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A Fuzzy-AHP Framework for Evaluation of Eco-Design Alternatives

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***Abstract*—This paper presents a model that integrates fuzzy logic and AHP for the selection of green product designs. Life cycle assessment (LCA) is a popular and comprehensive tool in the literature for analyzing the environmental impacts of a product from its origin (i.e. raw materials) to its end-of-life. However, LCA is unable to handle "uncertainty" when evaluating alternative designs and its time consuming in the data collection process. Therefore, the proposed Fuzz-AHP (FAHP)is combined with LCA to analyze the environmental impacts of a product. Some of the disadvantages of LCA can be remedied. The result is a tool that is easy to use by practitioners to obtain valuable information for evaluating various product designs, and particularly useful in the early stages of design when different options can be evaluated and screened out.**

***Index Terms*—Fuzzy, AHP, LCA, electronics product.**

I. INTRODUCTION

In recent years, the awareness of environmentally conscious practices has been improving [1]-[3]. These practices including environmentally friendly design (sometime refer to as eco-design), green procurement, sustainable operations, and also a number of end-of-life practices such as recycling and remanufacturing. The trend may be a consequence of regulatory pressures to protect the environment. For example, the European Council's directive [4] on energy using products (EuPs) restricts manufacturers to comply with it eco-design principles in order to sell their products to the European Union. Preventive rather than corrective actions should be taken as early as possible during the design phase of EuPs in order to identify and reduce the environmental impact of product's whole life cycle. It is becoming an important element when considering new product development. Decisions regarding raw materials selection, electricity consumption during use phase, packaging design, end-of-life treatment, etc., can potentially have a profound environmental impact. Above trend may exert further burden to organizations, but on the other hand also helps to boost the progression of organizations to reduce adverse effects on the environment [3].

LCA is a systematic and scientific tool that can help designers analyze the environmental impact of a product, and has been applying in various applications over the last three decades [6]. In an LCA, the whole product life cycle of a product is taken into consideration [7]. That means LCA can provide the designers a complete picture of the environmental output and hence impacts of the product. Because of this unique feature, LCA has attracted increasing attention in both the academy and practitioners and numerous studies can be found in the literature (e.g. [8]-[9]). LCA may also be employed to address legislative mandates, especially in light of the requirements introduced in the European Union (e.g. the EuP directive) [10]-[11].

As discussed, the major shortcoming of traditional AHP is that it cannot handle uncertain variables. In this connection, another stream of research focuses on FAHP. For example, Kang and Li [12] presented a FAHP method for 'green rationality evaluation' of degradable packaging with respect to LCA. Zheng et al. [13] applied an FAHP assessment model to evaluate energy conservation in the building sector. Both studies developed the hierarchy models based on the AHP concept, and then the weightings of the evaluation factors were determined following the AHP procedures. In addition, fuzzy membership degrees were only employed in the lowest hierarchy to measure each criterion. Therefore, such approach is not full FAHP and cannot address the aforementioned shortcoming.

In the eco-design domain, Ng and Chuah [14] employed TOPSIS as the fuzzy decision-making tool in FAHP for evaluating different eco-design alternatives. Their research outlined the advantages of FAHP. Different from this study, they ignored the life cycle issues and based their hierarchical model on the three factors: Economic, Environmental, and Social. As a matter of fact, fuzzy TOPSIS separates qualitative and quantitative variables and is not designed for comparative analysis of different criteria [15]. As a consequence, fuzzy TOPSIS is limited to one-tier decision problem [16]. This is also the motivation for employing the FAHP outlined in this paper.

II. CONSTRUCTING THE HIERARCHY OF ECO-DESIGN

One major drawback of LCA is to assess the potential environmental impact associated with a product by compiling an inventory of relevant inputs and outputs, which of course can help establish links between the environmental impacts, operation and economics of the process. Nevertheless, this will require substantial data, which should be scientifically proven, from the industry. This is a big hurdle to many organizations, especially small and medium enterprises, as they would not be able to devote resources or expertise to carry out a complete and systematic LCA. Therefore, a simple and cost effective method is desired. Although AHP is a good candidate from this perspective as the discrete scale of AHP has the advantages of simplicity and ease of use for

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pairwise comparison of different designs, it is not without shortcomings. Most importantly, it cannot handle the uncertainty and ambiguity present in deciding the ratings of different attributes, and it is often difficult to compare different factors due to a lack of adequate information [17].

In this connection, an LCA-based FAHP is employed for assessing the risk associated with different environmental impacts of a product design over its entire product life cycle. The proposed method can address the aforementioned drawbacks of both LCA and AHP: a full LCA is not needed and the solution can be come up quickly, and uncertainty can be taken into account. A step by step approach for the selection of green designs, which considers all environmental issues from cradle to grave, are proposed as follows:

- Like many decision-making problems, the first step is to defining the problem under study, which is the risk assessment of different criteria with respect to different environmental assessment attributes. A panel of experts, which can include product designers, engineers, production people, and so on, is formed to participate in the evaluation process.
- The whole produce life cycle (including raw material selection and use; manufacturing; distribution; installation and maintenance, usage; and end-of-life) is to be analyzed systematically based on the LCA principle, although we don't need to go through the tedious LCA process. The output of this step is to identify the main criteria within each phase that are contributing factors to the analysis.
- The next step is the data collection process. Relevant data can be collected through documentations like the bill of material, plant visit to understanding the manufacturing processes and associated consumption of energy and so on.
- Then, the hierarchical structure for green design selection can be constructed (to be discussed in subsequent section).
- The final step involves the collection of relevant data for the environmental impact assessment with respect to the criteria defined in previous step. Since this is not a full LCA, comprehensive data are not required. Instead, expert opinions will be collected in the proposed approach to come up with the conclusion.

Once the hierarchy is constructed and data are collected, the proposed FAHP outlined in Section 4.2 is utilized to estimate comparative ratings for the environmental performance of alternative designs against each criterion. Moreover, it is also used to estimate comparative weightings for life cycle phases and associated criteria. Details of the key steps are discussed below.

Level 1: Overall Objective

The overall objective is obviously the selection of the best green design. The actual problem, however, is how the design can be broken down into a number of criteria (i.e. Level 2 to be discussed below). With the help of LCA principle, this can be done very easily.

Level 2: The six life cycle phases

Level 2 in the hierarchy consists of the life cycle phases. The definition of different life cycle is different in various studies. Therefore, in this study, the definition from the Energy using Products (EuPs) directive [4] is adopted. 'Life cycle' means the consecutive and interlinked stages of an EuP from raw material selection, through production and distribution, then customer usage till the final disposal. It is recommended that the analysis should be broken down into the following six phases: (i) Raw material selection and use (L_1); (ii) Manufacturing (L_2); (iii) Packaging, transport, and distribution (L_3); (iv) Installation and maintenance (L_4); (v) Usage (L_5); and (vi) End-of-life, i.e. the state of an EuP having reached the end of its first use until its final disposal (L_6). In some applications, not all six phases are required (like the case study to be discussed). However, a generic diagram consists of six phases is illustrated in Fig.1, together with Level 1.

Level 3: The decision criteria within each phase

This is the most important level in the analysis. In short, the main criteria under each phase should be identified. For example, in the 'Material Selection' phase, plastics, metals or electronic components used, among others, are the main types of raw material used and should be put down as judging criteria. Relevant data, such as the bill of materials mentioned in previous steps, should be collected to support the identification process. In the next phase, 'Manufacturing' phase, all the main manufacturing processes should be identified. This can be down by plant visit, interviews with production engineers, and so on. Details of common criteria under other life cycle phases will be further explained in the illustrative case study. A generic diagram of each phase is demonstrated in Fig. 2, using phase 1 as an example.

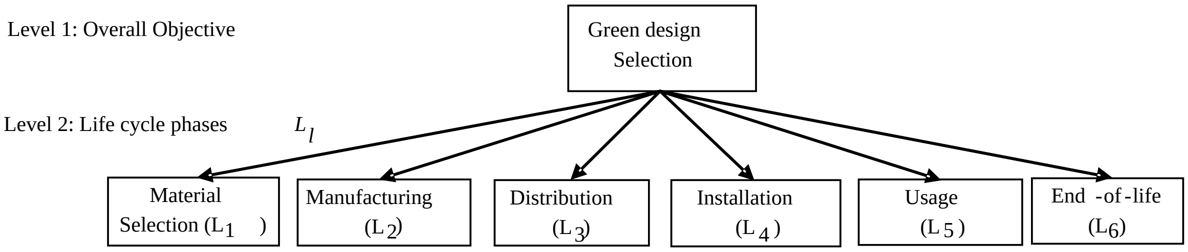

Fig. 1. First two levels of the hierarchical structure for green design selection

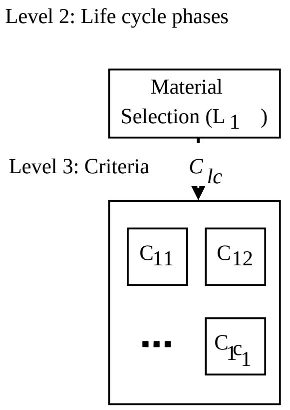

Fig. 2. Level 3 of the hierarchical structure (Phase 1 as an example)

Level 4: The five attributes of environmental impact assessment for each criterion

Defining the performance measures of a multi-criterion decision-making problem is always difficult. One reason is that different measures can be used as a proxy of a performance evaluation. Fortunately, the EuP directive proposes five assessment attributes and they are employed in this study. They are (i) Consumption of material, energy and other resources (EA_1); (ii) Emission to air, water or soil (EA_2); (iii) Anticipated pollution (EA_3); (iv) Generation of waste material (EA_4); and (v) Possibility of re-use, recycling, and recovery of materials and/or of energy (EA_5).

Level 5: Different product designs

Finally, the green product design alternatives (X_n) are located at Level 5 of the hierarchy. Fig.3 depicts the overall hierarchical structure.

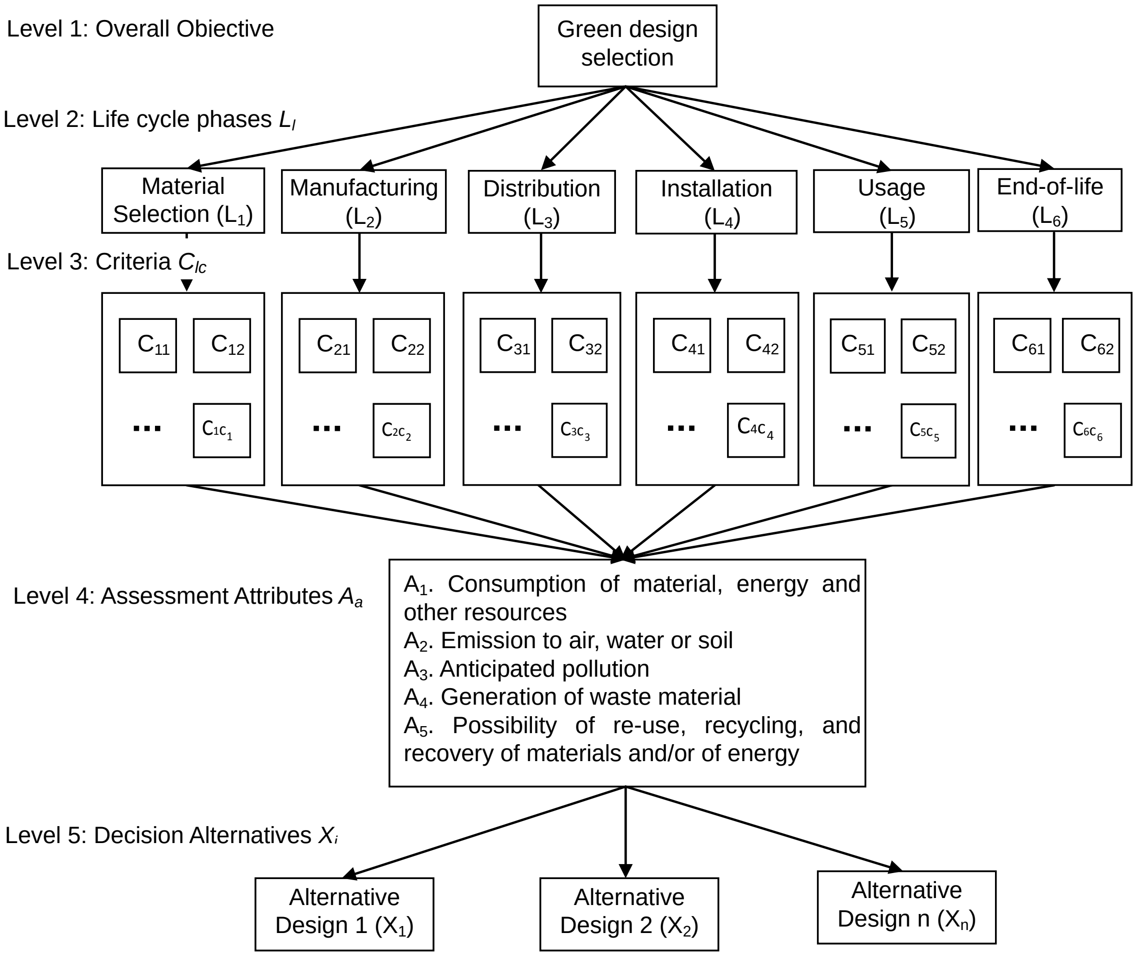

Fig. 3. Overall hierarchical structure for green design selection (Chan *et al*. 2012)

III. FUZZY-AHP (FAHP) METHOD

The proposed method utilize the advantages of Fuzzy set theory, which was developed by Zadeh in the 1960s, that can incorporate imprecise and uncertain variables [18].In the 1980s, some scholars started combining the fuzzy concepts with AHP (e.g. Van Laarhoven and Pedrycz [19]) to form the FAHP strand of research. Since then, FAHP has been applied in different applications (e.g. [20]). In this paper, FAHP is employed to help understand the risk of an environmentally friendly product design with respect to different assessment attributes. Obviously, the main rationale behind this is owing to the uncertain nature of the problem, which involves different combinations of material selection, process designs, and so on. One beauty of FAHP is that when assessors evaluate each environmental output of a design with different criteria, linguistic terms (e.g. high, very high) or a fuzzy number can be assigned instead of providing a precise numerical value. A fuzzy number is a special fuzzy set, such that $M = \{(x, \mu_M(x), x \in \mathrm{R})\}$, where the value of x lies on the real line $\mathrm{R} \rightarrow [0, 1]$. We define a fuzzy number M on R to be a triangular fuzzy number (TFN) and the membership function can be described as:

$$\mu_M(x) = \begin{cases} (x - m_1)/(m_2 - m_1), x \in [m_1, m_2] \\ (m_3 - x)/(m_3 - m_2), x \in [m_2, m_3] \\ 0, \qquad\qquad otherwise \end{cases}$$

where $m_1 \le m_2 \le m_3$, m_1 and m_3 stand for the lower and upper value of the support of M respectively, and m_2 denotes to the most promising value. TFNs M_1, M_3, M_5, M_7 and M_9 are used to represent the pairwise comparison of decision variables from "Equal" to "Absolutely Better" and TFNs M_2, M_4, M_6 and M_8 represent the middle preference values between them. The membership functions of the TFNs are shown in Fig. 4, $M_z = (m_{z1}, m_{z2}, m_{z3})$, where $z = 1, 2, \ldots, 9$. Here m_{z1}, m_{z2}, m_{z3} are the lower, middle and upper values of the fuzzy number m_z respectively, where m_{z1}, and m_{z3} represent a fuzzy degree of judgment. The greater m_{z3}-m_{z1} is, the greater fuzziness of the judgment. When $m_{z1}= m_{z2}= m_{z3}$, the judgment is a non-fuzzy number (i.e. the assessor knows the exact rating or value of the judgment).

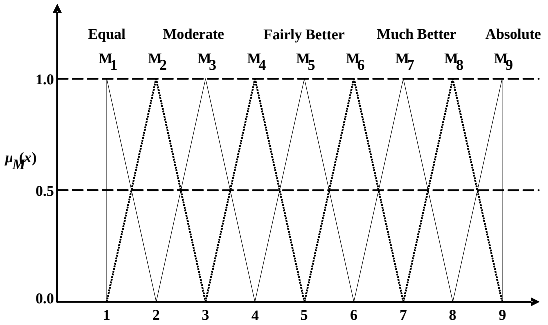

Fig. 4. Membership functions of triangular fuzzy numbers

The procedure for standard FAHP has been well-documented in the literature and the following is a summary of the procedures with reference to study conducted by Hsieh et al. [21]:

Step 1: Construct pairwise comparison matrices from a panel of experts. Linguistic variables could be used so the following matrix (per expert) is constructed by Equation (1). For simplicity, reference to different experts is omitted (see Step 2):

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & & \tilde{a}_{2n} \\ \vdots & & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n1} & \cdots & 1 \end{bmatrix} \tag{1}$$

where $\tilde{a}_{ij} = 1/\tilde{a}_{ji}$
and

$$\tilde{a}_{ij} = \begin{cases} \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9} & if\ criterion\ i\ is\ relatively\ important\ to\ criterion\ j \\ 1 & if\ i = j \\ \frac{1}{\tilde{1}}, \frac{1}{\tilde{3}}, \frac{1}{\tilde{5}}, \frac{1}{\tilde{7}}, \frac{1}{\tilde{9}} & if\ criterion\ i\ is\ relatively\ less\ important\ to\ criterion\ j \end{cases}$$

Step 2: Since the evaluation of different experts would lead to different matrices, we need to integrate the opinion of different experts to form one synthetic pairwise comparison matrix. Obviously, this step can be skipped if there is only one expert in Step 1. The elements of the synthetic pairwise comparison matrix ($\tilde{a}_{ij}$) are calculated by using the geometric mean method proposed by Buckley [22]:

$$\tilde{a}_{ij} = (\tilde{a}_{ij}^1 \otimes \tilde{a}_{ij}^2 \otimes \ldots \otimes \tilde{a}_{ij}^E)^{1/E} \tag{2}$$

The superscript in Equation (2) is the index refers to different experts and there are total of E experts.

Step 3: Make use of the synthetic pairwise comparison matrix from Step 2, define the fuzzy geometric mean $(\tilde{r}_i)$ and fuzzy weights of each criterion $(\widetilde{w}_i)$ using Equation (3) and Equation (4) respectively:

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \ \ldots \otimes \ \tilde{a}_{in})^{1/n} \tag{3}$$

$$\widetilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \ \ldots \oplus \ \tilde{r}_n)^{-1} \tag{4}$$

Step 4: Since the calculation so far involves linguistic variables, the next step is to defuzzify the weights to form meaningful figures for analysis (e.g. ranking). Many methods exist in the literature but Centre of Area (COA) is by far the most popular and easy to use one (e.g. [21]). Assume the fuzzy weights of each criterion (w_i) can be expressed in the following form:

$$\widetilde{w}_i = (Lw_i, Mw_i, Uw_i) \tag{5}$$

whereLw_i, Mw_i, Uw_i represent the lower, middle and upper values of the fuzzy weight of the i^{th} criterion.

Then, the non-fuzzy (i.e. defuzzified) weight value of the i^{th} criterion (w_i) is given by Equation (6):

$$w_i = [(Uw_i - Lw_i) + (Mw_i - Lw_i)]/3 + Lw_i \tag{6}$$

Step 5: The last step is to calculate the risk ratings of different criteria with respect to the five environmental assessment attributes. The procedure is similar to Step 1 to Step 4 and the major difference is just the object of the pairewise comparison. A similar matrix as in Equation (1) should be constructed by different experts. A synthetic pairwise comparison matrix can then be calculated using the geometric mean method outlined in Step 2. After that, the fuzzy geometric mean and fuzzy weights of each criterion with respect to different environment attributes can be defined using Equation (3) and Equation (4). This is referred to as fuzzy environmental risk ratings, in contrast to the regular weightings for different criteria. The rating of each attributed EA_i can be expressed in the following format, analogous to Equation (5):

$$\widetilde{EA}_i = (LEA_i, MEA_i, UEA_i) \tag{7}$$

In ranking the environmental assessment attributes, the final synthetic decision can be conducted and a resulting fuzzy synthetic decision matrix $\tilde{R}$ can be computed as follows:

$$\tilde{R} = \widetilde{EA} \otimes \widetilde{W} \tag{8}$$

where $\widetilde{W}$is the criteria weight vector calculated in previous step.

Each element of the fuzzy synthetic decision matrix $\tilde{R}$, $\widetilde{R_{ij}} = (LR_{ij},\ \ MR_{ij},\ \ UR_{ij})$, with respect to the criterion C_{ij} can be estimated by the following equations:

$$LR_{ij} = LEA_{ij} \times LW_{ij} \tag{9}$$

$$LR_{ij} = LEA_{ij} \times LW_{ij} \tag{10}$$

$$UR_{ij} = UEA_{ij} \times UW_{ij} \tag{11}$$

Finally, $\tilde{R}$ needs to be defuzzified using the COA method given by Equation (6).

The remaining ranking procedures will follow regular AHP analysis if the pairwise comparisons are not fuzzy in nature (i.e. crisp values are used). Even if the comparisons are carried out using fuzzy membership functions, the procedure would just a repeat of the above so discussion is omitted here.

IV. CONCLUSION

Facing shorter and shorter product life cycle, conducting LCA for all product designs and associated options is impossible. However, the regulatory pressure exerts on manufacturers for green product design has been escalating. These two factors make the proposed framework more applicable in the current arena. That can shorten the development lead time by screening out various design options at the early design stage. This can help to prioritize alternatives and select new design options for product improvement in a timely manner. Having said that, the authors would like to clarify that the aim of the proposed approach is not to replace LCA or undermine the usefulness of LCA.

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