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Evidential reasoning-based Fuzzy AHP approach for the evaluation of design alternatives' environmental performances

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ABSTRACT

With the growing general awareness of the need to protect the environment as well as the increasingly stringent regulatory requirements imposed by various national and cross-national bodies, manufacturers have to minimise the environmental impacts of their products. Environmental considerations have therefore become a new key criterion for evaluating design alternatives during the product development stage. To facilitate non-Life Cycle Assessment (LCA) experts, such as most product designers, in evaluating the design alternatives in terms of environmental friendliness, this paper introduces a decision-making mechanism that combines the multiple criteria decision making (MCDM) approaches with LCA methodology. This evidential reasoning-based approach is a fast-track and objective tool which ranks the available design alternatives according to their potential environmental impacts. The environmental impacts of design alternatives assessed by the LCA are used for the weight elicitation processes of the proposed approach. A case application is conducted to illustrate the use of the proposed method to evaluate the environmental performances of design alternatives.

1. Introduction

Environmentally conscious design considerations during product developments are necessary today to meet public expectation of corporates' social responsibility with regard to environmental protection and to satisfy emerging regulatory requirements. Manufactures have to take environmentally conscious design as one of the key design criteria when developing their new products. The level of potential environmental impact might be reduced by making appropriate design decisions, including selections of light-weighted materials, packaging designs, and energy sources. However, due to the environmental impact involves different units and categories, there is no reliable information or handy method available for product designers to assess the level of their product's potential environmental impact might be reduced by adjusting their designs.

To perform product-oriented environmental impact evaluations, Life Cycle Assessment (LCA) is a widely used approach to quantify the environmental impact of a product over its entire life cycle. LCA is regarded as a comprehensive tool to assess the environmental impact along product's life cycle phases from materials, manufacturing, packaging, use, and end-of-life. A LCA process first begins with identifying the environmental impact of an existing product. The tasks included selecting relevant system boundaries, identifying impact indicators, and determining data requirements. Second, Life Cycle Inventory (LCI) analysis has to be performed by calculating the mass and energy balance of all inputs and the outputs. Third, Life Cycle Impact Assessment (LCIA) involves associating the LCI analysis results with specific environmental impact and attempting to understand those impacts. Finally, interpretation is to identify, verify and evaluate the LCIA results [1].

Concurrently, in addition to the time and resources consuming attributes of conducting full LCAs, many studies have addressed the LCA's limitations related to the uncertainty. The uncertainty associated with the data inaccuracy due to the calibrations of measuring instruments [2]. Data collection would affect the quality of the data. Without standards to collect the data, the accuracy of the data may be unknown [3]. A lack of LCI data in the existing LCA libraries may lead to data from similar processes being used as substitute, but these data may not be fully compatible or comparable [4]. Also, uncertainty often associated with the data due to inherent variations, lack of information, inconsistent experts' judgement in setting system boundaries of LCA study, or simply human error [5].

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Several studies have been carried out to deal with the uncertainty in LCA over the years, however, the closest studies related to design alternatives evaluations are very limited. Analytical Hierarchical Process (AHP) [6] and LCA are adopted to evaluate the environmental impact of the biodegradable packaging materials [7]. The fuzzy extended AHP is applied for evaluating the recyclability of glasses [8]. An assessment model developed by integrating the Fuzzy AHP and LCA is applied for the evaluation on the consumer electronic product designs [9]. Among these studies, qualitative assessments are adopted in the evaluation processes and the relevant probablisitics theories are employed to deal with the qualitative data. Since the preference assignments of these approaches are highly relies on the decision makers' subjective judgements, therefore, different results are expected to be obtained while the judgements are performed by another decision maker using the same set of data and criteria. To overcome the problems mentioned, there is a need for a handy and objective method that would allow designers to deal with the uncertainty of LCA without going through any qualitative assessment during the weight elicitation processes. This leads to our discussion of the use of AHP, Fuzzy Set Theory (FST), Evidential Reasoning (ER), and LCA for the evaluation of products' environmental performances.

AHP is a systematic technique to evaluate the relative importance between two or more attributes by means of pairwise comparisons [10]. While the importance of life cycle phases is relative to each other by nature, it is logical to elicit the weights of life cycle phases using pairwise comparisons. Hence, AHP can be employed to evaluate the environmental performances of each life cycle phase. As noted earlier, uncertainty of LCA results induced due to the data gaps, lack of information, and compatibility of data. The uncertainty of LCA is a common issue when conducting products' environmental performances in product development processes. The information with inherent uncertainty cannot be simply expressed by a discrete scale [9]. Thus, the existing form of AHP which uses a simple nine-point scale (1–9) is insufficient to deal with the problem of uncertainty which might impair the reliability of the evaluation. A variant of AHP named Fuzzy AHP comes into implementation to address this AHP limitation and has successfully been applied in many MCDM studies [11–14]. The distinct advantage of Fuzzy AHP is its capability to deal with the uncertainness of AHP using the FST.

However, for the evaluation of the design alternatives' environmental performances, the design alternatives under each attribute of AHP hierarchy normally can be compared using a common scale of linguistic term of preferences, so the environmental performances should be evaluated using a common scale instead of obtaining the priority weights by comparing their relative importance. In order to facilitate the evaluations of the alternatives, a five-grade scale "Very Low", "Low", "Medium", "High" and "Very High" is used to evaluate the alternatives in a common scale, and then using the ER approach to tackle the uncertainty induced by the alternatives' information.

Developed by Yang and Singh, ER has been applied for supporting MCDM analysis based on the framework and the evidence combination rule of the Dempster–Shafer (D–S) theory [15–17]. The ER approach models both quantitative and qualitative attributes with uncertainty using a distributed modeling framework, in which each attribute is determined by a set of collectively exhaustive assessment grades which is called belief structure [18]. The integration of AHP and ER approaches has been applied in many MCDM studies such as project screening, bridge condition assessment, and risk management [10,19,20]. During the initial product development stage, only the estimated data may be available to support the evaluation of design alternatives. The evidence reasoning-based approach can be adopted to systematically prioritize the design alternatives with the help of a belief structure based on the uncertain or incomplete information.

A belief structure used in the ER approach is a distributed assessment with beliefs. A five-grade scale "Very Low", "Low", "Medium", "High", and "Very High" is adopted for the evaluation of alternatives. In most of the evaluation processes, it is difficult to represent the importance on a design alternative simply by a grade along a linguistic scale because of the uncertain data of the design alterative. Fuzzy logic can be used for approximating information and uncertainty to support decision making. Instead of point estimations, fuzzy evaluations can be applied for preference or grade assignments, in which information is incomplete or imprecise, and therefore, the FST is suggested be employed to transform the linguistic preference into fuzzy numbers for assessing the design alternatives in the proposed approach.

This paper discusses how the evidential reasoning-based approach to evaluate the design alternatives' environmental performances with the support of LCA results. The paper proposes to use the ratios for the weights elicitations according to the results obtained from the simplified LCAs for the determinations of preference assignments of Fuzzy AHP or belief structures of ER. The remaining sections of this paper are structured as follows: Section 2 highlights the key modifications made on LCA, Fuzzy AHP and ER. The proposed approach is described in Section 3. A case application of the proposed approach is detailed in Section 4. The results are discussed in Section 5. Section 6 draws the conclusions.

2. Rough-cut LCA, Fuzzy AHP and evidential reasoning

To assess the environmental performances of the alternatives, a fast-track LCA which is called as rough-cut LCA is proposed. The preference assignments and weight elicitations for the life cycle phases and alternatives then can be determined with the support based on the rough-cut LCA results.

Rough-cut LCA can be classified as a simplified version of a full LCA. It aims at providing prompt checking on environmental performances of a product. The less-than-perfect results can still be considered for quick screening analyses which are better than no results at all [21]. Rough-cut LCA attempts to quantify the environmental performances of the design alternatives according to the design specification, key processes, and bill of materials obtained in the product development process. It includes these four critical steps: Goal and Scope Definition, Life Cycle Inventory Analysis, and Life Cycle Impact Assessment. In this paper, the Global Warming Potential (GWP) of CML methods [22] is used as the LCIA method to represent the environmental burdens of each design alternative along the life cycle phases for demonstrating the applicability of the proposed approach.

To evaluate the environmental performances of the Life Cycle phases with uncertain information, the Fuzzy AHP is used for generating the weight of each Life Cycle phase. The computations of Fuzzy AHP follow the typical procedures of weights elicitations, synthetization, and defuzzification. Much has been written on the definitions and computations of the Fuzzy AHP [23–25] and are summarised in Appendix A. Specifically to the evaluation of Life Cycle phases, since the importance of the Life Cycle phases is relative to each other, the pairwise comparisons are used for evaluating the rough-cut LCA results of life cycle phases. By applying the relative difference equation, the relative difference between the rough-cut LCA results of two Life Cycle phases can be calculated for the weight elicitations.

$$\text{Relative}\quad\text{difference}, \text{rd} = \frac{x - y}{\max(x, y)} \tag{1}$$