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A multi-leveled ANP-LCA model for the selection of sustainable design options

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Abstract. The aim of this paper is to propose a new model for the selection of sustainable design options. This model is based on the environmental, the economic, and the social life cycle assessments. It deals with the uncertainties and the imprecisions due to the technological choices and their potential impacts since early design phase of the product. The proposed model is based on four principles, namely: Early integration, life cycle thinking, functionality thinking, and the multi-criteria concept. A case study is presented to validate the applicability of the proposed model on the design of batteries.

Keywords: Sustainable design, Eco-design, ELCA, EcLCA, SLCA, Fuzzy ANP

1 Introduction

The sustainable development has become widely embraced by industries. It links the concept of sustainability to the social, economic and environmental challenges faced by humanity [1]. To this end, designers have to improve the reliability of the product since its design phase. Despite the acknowledgment of the sustainability approaches, its application has been limited to single aspects which the best known is the eco-designs approaches [2]. The implementation of the design strategies is not an easy task due to the lack of necessary roadmaps [3]. In this context, many tools are available, the most suitable ones are the Environmental Life Cycle Assessment (ELCA) [4], the Economic Life Cycle Assessment (EcLCA) [5], and the Social Life Cycle Assessment (SLCA) [6]. However, these methods are more complex at an early stage of the design phase since they require significant data through all the life cycle phases which leads to uncertain and imprecise results. To this end, we propose a new model which combines the eco-design strategies with the concept of sustainable development. This model aims to select the optimal sustainable design option for a product at an early stage using simplified ELCA, EcLCA and SLCA and the fuzzy ANP [7] [8] [9]. The remainder of
this paper is laid out as follows: Section 2 presents the problem statement and the motivation. Section 3 describes and details the different steps of the proposed model. Section 4 presents the implementation of the model on a case study. Finally, section 5 concludes the research.

2 Problem statement and motivation

In the literature, several researches have been conducted on the sustainable design. Table 1 summarizes the most recent ones.

| Existing works | Sustainable design | Early integration | Life cycle thinking | Functional thinking | Multi-criteria concept | Uncertainties issues |
|----------------|-------------------|-------------------|---------------------|---------------------|------------------------|---------------------|
| Romli et al. [10] | X | N.A | N.A | Design process | The use of LCA | Quality function deployment, functional unit | The use of LCA | N.A |
| Wang et al. [11] | X | N.A | N.A | Design process | The use of LCA | Functional unit | Criteria defined for each life cycle phase | Fuzzy logic |
| Ng and Chuah [12] | X | N.A | N.A | Design process | The use of rough-cut LCA | Functional unit | AHP | Fuzzy logic, Evidential Reasoning |
| Fragnoli et al. [13] | X | Ergonomic issues | Safety issues | Redesign process | N.A | Function analysis | Environmental, quality and costs indices | N.A |
| Bereketli and Genevouis [14] | X | X | X | Design process | N.A | QFDE | AHP | Fuzzy AHP |
| Younesi and Roghani [15] | X | X | Produ c t quality | Design process | N.A | QFDE | ANP | Fuzzy logic, DEMATEL |
According to the related works and the international standards [2] [4] [16], the following principles are recommended for designers in order to achieve a sustainable design: (i) **Early integration**: The improvement of the environmental performance of the product must be considered at early stages of the design process because such improvement will be more difficult if the product is already developed. (ii) **Life cycle thinking**: The consideration of all the stages of the life cycle is necessary to better locate where and how the product can affect the environment, the economy and the society. (iii) **Functionality thinking**: The purpose and performance requirements of the products must be taken into account through the life cycle analysis. (iv) **Multi-criteria concept**: The combination between criteria such as environment, economy and society must be considered through the design process.

In addition, most of the related works (See Table 1) have ignored the economic and social aspects. Their proposed frameworks treated only the environmental issues. Moreover, these researchers pointed out the complexity of the LCA method at the design phase which leads to uncertain results and unsuitable design decisions.

To overcome these weaknesses, our proposed model is based on simplified ELCA, EcLCA, and SLCA methods. The simplified life cycle assessment was proposed by Ng C.Y [17] as a rough-cut LCA in order to address the complexity of the full LCA and to obtain the environmental performance of the desired product with the available data. Then, our idea is to connect these results to a multi-leveled fuzzy Analytic Network Process [7] [8] [9] for decision support.

### 3 A new model for the selection of sustainable design options

The proposed model is outlined in Fig.1. The model selects the optimal sustainable design option for a specific product during its design phase taking into account its life cycle phases LCP$_j$ where $j = [1..5]$, LCP$_1$ is the extraction of raw materials, LCP$_2$ is the manufacturing, LCP$_3$ is the distribution, LCP$_4$ is the use and maintenance and LCP$_5$ is the end of life. This model is based on an environmental, economic, and social life cycle assessments conducted on each option on the basis of a unique functional unit which is a quantified description of the main function of the product. The functional unit is considered as a mutual reference between the three life cycle assessments. The model is detailed as follows:

Let PDO$_i$ be the set of the product's design options where $i = [1..n]$ and $n$ is the number of design options.

Let PDO$_s$ be the selected optimal sustainable design option.

- For each PDO$_i$, the environmental, economic, and social impacts are assessed on the basis of multi-criteria and life cycle approaches in order to evaluate the impacts through all the life cycle phases. The results of these assessments are a set of environmental indicators EI$_x$, economic indicators ECI$_y$ and social indicators SL$_Z$ where $x$, $y$ and $Z$ are the numbers of the set of environmental, economic and social indicators.
For each life cycle phase $LCP_j$, the priority weights relative to each $PDO_i$ are computed through a multi-criteria decision-making system using the environment, the economy and the society as criteria, and the aforementioned indicators as the relative sub-criteria.

For each PDO, the global score is computed on the basis of the calculated priority weights per life cycle phase, the PDOi with the highest score is the selected option PDOs.

Fig. 1. Conceptual framework of the proposed model

3.1 Impacts assessment

Environmental impacts assessment

The potential environmental impacts of the product are assessed using the ELCA method taking into account all the phases of the life cycle [4]. It allows the definition of the environmental profile of the product for each PDO, this method consists of four main iterative steps: The first defines the goal and the scope of the study. The second determines the inventory of the elementary and intermediate flows related to the environment. The third is dedicated to the assessment of the environmental impacts related to the identified flows. In fact, these latter are classified and characterized by impacts and damage categories. At this stage, environmental databases such as the ecoinvent [18] and aggregation methods such as Impact 2002+ [19] are used. The choice of these methods depends on the environmental impacts categories and the consideration of time and space. The final step interprets the results of the studies compared to the identified
objectives. In this model, we have chosen a simplified version of the full ELCA [17]. In fact, the product is not manufactured yet. Thus, the inventory data are estimated on the basis of the PDO. Environmental indicators EI of impacts categories are resulted from the life cycle impacts assessment.

Economic impacts assessment

The economic impacts assessment has been proposed by Neugebauer et al. [5]. The EcLCA proposes characterization tools considering economic midpoint categories and endpoint damage categories. It is the most suitable version since it is compatible with the ELCA structure. The assessment of the economic impacts results indicators ECI relative to each life cycle phase.

Social impacts assessment

The SLCA [6] analyzes the social impacts of the product through its life cycle phases following the same steps of the ELCA. The social impacts relative to each PDO may affect the stakeholders (e.g. the employees, the society, the consumers) positively and negatively. In addition, many impacts categories are identified such as the safety and the human rights. As described in the ELCA, there are databases, classification and characterization methods in order to calculate the social indicators SI.

3.2 Selection of the optimal sustainable design option

At this stage, on the basis of the indicators computed above, the optimal sustainable product design option PDOs is selected using the fuzzy ANP [9]. The choice of this method is due to the dependency among the three aspects and the uncertainty and imprecision of the ELCA, EcLCA, and SLCA results and the judgments of the decision-makers. The fuzzy ANP considers triangular fuzzy numbers denoted l, m, and u where l is the smallest possible value, m is the most promising value and u is the largest possible value. These parameters describe a fuzzy event and their relative membership function is defined below [20]:

\[
\mu(x) = \begin{cases} 
\frac{x-l}{m-l} & \text{if } l \leq x \leq m \\
\frac{u-x}{u-m} & \text{if } m \leq x \leq u \\
0 & \text{Otherwise}
\end{cases}
\]  

(1)

Therefore, the fuzzy pair-wise comparison matrix \( \mathbf{M} \) is presented below:
The environment (E), we suggest the multi-
product design options PDO. We note that all the fuzzy
matrix relative to the proposed model are outlined below:

Let $W_{k}^{i,m,u} = (W_{k}^{i}, W_{k}^{m}, W_{k}^{u})$ be the
be the global score of each PDO.

1. Determine the comparison matrix between each criterion by supposing that they are
2. Determine the comparison matrix between each criterion by considering the depend-
3. Compute $W_{C}^{i,m,u}$ by multiplying $W_{C}^{i,m,u}$ and $W_{DC}^{i,m,u}$.
4. Determine the comparison matrix between the sub-criteria with respect to the criteria
5. Compute $W_{C}^{i,m,u}$ by multiplying $W_{C}^{i,m,u}$ and $W_{SC}^{i,m,u}$ for each sub-criterion.
6. For each LCP, determine the comparison matrix between the alternatives with re-

\[
\tilde{M} = \begin{pmatrix}
(1,1,1) & (E_{1,12}^1, E_{1,12}^m, E_{1,12}^u) & \cdots & (E_{1,n}^1, E_{1,n}^m, E_{1,n}^u) \\
(\frac{1}{E_{1,12}^1}, \frac{1}{E_{1,12}^m}, \frac{1}{E_{1,12}^u}) & (1,1,1) & \cdots & (E_{2,n}^i, E_{2,n}^m, E_{2,n}^u) \\
\vdots & \vdots & \ddots & \vdots \\
(\frac{1}{E_{1,n}^i}, \frac{1}{E_{1,n}^m}, \frac{1}{E_{1,n}^u}) & (\frac{1}{E_{2,n}^i}, \frac{1}{E_{2,n}^m}, \frac{1}{E_{2,n}^u}) & \cdots & (1,1,1)
\end{pmatrix}
\]  

(2)

Where $E_{ij}^{i,m,u} = (E_{ij}^{i}, E_{ij}^{m}, E_{ij}^{u})$ and $E_{ij}^{i,m,u} = (\frac{1}{E_{ij}^{i}}, \frac{1}{E_{ij}^{m}}, \frac{1}{E_{ij}^{u}})$ are the fuzzy preference
which compare the $i^{th}$ with the $j^{th}$ element where $i$ (resp.$j$) = [1..n] is the number of rows
(resp. columns) of the matrix $\tilde{M}$. The weights relative to each element $k$ of the matrix
$\tilde{M}$ where $k = [1..n]$ and $n$ is the number of the elements, are computed as follows: Let
$W_{k}^{i,m,u} = (W_{k}^{i}, W_{k}^{m}, W_{k}^{u})$ be the triangular fuzzy weight relative to the $k^{th}$ element
of the matrix $\tilde{M}$. $W_{k}^{i,m,u}$ is computed using the logarithmic least squares method given in

equation (3) [20].

\[
W_{k}^{i,m,u} = \left( \prod_{j=1}^{n} \frac{E_{ij}^{u}}{E_{ij}^{l}} \right)^{1/n}
\]  

(3)

Since the ANP method is applied for each life cycle phase, we suggest the multi-
leveled fuzzy ANP. The criteria relative to our model are: The environment (E), the
economy (Ec), and the society (S). the sub-criteria are: EI, ECl, SI. The alternatives are:
The product design options PDO. We note that all the fuzzy pair-wise comparison
matrices are determined using (2) and all the fuzzy weights are computed using (3).
The steps to conduct the fuzzy ANP relative to the proposed model are outlined below:

Let $W_{C}^{i,m,u}$ (resp. $W_{DC}^{i,m,u}, W_{SC}^{i,m,u}, W_{A}^{i,m,u}$) be the set of weights relative to independent
(resp. dependent criteria, sub-criteria, alternatives).

Let $G_{S}^{i}$ be the global score of each PDO.
7. Compute $W_A^{l,m,u}$ and then $W_{GP}^{l,m,u}$ for each alternative by multiplying $W_A^{l,m,u}$ and $W_{GP}^{l,m,u}$. Once $W_{GP}^{l,m,u}$ are computed for all the life cycle phases, the last step is to compute the $G_S_i$ for each PDO by summing the $W_{GP}$ of each life cycle phase.

4 Case study

In order to illustrate the proposed model, we present its application within a company that designs and manufactures electronic products for a specific usage. Designers have chosen to apply the proposed model for the selection of the optimal battery technology with the aim to design a sustainable product.

4.1 Identifying the PDO

To simplify the application of the proposed model, only four batteries technologies noted as design options PDO$_1$, PDO$_2$, PDO$_3$, and PDO$_4$ are defined in Table 2 in order to select the most sustainable one.

| PDO$_i$ | Type of chemistry cell | Technical data | Specific energy (Wh/kg) |
|---------|------------------------|----------------|------------------------|
| PDO$_1$ | Lithium iron phosphate | 2, 1000-2000   | 90-120                 |
| PDO$_2$ | Lithium nickel cobalt aluminum oxide | 3, 1000-1500 | 200-260                |
| PDO$_3$ | Lithium manganese oxide | 2.5, 300-700 | 100-150                |
| PDO$_4$ | Lithium cobalt oxide   | 205, 500-1000 | 150-200                |

- **PDO$_1$: Lithium iron phosphate (LiFePO$_4$).** This option consists of a graphite carbon anode and an iron phosphate cathode. It is characterized by a lower specific energy, a longer life span and a better specific power than the other lithium ions batteries. PDO$_1$ offers good safety characteristics regarding the users and manufacturers consider it as a potential replacement for the common lead acid batteries. The materials have low costs and do not harm the environment compared to the other options [21].
- **PDO$_2$: Lithium nickel cobalt aluminum oxide (LiNiCoAlO$_2$).** This battery consists of a graphite carbon anode and a nickel cobalt aluminum oxide. The aluminum...
offers specific energy and power and a long-life span. However, the costs relative to this option are high and the percentage of its safety is very low [22].

- **PDO3**: Lithium manganese oxide (LiMn$_2$O$_4$). This option consists of a graphite carbon anode and a manganese oxide cathode. It is considered safer than lithium cobalt in terms of overheating risks and also less expensive. PDO3 is known for its high power but less capacity and a short life span. In addition, it is composed of nontoxic material which does not treat the environment and the human being [23].

- **PDO4**: Lithium cobalt oxide (LiCoO$_2$). This battery is composed of a graphite carbon anode and a cobalt oxide cathode. It is characterized by its high specific energy which has increased its market share. However, the cobalt material is known for its high costs. Besides, PDO4 has a short life span and a low thermal stability compared to the remaining options. Regarding the environment and the society, this battery contains material with very low percentage of toxicity but these materials may harm the environment and the human-being in case of improper disposal at the end of life [21].

### 4.2 Conducting a life cycle assessment

For each PDO$_i$, simplified EcLCA, and SLCA methods have been conducted using the Quantis software and the Ecoinvent 2.2 database [18]. The three assessments are based on a unique functional unit which is the use of the battery for five years. All the collected data are normalized to the functional unit and then treated in order to evaluate the potential impacts. At this stage, the IMPACT 2002+ method [19] has been chosen. For simplicity reasons, the endpoint indicators are computed and taken into account in the case study.

**Environmental assessment**

As shown in Fig.2, four impacts indicators, namely: EI$_1$: human health, EI$_2$: ecosystem quality, EI$_3$: climate change, and EI$_4$: resources are computed for each PDO$_i$ through all the life cycle phases. We can remark that all PDO$_i$ have approximately the same impacts on the human health in LCP$_1$ ($\approx 22\%$). In fact, all options are lithium based and this element is extracted through lithium mining. This process is considered harmful for the environment. Besides, the exposure of workers to the lithium dust for a long period causes respiratory problems and air pollution. In addition, PDO$_1$ and PDO$_3$ have the same impacts in LCP$_4$ ($\approx 28\%$) regarding the climate change due to the carbon emissions when charging the batteries. Moreover, PDO$_1$ has greater impact on the climate change in LCP$_2$ ($\approx 28\%$) and LCP$_5$ ($\approx 24\%$) because it generates more carbon dioxide during these phases compared to the other PDO$_i$. Also, we can remark that PDO$_2$ has a significant impact on the ecosystem quality ($\approx 25\%$) and the human health ($\approx 24\%$) especially in LCP$_2$ and LCP$_3$ because the aluminum is considered as a toxic metal and it has significant effects on the aquatic and terrestrial ecosystems due to the emission of this metal during the manufacturing phase and its disposal at the end of life phase. PDO$_1$ and PDO$_3$ have lower impacts on the human health ($\approx 23\%$) in LCP$_3$ than
PDO\textsubscript{2} and PDO\textsubscript{4} (≈ 25\%). In fact, manganese and iron have lower toxicity percentage whereas nickel and cobalt belong to the hazardous material category. Finally, we can remark that all PDO\textsubscript{i} have approximately the same impacts on LCP\textsubscript{1} due to the assumptions that the distribution phase is similar for all options regarding the distance and the fuel consumption and emissions (i.e. EI\textsubscript{1} ≈ 24\%, EI\textsubscript{2} ≈ 25\%, EI\textsubscript{3} ≈ 25\%, EI\textsubscript{4} ≈ 26\%).

![Fig. 2. Results of the ELCA impacts assessment](image)

**Economic assessment**

Two indicators are computed from the impacts assessment of the EcLCA as illustrated in Fig.3: ECI\textsubscript{1}: economic prosperity and ECI\textsubscript{2}: economic resilience. ECI\textsubscript{1} is estimated through the profitability, productivity of the organization and the consumer satisfaction deduced from the market share of the product. ECI\textsubscript{2} expresses the ability to prevent changes without drawbacks for the economic stability [5]. We can note from Fig.3 that PDO\textsubscript{2} and PDO\textsubscript{4} have the highest impact on the economic prosperity due to the high costs of the raw materials (≈ 50%), manufacturing (≈ 40%), and the end of life treatments, and the end of life treatments (≈ 28\%). In addition, PDO\textsubscript{1} and PDO\textsubscript{3} have the highest impact on the economic resilience especially during LCP\textsubscript{4} (≈ 65\%) since the level of competitiveness on the market has increased due to investments on improving the nickel metal hybrid and the absorbed glass mat batteries that are characterized by their low costs, safer for the environment, and affordable by the consumer.

**Social assessment**

The impacts assessment relative to the SLCA results an indicator that estimates the well-being of stakeholders SI\textsubscript{1} (See Fig.4). In this context, the stakeholders are all human-being that are involved within the product (i.e. employees, consumers, managers, governors).
As shown in Fig.4, we can remark that PDO2 and PDO4 have significant impacts on the human well-being particularly during LCP2 (≈ 26%) and LCP4 (≈ 28%). In fact, the workers are exposed to hazard materials as well as the consumers. PDO1 and PDO3 have the lowest impacts on all phases since they offer good safety characteristics and consist of non-toxic materials.

4.3 Selecting the optimal sustainable design option

Following the steps of the fuzzy ANP, the first step is to set the main comparison matrix $\tilde{M}$ for the criteria $E$, $Ec$, and $S$ using (2) with respect to the goal which is the selection of PDOs. Supposing that the criteria are independent, the comparison is based on a judgment scale predefined using (1) [9]. $\tilde{M}$ is defined on the basis of the judgments
of the designers taking into account the properties of the different PDO, and obtained as follows:

$$\tilde{M} = \begin{pmatrix}
E & Ec & S \\
E & 1 & 1 & 3 & 3.5 & 4 & 5 & 5.5 & 6 \\
Ec & 0.25 & 0.285 & 0.333 & 1 & 1 & 1 & 0.666 & 0.666 \\
S & 0.166 & 0.181 & 0.2 & 1.5 & 1.5 & 1 & 1 & 1
\end{pmatrix}$$

For example, the Environment (E) is moderately to strongly preferred than the Economy (Ec) with respect to the goal. Then, considering the dependencies between the criteria, we set the matrix $\tilde{M}_{\text{inter-depencies}}$ by comparing the criteria with respect to each other’s. For instance, we compare Ec and S with respect to E. $\tilde{M}_{\text{inter-depencies}}$ is obtained as follows:

$$\tilde{M}_{\text{inter-depencies}} = \begin{pmatrix}
E & Ec & S \\
E & 1 & 1 & 1 & 0.449 & 0.4 & 0.449 & 0.5 & 0.5 & 0.5 \\
Ec & 0.224 & 0.222 & 0.224 & 1 & 1 & 1 & 0.5 & 0.5 & 0.5 \\
S & 0.775 & 0.777 & 0.775 & 0.55 & 0.16 & 0.55 & 1 & 1 & 1
\end{pmatrix}$$

Then, we obtain two comparison matrices for the sub-criteria EI, ECI with respect to E and Ec respectively. Since we have one social sub-criteria, the relative weight is equal to 1. We present in Table 3 all the weights relative to E, Ec, S, EI, ECI, SI, computed using (3).

**Table 3.** The overall priority weights relative to the criteria and the sub-criteria per LCP$_1$

| Criteria | Wc | Sub criteria | Wc | Wop |
|----------|----|--------------|----|-----|
| l | m | u | l | m | u | l | m | u |
| E | 0.3277 | 0.3281 | 0.328 | EI | 0.3096 | 0.3244 | 0.3489 | 0.1014 | 0.1063 | 0.1144 |
| Ec | 0.2603 | 0.2623 | 0.2467 | 0.0853 | 0.0861 | 0.0809 |
| S | 0.1503 | 0.1316 | 0.1576 | 0.0492 | 0.0431 | 0.0517 |
| | | | | EI | 0.2797 | 0.2818 | 0.2467 | 0.0917 | 0.0924 | 0.0809 |
| | | | | ECI | 0.2614 | 0.2614 | 0.2614 | 0.0653 | 0.0581 | 0.0522 |
| S | 0.4107 | 0.4104 | 0.4104 | SI | 1 | 1 | 1 | 0.4107 | 0.4104 | 0.4104 |

At this stage, for each LCP$_1$, seven comparison matrices for PDO with respect to EI, EI, and SI, are identified from the judgments of designers on the basis of the impacts assessments results shown in Fig.2, Fig.3, and Fig.4. since the same step is performed for each LCP$_j$, we present the results of the application of the fuzzy ANP for LCP$_1$. The seven comparison matrices for the PDO, with respect to EI, EI, and SI, are detailed in Table 4. The following step is to determine the priority weights relative to each PDO for LCP$_1$ as presented in Table 5. Then, $W_{GP}$ is obtained by multiplying $W_{A,m,u}$ and $W_{O,p,m,u}$. 
Table 4. The comparison matrices relative to PDO\(_i\) with respect to EI\(_x\), EI\(_y\) and SI\(_z\) for LCP\(_i\).

|        | PDO\(_1\) | PDO\(_2\) | PDO\(_3\) | PDO\(_4\) |
|--------|-----------|-----------|-----------|-----------|
|        | l m u     | l m u     | l m u     | l m u     |
| EI\(_x\)|           |           |           |           |
| PDO\(_1\)| 1 1 1    | 1 1 1    | 1 1 1     | 1 1 1     |
| PDO\(_2\)| 0.666 0.666 | 0.333 0.285 | 0.333 0.285 | 0.333 0.285 |
| PDO\(_3\)| 2 1 4    | 3.5 3    | 1 1 1     | 1 2 2     |
| PDO\(_4\)| 0.666 0.666 | 1.5 1.5 | 0.5 0.5 | 1 1 1 |
| EI\(_y\)|           |           |           |           |
| PDO\(_1\)| 1 1 1    | 1 2 2    | 3 4 4.5   | 1 2 2     |
| PDO\(_2\)| 0.5 0.5 1 | 1 1 1    | 0.333 0.285 | 0.333 0.285 |
| PDO\(_3\)| 0.222 0.25 | 0.333 0.222 | 0.333 0.333 | 1 1 1 |
| PDO\(_4\)| 0.5 0.5 1 | 0.666 0.666 | 6 5.5 5 | 1 1 1 |
| EI\(_z\)|           |           |           |           |
| PDO\(_1\)| 1 1 1    | 0.2 0.181 | 0.333 0.25 | 0.2 0.142 |
| PDO\(_2\)| 6 5.5 5  | 1 1 1    | 3 4.5 5    | 0.333 0.222 |
| PDO\(_3\)| 4.5 4 3  | 0.2 0.222 | 0.333 0.142 | 0.166 0.142 |
| PDO\(_4\)| 9 7 5    | 5 4.5 3  | 7 6 5 1     | 1 1 1     |

Finally, the global score GS of each PDO\(_i\) is computed by summing the \(W_{GP}\) of the PDO\(_i\) per life cycle phase. \(W_{GP}\) and GS are presented in Table 6.
Table 5. The priority weights relative to PDO with respect to EI, ECI, SI, for LCP

| PDO<sub>i</sub> | W<sub>A</sub> | W<sub>l</sub> | W<sub>i</sub> | W<sub>m</sub> | W<sub>u</sub> |
|---------------|-------------|-------------|-------------|-------------|-------------|
| LCP<sub>1</sub> | 0.2375      | 0.3358      | 0.156       | 0.1323      | 0.5496      | 0.0502      | 0.1127      |
| LCP<sub>2</sub> | 0.1631      | 0.2823      | 0.1312      | 0.1385      | 0.2312      | 0.2312      | 0.0572      |
| LCP<sub>3</sub> | 0.3995      | 0.0783      | 0.5567      | 0.6095      | 0.2867      | 0.0962      | 0.326       |
| LCP<sub>4</sub> | 0.1997      | 0.3034      | 0.156       | 0.1196      | 0.0443      | 0.6223      | 0.504       |

According to Table 6, PDO<sub>i</sub> has the highest score. This option is considered the most suitable for the design of the product since it generates the minimum environmental, economic, and social impacts through all the life cycle phases.

5 Conclusion

In this paper, we proposed a new model for the selection of the optimal sustainable design option. Our contribution is mainly observed through the integration of the environmental, economic, and the social aspects by using simplified assessment methods and by adding a multi-criteria decision making for the selection of a sustainable design option. In addition, we highlighted through the case study the extension of the eco-design concept towards a sustainable design. In fact, we used the inventory data collected from similar previous designs of the batteries. These data are then classified and their relative impacts are evaluated by categories of indicators. The results showed that PDO<sub>i</sub> is the optimal sustainable design option. This option generates the least impacts.
through the life cycle phases comparing to the remaining options. It consists of non-toxic materials and has low costs. PDO is considered safe for the consumer. Moreover, the experts confirmed the coherence of the obtained results with studies on similar batteries. However, it is important to note that these results depend on the time and space aspects due to the choice of the IMPACT2002+ method.

References

[1] G. Bruntland, "World commission on environment and development (WCED)," *Our common future*, 1987.
[2] I. 14062, "Environmental Management-Integrating Environmental Aspects into Product Design and Development.," 2002.
[3] D. C. Pigosso, H. Rozenfeld and T. C. McAloone, "Ecodesign maturity model: a management framework to support ecodesign implementation into manufacturing companies.," *Journal of Cleaner Production*, vol. 59, pp. 160-173, 2013.
[4] I. 14044, "Environmental Management--Life Cycle Assessment, Requirements and Guidelines," 2006.
[5] S. Neugebauer, S. Forin and M. Finkbeiner, "From Life Cycle Costing to Economic Life Cycle Assessment—Introducing an Economic Impact Pathway," *Sustainability*, vol. 8, p. 428, 2016.
[6] L. Dreyers, M. Hauschild and J. Schierbeck, "A Framework for Social Life Cycle Impact Assessment," *International Journal of Life Cycle Assessment*, vol. 11, pp. 88-97, 2006.
[7] T. L. Saaty, "Decision Making with Dependence and Feedback: The Analytic Network Process.," RWS Publications, Pittsburgh, 1996.
[8] L. Zadeh, "Fuzzy sets," *Information and Control*, vol. 8, pp. 338-353, 1965.
[9] L. Mikhailov and G. Madan, "Fuzzy analytic network process and its application to the development of decision support system," *IEEE Transactions on Systems, Man, and Cybernetics-Part C: Application and Reviews*, vol. 33, pp. 33-41, 2003.
[10] A. Romli, P. S. R. Prickett and S. Soe, "Integrated eco-design decision-making for sustainable product development.,” *International journal of production research*, vol. 53, pp. 549-571, 2015.
[11] X. Wang, H. Chan and L. White, "A comprehensive decision support model for the evaluation of eco-designs,” *Journal of the Operational Research Society*, vol. 65, pp. 917-934, 2014.
[12] C. Ng and K. Chuah, "A hybrid approach for environmental impact evaluation of design options.," *International Journal of Sustainable Engineering*, pp. 1-11, 2016.

[13] M. Fargnoli, M. De Minicis and M. Tronci, "Design management for sustainability: An integrated approach for the development of sustainable products.," *Journal of Engineering and Technology Management*, vol. 34, pp. 29-45, 2014.

[14] I. Bereketli and M. Genevois, "An integrated QFDE approach for identifying improvement strategies in sustainable product development," *Journal of Cleaner Production*, vol. 54, pp. 188-198, 2013.

[15] M. Younesi and E. Roghanian, "A framework for sustainable product design: a hybrid fuzzy approach based on Quality Function Deployment for Environment," *Journal of Cleaner Production*, vol. 108, pp. 385-394, 2015.

[16] B. Marques, A. Tadeu, J. De Brito and J. Almeida, "A Perspective On The Development Of Sustainable Construction Products: An Eco-design Approach.," *International Journal of Sustainable Development and Planning*, vol. 12, pp. 304-314, 2017.

[17] C. Ng and K. Chuah, "Evaluation of Design Alternatives' Environmental Performance Using AHP and ER Approaches.," *IEEE Systems Journal*, vol. 8, pp. 1185-1192, 2014.

[18] G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz and B. Weidema, "The ecoinvent database version 3 (part I): overview and methodology.," *International Journal of Life Cycle Assessment*, pp. 1-13, 2016.

[19] O. Jolliet, M. Margni, R. Charles, S. Humbert, J. Payet, G. Rebitzer and R. Rosenbaum, "IMPACT 2002+: a new life cycle impact assessment methodology," *International Journal of Life Cycle Assessment*, vol. 8, pp. 324-330, 2003.

[20] S. Onut, S. Kara and E. Isik, "Long term supplier selection using a combined fuzzy MCDM approach: A case study for a telecommunication company.," *Expert Systems with Applications*, vol. 36, pp. 3887-3895, 2009.

[21] B. Scrosati and J. Garche, "Lithium batteries: Status, prospects and future.," *Journal of Power Sources*, vol. 195, pp. 2419-2430, 2010.

[22] C. H. Chen, J. Liu, M. E. Stoll, G. Henriksen, D. R. Vissers and K. Amine, "Aluminum-doped lithium nickel cobalt oxide electrodes for high-power lithium-ion batteries.," *Journal of Power Sources*, vol. 128, pp. 278-285, 2004.

[23] M. M. Thackeray, C. S. Johnson, J. T. Vaughan, N. Li and S. A. Hackney, "Advances in manganese-oxide ‘composite’electrodes for lithium-ion batteries," *Journal of Materials Chemistry*, vol. 15, pp. 2257-2267, 2005.