Environmental and Contextual Materials Selector for Product End-Of-Life (ECMSPEOL). The software effectively automates the operations of data search and calculations. We use an external file to store the various values of the known properties of materials (corrosion resistance, recyclability, degradability, compatibility of recycling, capacity of sorting) and to store the data necessary for materials evaluation by fuzzy logic (weighting of the properties according to the end of life, optimal values for every property according to the end of life).

Table 3. Evaluation table for materials uniformity in a component

Linguistic value	Description	Numerical value
Very low	Material is used with insert made up another material and by paint, by covers not compatible with the end of life	[0 ; 0,25[
Low	Material is used with insert made up another material not compatible with the end of life.	[0 ; 0,5[
Medium	Material is used with several types of covers or paints not compatible with the end of life.	[0,25 ; 0,75[
High	Material is used with a cover or one paints not compatible with the end of life.	[0,5 ; 1[
Very high	Material is used alone, without inserts, paints, or covers not compatible with the end of life.	[0,75 ; 1]

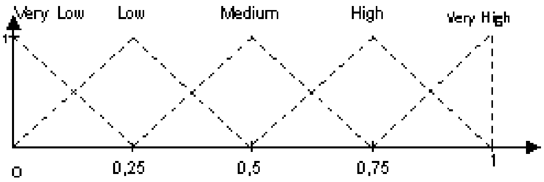

Figure 2. Materials uniformity in component

5 CASE STUDY

5.1 Studied case and product

ECMSPEOL was applied on several industrial products: a simple monostable jack (6 parts), a door closer (29 parts), etc. In this presented case study we choose a short example to show that the created method answers the need: supply information to help the engineer in the selection of materials for product end of life. Software reaction to a change of product EOL is tested. To be sure that we accurately measure the influence of end of life, the initial conditions are frozen: weighting of the properties, targeted value of properties, the real value of materials properties. The studied product is a monostable jack; composed of only 6 different components. This product was already used by Boothroyd (1983) to illustrate his design-for-assembly method. Figure 3 and Table 4 present a good description of this product. For this product, the initial conditions are defined: if components have a technical obligation to be filled by a certain material (standard components), this material is allocated to the component. Furthermore, the components that undergo significant requests are noted. For each study, the following information is recorded: ranking of materials before final selection of component material; final material choice of the engineer for the component. For the monostable jack, material is directly assigned for two components because they must have the specified materials to respect the technical constraints of the product.

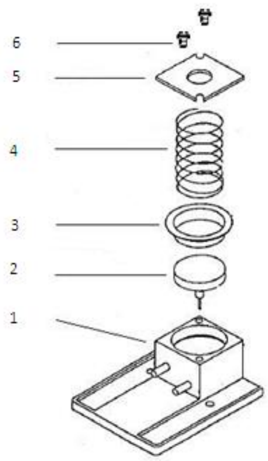

Figure 3. Monostable jack

Table 4. Nomenclature of monostable jack

Number	Component name	Attributed material
1	Body	Steel
2	Piston	Aluminium
3	Stopper	PA
4	Spring	Steel
5	Cover	Steel
6	Screw	Steel

These are the stopper and the spring, which are respectively made from polyamide (PA) and steel. Six materials are estimated in our case study: steel, bronze, aluminum, PE, PA and PVC. Furthermore, three parameters must be informed by the design engineer during the process of selection: the marking of components (fixed to "Medium"); the durability of the material in the components and the uniformity of the material in components. The last two parameters are dependent on the component and on the material. The following are the input data for ECMSPEOL: durability and uniformity values.

5.2 Results

The case studies allows us to quantify two behaviors: the influence of end of life on the ranking supplied by ECMSPEOL and the influence of the method on the choice of materials compared with the existing product by considering that the material classified in first position is attributed to the component. One objective of the case studies is to compare the influence of end of life on material selection at the component level. For this purpose, we study the ranking of materials supplied by ECMSPEOL for every component and for every end of life. We calculate the rankings obtained by ECMSPEOL and make comparisons between a reference ranking (re-use) and rankings obtained for other EOL alternatives. If a material position is increasing or decreasing compared with the reference ranking, a change is recorded. Ranking divergence is calculated by Equation 9. A change is recorded when the position of a material in the ranking is modified compared with the reference ranking. Using this approach, we can quantify the influence of end of life on the ranking of each material. Results for the monostable jack are showed in Figure 4.

$$\frac{Number\ of\ changes}{Number\ of\ estimated\ materials} \tag{9}$$

To estimate the real contribution of the method on the choice of materials for a product, we consider that the engineer chooses the material classified in the first position by ECMSPEOL. We thus compare the allocation of materials generated by ECMSPEOL for every end of life to the original material selection when the product was first designed (the nomenclature is available in the product description, Table 4). Attribution divergence in allocation of materials is calculated by Equation 10.

$$\frac{Change\ number}{Component\ number} \tag{10}$$

Results are synthesized in Tables. By this means, we can compare the various differences of materials allocation according to the product EOL. A change is recorded when the material of a component attributed by ECMSPEOL is not the same as that already designed into the product (Table 4).

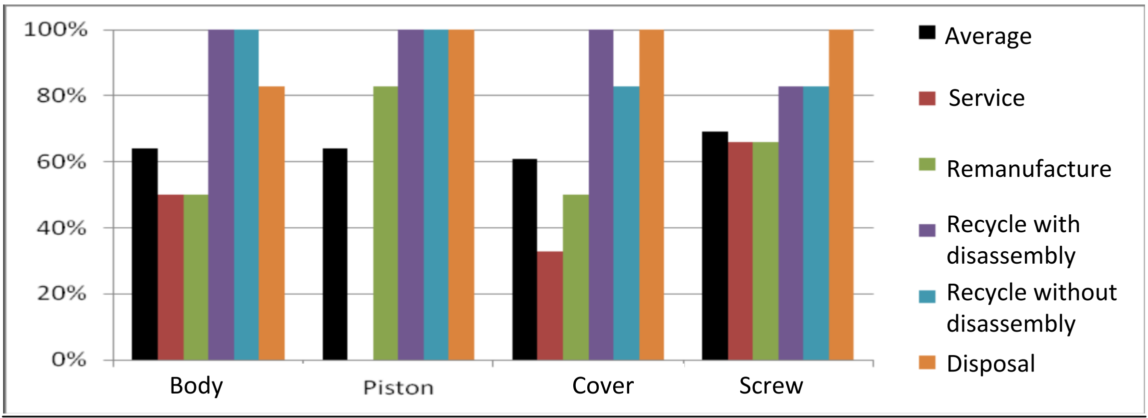

Figure 4. Ranking evolution of materials according to end of life for every component

5.2.1 Discussions

The case study was written to show the usefulness of a complete approach for a real case. It allows us to confirm the influence of the end of life on the ranking produced by ECMSPEOL. The difference in rankings obtained compared with the reference (re-use) is between 33 and 100 % on the studied components. Also, the calculation of the divergence average of rankings for each component confirms our observation: this divergence average is between 61 and 69 %. It seems certain that the product end of life influences materials ranking as generated by ECMSPEOL. Also, the ranking evolves depending on which component is treated. This leads us to conclude that the proposed method effectively takes into account product specificity and its components during materials selection. Concerning the influence of EOL on the attribution of materials, we note that the percent divergence for EOL: re-use, services and remanufacturing are of the same order for product (greater than or equal to 50 %). The result is the same for three alternative EOL (recycling with and without dismantling and disposal). The average percentage of material change for the jack is 39%. It should be noted that the EOL design criteria for the existing jack was recycling.

5.2.2 Adaptability of ECMSPEOL to real conditions

The graphic interface of ECMSPEOL facilitates use of the software. The engineer has only three types of information to enter: textual Information; level choice of parameters and choice of material. Textual information is minimal: product name, the number of components and the name of each component. The first two types of information do not require a significant amount of input data. The third type is entered by the design engineer into ECMSPEOL and requires more attention. Indeed, depending on the product EOL the number of parameters that must be entered is different.

6 CONCLUSION

This paper presents a new method of environmental selection of materials that takes into account the product end of life. After studying the available literature, we describe the framework and functionality of the proposed method, as well as its implementation and a case study. The method allows selection of materials for all end of life alternatives and for each component incorporated into the product as a function of the characteristics of the components and the designated product end of life. In addition, the method is adapted to technical and economic constraints by leaving freedom of choice to the design engineer. The case study shows that the method actually generates a surplus of information compared with existing methods.

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