A Fuzzy Logic-Based Approach for Handling Uncertain EOL Options in Product Design Stage

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Abstract

Today, companies must consider sustainability in addition to their own primary requirements (e.g., cost saving) and to outside constraints (e.g., environmental protection). End-of-life (EOL) option has emerged as a critical factor in sustainability. However, determining EOL options at the product design stage is complicated. For example, design-stage EOL options for retired bicycle components are various, and change with geographic location. Therefore, fixed EOL options in the design stage may not always be appropriate; thus, uncertain EOL options should be considered. Limited research exists discussing uncertainty in EOL options at the design stage, and this fact motivates this investigation. In our proposed approach, fuzzy logic is employed to handle uncertainty. The probability of each EOL option is determined by aggregating fuzzy set operations and left-right hand fuzzy rank method. An expected value is derived to represent sustainability value of EOL options. Coffee maker is used as a case study to illustrate the methodology.

Key Words: End-of-Life, Uncertainty, Fuzzy Logic, Modular Product Design.

1. Introduction

Product design is a creative process that harmonizes the needs of customers, the strategy requirements of companies, and the environmental constraints of government regulating agencies. Four stages comprise product design: problem definition, conceptual design, preliminary design and detail design; and all design requirements should be fulfilled through all four stages. Since approximately 70\% of product cost \cite{1} and 80\% of product quality \cite{2} are determined during the design stage of product planning, product design is a critical concern for developers.

Modularity is a methodology used to reduce complexity by breaking a complicated whole into several relatively simple parts. Modular product design (MPD) involves applying the module concept to product design to increase the efficiency and effectiveness of the design process. Many aspects of MPD methods benefit product design, such as easy assembly, low supply chain cost and mass customization. Therefore, applying an MPD method during the design stage has become a trend.

Given increasing environmental and social concerns, sustainability management, especially in product life cycle management, has gained a great deal of attention. Product life cycle management involves a product’s entire life and end-of-life (EOL) options. EOL options create lots of energy waste, environment pollution, and cost during the entire product life cycle; accordingly, research efforts have increasingly tended to focus on this area and take product EOL options into account during the design stage. The aggregation of MPD and life cycle management in the design stage is currently popular, and many researchers have developed new product design methodologies. However, both entire life cycle-based and EOL-based methods hold a critical assumption: EOL options have typically been determined before developing methods, which means that EOL options are fixed and treated as constant inputs [e.g., 3, 4, 5, 6, 7, 8, 9]. There is almost no research considering uncertainty in EOL options and MPD simultaneously. Therefore, the purpose of this research is to develop an approach to handle uncertainty in EOL options, and show its implementation within MPD at the design stage.
2. Literature Review

Demographic growth, combined with increasing product requirements, generates an extreme amount of retired products each year. Due to the concerns of environmental pollution, EU has formulated new regulations based on the principle of extended producer responsibility [10], requiring the manufacturer to be more responsible for the life cycle of their products, especially the EOL phase. In response to this requirement, many researchers have conducted investigations on the EOL phase. In this section, we will review several product EOL option definitions and selection methods.


As per the summarized classifications above, there are eight unique EOL option definitions, and they cover all possible handling methods for retired products. The definition in CRR [18] is complete and detailed, not only because it is the most recent from an organization of authority, but also this set was built on the former works and provided advantages and disadvantages for each EOL option. However, CRR [18]’s definition is based only on product characteristics’ summarization and lacks numerical analysis; therefore, it is good for qualitative analysis but not so for quantitative evaluation. Although Marco et al. [11]’s work is two decades old, their work used formulas offered by Lee et al. [19], and therefore is appropriate in that it could be used as quantitative analysis. Hence, due to the EOL options’ quantitative evaluation consideration, we adopt Marco et al. [11]’s seven EOL options definition.

When the definition of EOL options is done, it is reasonable to select EOL options for each of product components in the next step. In this section, we will review former work of EOL options selection. Several researchers provided evaluation criteria for EOL option selection. Keeney and Raiffa [20] provided five rules for criteria selection:

- Completeness: all important points of view are covered;
- Non-redundancy: two or more criteria should not measure the same thing;
- Minimality: the dimension of the problem should be kept to a minimum;
- Operationality: the set of criteria can be measured and meaningfully used in the analysis;
- Discrimination ability: the criteria should discriminate between EOL alternatives: if all EOL alternatives have the same value on certain criteria then these criteria will not play roles in comparison of the EOL alternatives.

Lee et al. [19] assigned seven EOL options to components based on materials, such as metal without other alloy is recommended to primary recycling, alloy is recommended for secondary recycling, ceramic is recommended for secondary recycling or landfill, etc. Rose [15] summarized five groups of evaluation characteristics. The details are shown in Table 1.

Bufardi et al. [21] described three criteria: direction of preference, scale of measurement and unit of measurement. Li et al. [6] provided five criteria for EOL evaluation: component classification, life cycle spanning, recycling methods, material compatibility, special handling and material classification.

From the selection criteria literature review, it is evident that EOL options determination needs to consider several criteria. The criteria should consider all possible impacts of components completely, which should cover influence
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of component inside, such as material; component itself; among components but inside of product; and outside of product. However, none of the published papers involves all these four aspects; therefore, we will re-consider EOL determination criteria in our newly developed modular design method.

Table 1 ELDA EOL Evaluation Characteristics [15]

<table>
<thead>
<tr>
<th>Factors</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>External</td>
<td>Cycle design; wear-out life; technology cycle; technology research focus; company design focus; reason for obsolescence; functional complexity</td>
</tr>
<tr>
<td>Material</td>
<td>Penalties associated with recycling; cleanliness of the product; number of materials; recycling value drivers; EOL path categorization</td>
</tr>
<tr>
<td>Disassembly</td>
<td>Disassembly time; number of connectors; number of modules; number of parts; disassembly time/step</td>
</tr>
<tr>
<td>Disassembly Continued</td>
<td>Disassembly motivation; overall access to components</td>
</tr>
<tr>
<td>Inverse Supply Chain</td>
<td>Responsibility for recycling costs; responsibility for collection and transportation costs; recycling drop off centers; trade in possibilities; beneficiaries of recycling</td>
</tr>
</tbody>
</table>

3. Methodology

As a result of the increasing population growth and increasing product requirements, a huge quantity of retired products has been generated. These have been found to cause sustainability problems, such as environmental pollution, economic waste and, adverse effects on human health. Due to the significance of these retired products, researchers have investigated how to determine and select EOL options to address and meet practical requirements. One widely used method involves applying multi-criteria decision making in EOL selection [e.g., 6, 17, 21]. This stream of research adopts MCDM methods to balance several design criteria and reaches a compromising EOL alternative; the advantage of this method is that it can take many design objectives into account. Another set of methods applies pure mathematical algorithms to select optimal EOL alternatives [22]. However, many qualitative and quantitative methods for determining an appropriate EOL option suffer from vagueness due to either the use of incomplete data sets or the unavailability of data expressed as exact numbers [23]. Therefore, linguistic assessment is recommended instead of a methodology requiring exact data [24]. Fuzzy numbers and membership functions are widely used in linguistic expression. In order to overcome the ambiguity in linguistic assessment, triangular and trapezoidal membership functions can be developed [25]. These membership functions are used to transform the linguistic variables into fuzzy numbers [26]. We use Fuzzy logic to represent EOL options in the proposed methodology.

Before representing EOL options via fuzzy logic, we have to identify EOL options. In literature review section, we identified several EOL options definition methods. For this paper, we opt to adopt Marco et al. [11]’s definition because we can quantify the EOL options based on the developed calculation formula by Lee et al. [19]. The EOL option definitions and corresponding cost calculation formula are listed in Table 2.

En route to defining EOL options in fuzzy representations, one needs to determine fuzzy characteristics. There are several fuzzy characteristics available [6, 15, 21]. Although these may relate to corresponding EOL definitions, they may not work with our definition. Therefore, we need to determine new fuzzy characteristics for our EOL options. It is evident that we need four streams of characteristics to evaluate EOL options. One stream must demonstrate the characteristics relevant to inside of the component, which are material focused (e.g., how does a hazardous material affect EOL option selection?) One stream must describe the characteristics of the component itself (e.g., how does component’s remaining life cycle affect EOL option selection?) One stream should discuss the relationship between components in the product (e.g., how does component disassembly affect EOL option selection?) Finally, there should be another stream, which takes external impacts into account (e.g., how does customer preference affect EOL option selection?). Table 3 shows all EOL characteristics.

It is difficult to specify an EOL option for each component in the design stage. However, we can find all possible EOL options information for each component easily, such as cost, energy consumption for each EOL options regarding each component. Therefore, one of the possible ways to deal with uncertainty in EOL options is using expected value. Expected value is calculated by multiplication of each EOL options information and corresponding
weights or possibility. Hence, the difficulty is transferred from uncertainty in EOL options to uncertainty in EOL options’ weights.

Table 2 EOL Option Definition and Corresponding Cost Formula

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse</td>
<td>Using in the same (direct reuse) or another (indirect reuse) application.</td>
<td>Cost of component – Miscellaneous Cost</td>
</tr>
<tr>
<td>Remanufacture</td>
<td>Retaining serviceable parts, refurbishing usable parts; replacing identical or reworked components from obsolete products.</td>
<td>Cost of component - Miscellaneous cost</td>
</tr>
<tr>
<td>Primary Recycle</td>
<td>Reprocessing a material into a form that can be used in the same or another “high” value product.</td>
<td>(Weight of component * Market value of material) - Miscellaneous cost</td>
</tr>
<tr>
<td>Secondary Recycle</td>
<td>Reprocessing a material into a “low” value product.</td>
<td>(Weight of component * Scrap value of material) - Miscellaneous cost</td>
</tr>
<tr>
<td>Incinerated</td>
<td>Incinerating a material to produce heat and electricity.</td>
<td>(Energy produced * Unit cost of energy) - Miscellaneous cost</td>
</tr>
<tr>
<td>Landfills</td>
<td>Landfilling waste products with no intrinsic value.</td>
<td>-(Weight of component * Cost of landfill) - Miscellaneous cost</td>
</tr>
<tr>
<td>Special Handling</td>
<td>Mandatory for all toxic or hazardous materials.</td>
<td>-(Weight of component * Cost of special handling) - Miscellaneous cost</td>
</tr>
</tbody>
</table>

Miscellaneous Cost = Collection Cost + Processing Cost

Table 3 EOL Characteristics

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component Quality</td>
<td>Remaining life cycle; repair complexity; technical obsolescence; aesthetic obsolescence</td>
</tr>
<tr>
<td>Functional/Module Complexity</td>
<td>Accessibility; disassembly force; positioning; tool requirement; material handling; fastening</td>
</tr>
<tr>
<td>Material</td>
<td>Material properties; material compatibility; hazardous materials; federal/local regulations</td>
</tr>
<tr>
<td>External</td>
<td>Market requirement; customer preference; succedaneum price</td>
</tr>
</tbody>
</table>

To capture the uncertainties associated with EOL options’ weights, we could get through evaluation of EOL characteristics by fuzzy logic. Fuzzy set theory provides a technical basis to evaluate and derive an approximate conclusion [27]. These fuzzy variables are also known as linguistic variables in fuzzy set theory [28]. We measure the EOL characteristics via a rating scale, and the ratings are measured at five levels: “very low”, “low”, “moderate”, “high” and “very high”. Table 5 shows the linguistic variables and their related fuzzy levels. Fig.1 shows EOL options’ weights fuzzification method flow chart.

The uncertainties of fuzzy numbers are evaluated using membership functions. Widely used membership functions include triangular and trapezoidal membership functions [25]. The advantages of triangular membership functions are their simplicity and the fact that they are commonly used in product development analysis [29, 30].

We evaluate every fuzzy characteristic and their weights in order to get each EOL option’s score. Therefore, the fuzzy input is a fuzzy characteristic evaluation with corresponding weights; fuzzy output is a score of EOL option. We normalize the EOL option scores and get weights of EOL options. Triangular membership function is used for both inputs and output. The linguistic variable levels and corresponding fuzzy sets are shown in Table 4.

For each component, we can assess the fuzzy evaluation for every EOL sub-characteristic’s linguistic variable in Table 4 with respect to EOL options (i.e., reuse, remanufacture, etc.) by answering the corresponding question. For example, for component A, the fuzzy characteristic is repair complexity, and EOL option is reuse; the corresponding
question is “Which fuzzy level is appropriate to evaluate component A’s repair complexity with respect to EOL option reuse?” We answer this question as follows: if repairing the component A is complex, then it is not good for reuse; thus, the fuzzy level is “very low” and corresponding fuzzy set is (0, 1.5, 3). Using this method, we can determine all fuzzy characteristic evaluations for every component with respect to all EOL options.

To integrate all fuzzy characteristic evaluations for each component with respect to each sustainability measure, weights of each fuzzy characteristic should be identified based on product requirements. The weight hierarchy of fuzzy characteristics is presented in Figure 2. For example, \( w_q \) is used to show the weight of component quality, and \( w_{11} \) is used to represent the weight of remaining life cycle. Weight is represented using a fuzzy set.
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We use fuzzy operations [33] to aggregate fuzzy sets. Eq. 1 is used to calculate EOL option fuzzy set. Eq. 2 shows calculation of EOL characteristic fuzzy rating score. The calculation is based on fuzzy number operations.

\[
E_{C_i} = \frac{\sum_j E_{C_ij} \otimes w_{ij}}{\sum_j w_{ij}}
\]

\[
E_{C_{ij}} = \frac{\sum_k E_{C_{ijk}} \otimes w_{ijk}}{\sum_k w_{ijk}}
\]

where:
- \(EC_i\) is EOL characteristic fuzzy rating score and fuzzy,
- \(EC_{ij}\) is EOL sub-characteristic fuzzy rating score,
- \(w_i\) is importance weight for \(EC_i\),
- \(w_{ij}\) is importance weight for \(EC_{ij}\),
- \(w_{ijk}\) is importance weight for \(EC_{ijk}\).

If we have more information, such as function/module complexity, material and external, then we could derive the score of EOL option, to be also shown as a fuzzy number. We need a real number for EOL option score, and fuzzy number is not practical. Generally, transferring from fuzzy number to real number uses “if-then” rules. However, adoption of this method requires a high number of “if-then” rules. We have seventeen EOL characteristics, and each of them has five fuzzy levels; therefore, the number of “if-then” rules is \(5^{17}\), which is impractical to develop. Hence, we adopt fuzzy ranking, which could approximate fuzzy set into a single number. Several methods are developed to rank fuzzy sets [31, 32]. Here, the ranking of fuzzy numbers is based on Chen and Hwang’s left-right fuzzy method. The method defuzzifies the fuzzy set by aggregating the minimum number and the maximum number in the fuzzy set.

4. Case Study

We use a coffee maker to show the implementation of this methodology. Coffee maker includes eleven components, and each component interacts with other components in the product in order to generate primary product functions. Each component has its own attributes, such as material, cost, energy, etc. We estimate and evaluate the EOL options by the expected value approach. Expected value of EOL options is derived from summation of multiplication of each EOL options’ weights and values. We get the weights via fuzzy logic based on seventeen characteristics shown in Fig. 3, and calculate each EOL option’s values from websites, such as rivcowm.org, alibaba.com, earthworksrecycling.com, recycleinme.com, recycle.net. In order to calculate the cost value, we need further assumptions:

- No collection cost. Manufacturers don’t need to pay for collecting retired coffee makers back.
- Processing cost for reuse, remanufacture and recycle are 20%, 40%, 60% of manufacturing cost.
- The retired coffee maker is not damaged, which means there is no weight loss for each component.
- No incineration for copper, glass and steel.

We get price data from the above websites and derive EOL option costs for components as shown in Table 5.

<table>
<thead>
<tr>
<th>Component</th>
<th>Reuse ($)</th>
<th>Remanufacture ($)</th>
<th>Primary Recycle ($)</th>
<th>Secondary Recycle ($)</th>
<th>Incinerate ($)</th>
<th>Landfill ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Basket</td>
<td>0.752</td>
<td>0.564</td>
<td>-0.49136</td>
<td>-0.49817</td>
<td>0.056750</td>
<td>-0.60325</td>
</tr>
<tr>
<td>Filter Basket Holder</td>
<td>0.752</td>
<td>0.564</td>
<td>-0.48264</td>
<td>-0.49027</td>
<td>0.063560</td>
<td>-0.60364</td>
</tr>
<tr>
<td>Lid</td>
<td>0.512</td>
<td>0.384</td>
<td>-0.34187</td>
<td>-0.34582</td>
<td>0.032915</td>
<td>-0.40189</td>
</tr>
<tr>
<td>Warming Plate</td>
<td>1.472</td>
<td>1.104</td>
<td>-1.04654</td>
<td>-1.04795</td>
<td>0</td>
<td>-1.00291</td>
</tr>
<tr>
<td>Main Housing</td>
<td>1.056</td>
<td>0.792</td>
<td>0.226413</td>
<td>0.130937</td>
<td>0.795635</td>
<td>-0.84557</td>
</tr>
<tr>
<td>Heating Pipe</td>
<td>2.560</td>
<td>1.920</td>
<td>-1.71479</td>
<td>-1.71982</td>
<td>0</td>
<td>-1.61040</td>
</tr>
<tr>
<td>Carafe</td>
<td>2.640</td>
<td>1.980</td>
<td>-1.78474</td>
<td>-1.83704</td>
<td>0</td>
<td>-2.01248</td>
</tr>
<tr>
<td>Carafe Handle</td>
<td>0.408</td>
<td>0.306</td>
<td>-0.23493</td>
<td>-0.23948</td>
<td>0.031667</td>
<td>-0.60336</td>
</tr>
<tr>
<td>Bottom Plate</td>
<td>1.064</td>
<td>0.798</td>
<td>-0.60428</td>
<td>-0.60903</td>
<td>0</td>
<td>-0.60981</td>
</tr>
<tr>
<td>Power Cord</td>
<td>0.640</td>
<td>0.480</td>
<td>-0.31597</td>
<td>-0.32761</td>
<td>0.026616</td>
<td>-0.40065</td>
</tr>
<tr>
<td>Switch</td>
<td>1.280</td>
<td>0.960</td>
<td>-0.95404</td>
<td>-0.95451</td>
<td>0.003632</td>
<td>-1.00027</td>
</tr>
</tbody>
</table>
In Table 5, a negative value means company needs to pay money to adopt the EOL option. For example, for handling each piece of the filter basket by primary recycle, company needs to pay $0.49136. A positive value means company can get money back from this EOL option. For example, company could earn $0.05675 from incineration of each piece of filter basket.

We apply fuzzy logic to determine EOL option probabilities for each component. We only provide hypothetical data due to the time limitations, and we will contact manufacturers to get real survey data for our future work. The reuse option of filter basket fuzzy data is shown in Table 6.

### Table 6 Reuse Option Fuzzy Table for Filter Basket

<table>
<thead>
<tr>
<th>EOL Character (EC₁)</th>
<th>EOL Sub-Character (EC₁₂)</th>
<th>EOL Sub-Sub-Character (EC₁₃)</th>
<th>EOL Character Weight (wᵢ)</th>
<th>EOL Sub-Character (wᵢ₊₁)</th>
<th>EOL Sub-Sub-Character (wᵢ₊₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component Quality (EC₁)</td>
<td>Remaining Life Cycle (EC₁₁)</td>
<td>Low</td>
<td>W₁₁ High</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Repair Complexity (EC₁₂)</td>
<td>High</td>
<td>W₁₂ Moderate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Obsolescence Reason (EC₁₃)</td>
<td></td>
<td>W₁₃ Very Low</td>
<td>W₁₃₁ Very Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Function/ Module Complexity (EC₂)</td>
<td>Accessibility (EC₂₁)</td>
<td>Low</td>
<td>W₂₁ Moderate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Disassembly Force (EC₂₂)</td>
<td>High</td>
<td>W₂₂ High</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Positioning (EC₂₃)</td>
<td>High</td>
<td>W₂₃ High</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tool Requirement (EC₂₄)</td>
<td>High</td>
<td>W₂₄ Moderate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Material Handling (EC₂₅)</td>
<td>Low</td>
<td>W₂₅ Very Low</td>
<td>W₂₅₂ Very Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fastening (EC₂₆)</td>
<td>Moderate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material (EC₃)</td>
<td>Material Properties (EC₃₁)</td>
<td>Very High</td>
<td>W₃₁ Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Material Compatibility (EC₃₂)</td>
<td>Very High</td>
<td></td>
<td>W₃₂ Low</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hazardous Material (EC₃₃)</td>
<td>Moderate</td>
<td>W₃₃ High</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Federal/ Local Regulation (EC₃₄)</td>
<td>Very High</td>
<td>W₃₄ High</td>
<td></td>
<td></td>
</tr>
<tr>
<td>External (EC₄)</td>
<td>Market Requirement (EC₄₁)</td>
<td>Very Low</td>
<td>W₄₁ Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Customer Preference (EC₄₂)</td>
<td>Low</td>
<td>W₄₂ High</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
For the fuzzy linguistic variable in Table 4, we use the corresponding fuzzy set and plug the data into Eq.1-3. Thus, we could derive the fuzzy score for reuse option of filter basket (2.8, 4.02, 6.91). Then, we apply Chen and Hwang [31]’s left-right analysis and evaluation, and find the final score to be 4.73. Using the same method, we evaluate other EOL options for the filter basket by linguistic variables and the corresponding fuzzy set, and get the score for each EOL options, and then we derive the weight for each of EOL option by normalizing EOL scores.

Table 7 shows weight of EOL options for each component, and the data is also hypothetical at this time. In the upcoming phases of the research, we will calculate all EOL option weights for each component. For each EOL option weight of a component, there is a fuzzy table similar to Table 8. We use fuzzy operations and left-right fuzzy evaluation, and derive a score to represent the grade of an EOL option of a component. We can get the weights for each EOL option by normalizing all these scores.

### Table 7 Component EOL Option Weights

<table>
<thead>
<tr>
<th>Component</th>
<th>Reuse</th>
<th>Remanufacture</th>
<th>Primary recycle</th>
<th>Secondary recycle</th>
<th>Incinerate</th>
<th>Landfill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Basket</td>
<td>0.201669</td>
<td>0.196106</td>
<td>0.182198</td>
<td>0.15299</td>
<td>0.133519</td>
<td>0.1335188</td>
</tr>
<tr>
<td>Filter Basket Holder</td>
<td>0.186902</td>
<td>0.185540</td>
<td>0.182810</td>
<td>0.159618</td>
<td>0.139154</td>
<td>0.1459747</td>
</tr>
<tr>
<td>Lid</td>
<td>0.206003</td>
<td>0.195087</td>
<td>0.169168</td>
<td>0.152797</td>
<td>0.136426</td>
<td>0.1405189</td>
</tr>
<tr>
<td>Warming Plate</td>
<td>0.205443</td>
<td>0.193198</td>
<td>0.186393</td>
<td>0.165985</td>
<td>0.121087</td>
<td>0.1278922</td>
</tr>
<tr>
<td>Main Housing</td>
<td>0.166667</td>
<td>0.153955</td>
<td>0.155366</td>
<td>0.170905</td>
<td>0.187854</td>
<td>0.1652537</td>
</tr>
<tr>
<td>Heating Pipe</td>
<td>0.144664</td>
<td>0.153091</td>
<td>0.146066</td>
<td>0.199439</td>
<td>0.167134</td>
<td>0.1896065</td>
</tr>
<tr>
<td>Carafe</td>
<td>0.132209</td>
<td>0.192685</td>
<td>0.165964</td>
<td>0.208158</td>
<td>0.144867</td>
<td>0.1561176</td>
</tr>
<tr>
<td>Carafe Handle</td>
<td>0.136237</td>
<td>0.157304</td>
<td>0.175560</td>
<td>0.181180</td>
<td>0.192414</td>
<td>0.1573043</td>
</tr>
<tr>
<td>Bottom Plate</td>
<td>0.153845</td>
<td>0.118882</td>
<td>0.166432</td>
<td>0.177623</td>
<td>0.16084</td>
<td>0.2223774</td>
</tr>
<tr>
<td>Power Cord</td>
<td>0.161292</td>
<td>0.179522</td>
<td>0.161292</td>
<td>0.158484</td>
<td>0.141654</td>
<td>0.1977562</td>
</tr>
<tr>
<td>Switch</td>
<td>0.16084</td>
<td>0.13007</td>
<td>0.176224</td>
<td>0.177623</td>
<td>0.184615</td>
<td>0.1706281</td>
</tr>
</tbody>
</table>

By summation of products of EOL option weights from Table 8 and EOL option values from Table 8, we can get EOL options’ expected value as shown in Table 10. For example, the expected cost of the filter basket is:

\[
\text{Expected cost of filter basket} = 0.752*0.201669+0.564*0.196106+(-0.49136)*0.15299+(-0.49817)*0.133519+0.1335188
\]

\[
=0.023551
\]

The EOL option cost is an expected value, which combines all the probability of each EOL option for each component. The negative value means that the manufacturer needs to pay to deal with retired product components.

### Table 8 EOL Options Expected Value

<table>
<thead>
<tr>
<th>Component</th>
<th>EOL Expected Value ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Basket</td>
<td>0.023551</td>
</tr>
<tr>
<td>Filter Basket Holder</td>
<td>-0.000560</td>
</tr>
<tr>
<td>Lid</td>
<td>0.017731</td>
</tr>
<tr>
<td>Warming Plate</td>
<td>0.018426</td>
</tr>
<tr>
<td>Main Housing</td>
<td>0.365216</td>
</tr>
<tr>
<td>Heating Pipe</td>
<td>-0.234540</td>
</tr>
<tr>
<td>Carafe</td>
<td>-0.262240</td>
</tr>
</tbody>
</table>
Ma and Kremer

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carafe Handle</td>
<td>-0.06973</td>
</tr>
<tr>
<td>Bottom Handle</td>
<td>-0.0858</td>
</tr>
<tr>
<td>Power Cord</td>
<td>0.011051</td>
</tr>
<tr>
<td>Switch</td>
<td>-0.17693</td>
</tr>
</tbody>
</table>

The total EOL options cost for coffee maker is as the following:
The total EOL option cost = 0.023551 - 0.00056 + 0.017731 + 0.018426 + 0.365216 - 0.23454 - 0.26224 - 0.06973 - 0.0858 + 0.011051 - 0.17693 = $0.39383

5. Conclusion and Future Work

We develop a fuzzy EOL option representation method to handle the uncertainty in EOL stage. The proposed methodology considers uncertain EOL options in the design stage. It also develops four types of EOL options selection criteria, which cover almost all aspects of EOL options. In addition, the proposed methodology derives an expected value to represent EOL option cost in design stage, and it can be extended to other sustainability criteria, such as energy consumption and labor hour.

However, there are limitations of this approach. The approach provides an expected value to represent EOL stage sustainability value, which is not helpful to optimize product structure. The approach involves global survey data for each EOL option of every product component; therefore, may not be correct in reflecting manufacturers’ local conditions; weights should be recalculated based on the local conditions.

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References


