Life cycle assessment for eco-packaging design: a hybrid MCDA approach

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Abstract Green packaging plays an important role for organizations to achieve sustainable economic and environmental performance. However, introducing green packaging can bring various potential challenges to firms and supply chains. There is a need to develop a systematic and effective decision support tool to help industrial practitioners to evaluate various eco-packaging options. This paper proposes a comprehensive decision making methodology based on application of Life Cycle Assessment (LCA) and a hybrid Multiple Criteria Decision Analysis (MCDA) approach to support a more rational eco-packaging selection decision.

1. Introduction

The increasing public awareness of environment protection and the regulatory pressures coming from governments and organisations are driving businesses to introduce and promote practices that help to ease the negative environmental impact. Concepts such as Green Supply Chain Management (GSCM) have emerged in an attempt to clearly identify this emergent field of research (Srivastava, 2007). Among various environmentally conscious practices, green packaging has recently begun to attract more attention. These studies (Verghese and Lewis 2007; Franey et al. 2010; Dharmadhikari 2012) indicate that the environmental impact of packaging solutions has become of concern at a global level and in a wide range of sectors of commerce.

Among various green initiatives, eco-design, also known as design for environment (DfE), has been widely adopted for new product development (Chan et al. 2013). Whilst packaging itself is an important element in eco-design (European Council 2009), there are few studies in the existing literature that consider eco-packaging design. This is a significant deficiency since eco-packaging solution might require the use of new technologies in supply and production processes, the development of new raw material, as well as the improvement of recycling and reuse. Considering potential adjustments in the operation processes, the adoption of greener packaging solution could affect normal business operations of the organisations. Therefore, there is a need to develop a systematic and effective decision support tool to help industrial practitioners to evaluate various eco-packaging options in order to achieve sustainable economic and environmental performance.

In this article, a comprehensive decision making methodology is proposed based on application of Life Cycle Assessment (LCA) and a hybrid Multiple Criteria Decision Analysis (MCDA) approach to support a more rational eco-packaging selection decision. The reminder of the paper is organised as follows: Section 2 presents a review of relevant literature that explores the design and use of packaging materials. Section 3 presents how we adopt the methodology to evaluate alternative eco-packaging options. Finally, concluding remarks and future research directions are then given in Section 4.

2. Literature review

The literature around packaging material design reveals that the vast majority of research is concerned with its aesthetics and the role of packaging to influence consumer purchasing behaviour. Hise and McNeal (1988) however recognised that packaging materials have a much broader purpose than simply attracting consumers. They note that packaging is also designed to facilitate stackability, to enhance product lifespan and to protect contents from damage. Corey and Bone (1992) later called for further research into the ethics of packaging, observing that a great many factors influence packaging designs and solutions. Even relatively recently Verghese and Lewis (2007) commented that the literature has tended to focus upon packaging that is intended for consumers and had largely ignored the packaging of materials that are transported between industrial organisations. Despite this, contemporary studies still focus upon packaging that is intended for consumers (Qalyoubi-Kemp, 2009).

This tendency to overlook the importance of inter-organisational packaging issues may be explained, at least in part, by Nunan's (1999) overview of the policy and practice that surrounded the introduction of the Packaging Regulations in the UK. She notes that while packaging material producers, fillers and retailers formed part of the advisory groups that shaped the development of the Packaging Regulations, there is no mention of the groups containing any representation from manufacturing or other sectors. The lack of representation of industrial organisations, or those that do not package products directly for retail or the consumer, is indicative of systemic consumer myopia in both research and policy-making. No doubt this has been largely induced via consumer-lead pressure for improved environmental performance and reductions in packaging materials (Verghese and Lewis, 2007; Kassaye and Verma, 1992; Corey and Bone, 1992).

For instance, Labatt (1997) reported upon companies' responses to concerns and legislation around the disposal of packaging materials to landfill in Canada, finding that larger firms were more likely to display proactive efforts to reduce packaging waste whereas smaller companies tended to be more reactive. Matthews (2004) examined the development of a packaging return system in the electronics industry and Mollenkopf et al. (2005) explored the relationship between logistics and packaging solutions. Franey et al. (2010) examined the design of packaging to improve product reliability, as well as environmental performance, in the information technology sector and found that packaging design can provide substantial cost and environmental benefits as well as improved product protection. Most recently, Dharmadhikari (2012) examined the drivers behind the development of eco-friendly packaging in India while Gupta et al. (2013) report upon the increasing influence of environmental issues upon the management of supply chains in information technology companies in India.

Studies have indicated that the decisions around the design of packaging are more complicated than simply selecting the most optimum environmental solution. In fact, environmental concerns appear to be merely a small portion of the totality of pressures that are exerted on an organisation. These pressures comprise internal operational issues, including organisational culture, functional prerogatives, product integrity and quality, employee safety and ergonomics, but above all, cost concerns (Corey and Bone, 1992; Kassaye and Verma, 1992; Matthews, 2004; Franey et al. 2010). Other significant pressures arise from external sources including consumers and pressure groups, upstream and downstream supply chains especially customers and packaging producers, the presence of supporting infrastructure and the government (Corey and Bone, 1992; Kassaye and Verma, 1992; Labatt, 1997; Matthews, 2004; Verghese and Lewis, 2007; Dharmadhikari, 2012). The complexity of the decisions are further exacerbated by having to contend with legislation that decrees the packaging that is required for particular categories of products, such as explosives, fissile materials and foodstuffs, and even by the need to contend with subjects e.g. the elimination of pests and insects from wooden packaging materials (Molina-Murillo et al. 2005; Chen et al. 2006).

3. Proposed methodology

The proposed approach consists of a comprehensive literature review, the fuzzy Delphi method, and fuzzy AHP techniques. With a comprehensive review of literature, the critical aspects for achieving the goal of eco-packaging solution are first defined, and the criteria under each aspect are identified. Then, a decision panel is formed and the fuzzy Delphi method is applied to define the evaluative criteria and establish a hierarchical model. After that, through group assessment the importance weights can be calculated by applying Fuzzy AHP. Finally, the fuzzy AHP is also used to evaluate alternative packaging options. The detailed descriptions of the main steps are elaborated in each of the following sections.

3.1 Eco-packaging evaluation framework

As the decision requires a systematic approach to help integrate environmental considerations into packaging development, it is essential to break down this complex problem into more manageable sub-problems. As illustrated in Figure 1, the problem studied here has five levels of hierarchy. The overall objective is the selection of best eco-packaging design. The other four levels of hierarchy include five life cycle stages, evaluation criteria within each phase, four attributes of performance assessment, and the different packaging designs. The application of common stages throughout the entire life cycle and performance assessment of criteria under each stage for all alternative packaging designs make objective comparison possible. It helps to select the most operationally and environmentally sound packaging solution.

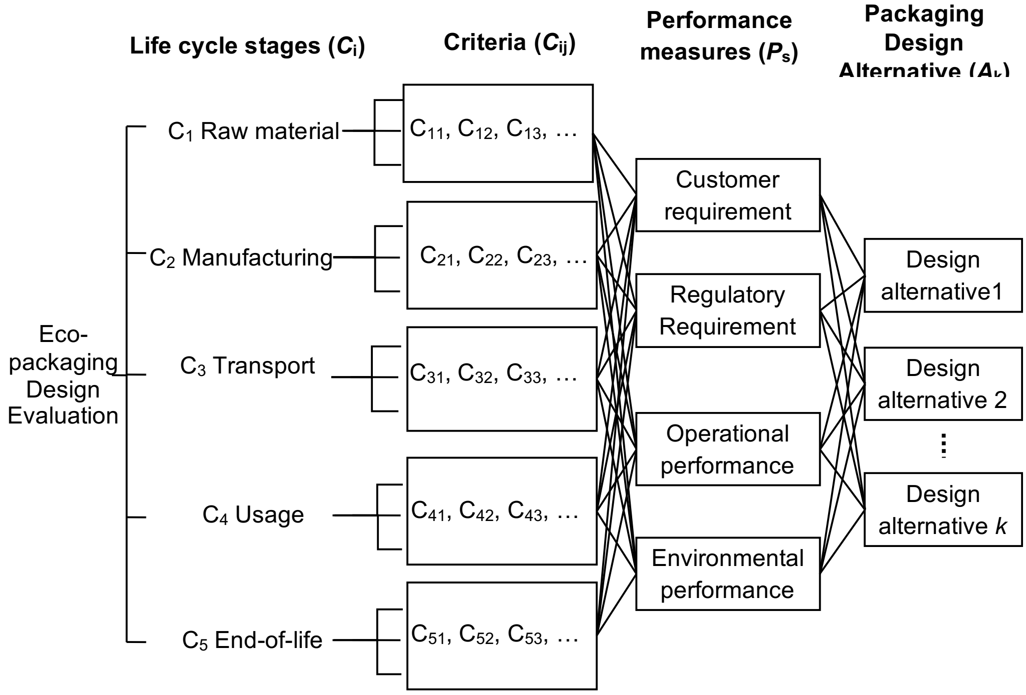

Figure 1. A hierarchical framework for the evaluation of eco-packaging design

The second level in the hierarchy is the life cycle phases. According to the Energy Related Product (ErP) directive (European Council 2009), 'Life cycle' means the consecutive and interlinked stages of an ErP from raw material use to final disposal. It is recommended that the analysis should break down in to the following six phases: L_1 Raw material selection and use; L_2 Manufacturing; L_3 Packaging, transport, and distribution; L_4 Installation and maintenance; L_5 Usage; and L_6 End-of-life (i.e. the state of an ErP having reached the end of its first use until its final disposal).

However, the number of phases included for eco-packaging evaluation is restricted to five as proposed in figure 2 since there is no installation and maintenance required for most packaging products. At the third level, the main criteria under each life cycle phase are identified. Relevant data such as bill of materials for a packaging product should be collected to support the identification process. For example, in the material selection phase, the main types of raw material such as plastics, metals or woods used need to be recorded as evaluation criteria. In the manufacturing phase, all the manufacturing processes for the packaging production should be identified. Criteria for transport should be selected from different transportation means, and weight and volume of product. In usage phase, wastes and liquid or gaseous residue should be considered. In the end-of-life phase, information about toxic material or reuse, remanufacture and recycling practices should be referred for the criteria identification.

Then, for all the criteria identified throughout the entire life cycle phases, the performance assessment can be carried out by grouping the output. This output is categorized into 4 assessment attributes at the fourth level: Customer requirement (P_1), Regulatory requirement (P_2), Operational performance (P_3), Environmental performance (P_4).

These are the four major influences upon the decisions when companies choose product packaging options. Customer-imposed requirements, for example, comprise those situations where large or dominant customers impose packaging specifications upon their supply base. This may be in the form of insisting upon the use of their own or sometimes branded, packaging crates, boxes and other materials. Additionally, those customers may impose specific delivery times, aligned with their production schedule, to improve their own efficiencies and minimise the stock that they hold. The packaging regulations themselves require that eligible organisations minimise the materials that they introduce into the packaging supply chain and promote the reuse, recovery, recycling, composting or biodegrading of materials. Furthermore, there are restrictions upon the nature of materials that may be used, in particular heavy metals. The nature of the organisation also introduces operational constraints upon the design of packaging. These are many and varied, and may change over time, but typically can include labour and material cost pressures, the design of safe and efficient working systems, the type of transport that is used, the availability of packaging materials and the specific quality requirements of the product that is being packed. Finally, any environmental initiatives may also introduce constraints upon the design of packaging solutions. The concern for environmental protection is an issue that exists beyond the boundaries of the firm and its supply chain. An organisation's own environmental management system (EMS) would also play a part in determining packaging materials and methods that are employed. Finally, the considered eco-packaging alternatives (X_n) are located at the right end of the hierarchical framework.

3.2 Fuzzy Delphi Method

To incorporate all the criteria identified through the comprehensive literature review into the evaluation is a challenging task since it is not easy to hand such a complicated pairwise comparison process. Here, fuzzy Delphi method is employed in this study to extract appropriate criteria from the criteria extracted from the literature. The objective is to establish a hierarchical model that consists of the evaluation criteria representing a consensus of experts' opinion. The Delphi method is a technique to obtain the most reliable consensus of a group of experts through a series of intensive questionnaires using controlled opinion feedback (Dalkey & Helmer 1963). Although it is a flexible technique that has been successfully used to explore new concepts, the traditional Delphi method does have its shortfalls (Kuo & Chen 2008; Lee et al 2010). One of the approaches to tackle the shortfalls is the incorporation of fuzzy set theory with Delphi method. It is a more efficient and cost effective approach which incorporates every expert opinion into consideration to achieve the consensus of group decisions (Kuo & Chen 2008). The fuzzy Delphi method has been widely applied in many management areas (Hsu & yang 2000; Kuo & Chen 2008; Hsu et al. 2010; Lee et al. 2010; Wang & Durugbo 2013). The steps for executing the fuzzy Delphi method were conceptualised as follow (Kuo & Chen, 2008; Lee et al. 2010):

Following sources such as Kuo and Chen (2008), Hsu et al. (2010), and Wang and Durugbo (2013), the steps for executing the fuzzy Delphi method were conceptualised as follow:

Step 1: Conduct a questionnaire and organize an appropriate panel of expert to express their option regarding the significance of each criterion in the possible criteria set *S* in a range from 1 to 5. A score is then denoted as $R_i, i \in S$, where the index of criteria *i* rated by expert *k* respectively.
Step 2: Organise expert opinions collected from questionnaires and determine the triangular fuzzy numbers (TFNs) for index $O_i = (L_i, M_i, U_i)$ for each criterion *i*. L_i indicates the minimum of all the experts' rating value as:

$LC_i = \min(L_{ik})$ (1)

A fuzzy number is a special fuzzy set, such that $\tilde{A}$ = {(*x*, *μA*(*x*), *x* ∈ *R*)}, where the value of *x* lies on the real line *R*→[0, 1]. We define a fuzzy number $\tilde{A}$ on *R* to be a triangular fuzzy number (TFN) and the membership function can be described as:

$$\mu_A(x) = \begin{cases} (x-L)/(M-L), x \in [L, M] \\ (U-x)/(U-M), x \in [M, U] \\ 0, \qquad otherwise \end{cases} \qquad (2)$$

where *L* ≤ *M* ≤ *U*, *L* and *U* stand for the lower and upper value of the support of $\tilde{A}$ respectively, and *M* denotes to the most promising value.
The M_i is the geometric mean of all the experts' rating for criterion *i*. It is obtained through Equation (3).

$M_i = (R_{i1} \times R_{i2} \times \cdots \times R_{ik})^{\frac{1}{k}}$ (3)

U_i indicates the maximum of all the experts' rating value as:
$U_i = \max(L_{ik})$ (4)

Step 3: Once the TFNs are determined for all the criteria, the Centre of Area (COA) approach (Hsieh et al., 2004) is used to defuzzify the TFN of each evaluation criterion to definite value G_i as:
$G_i = [(U_i - L_i) + (M_i - L_i)]/3 + L_i$ (5)

Step 4: Finally, evaluation criteria are screened out by setting the threshold α. The principle of screening is as follow:
If Gi ≥ α, then No. *i* criterion is selected for the evaluation criteria.
If Gi < α, then delete *i* criterion. (6)

3.3 Fuzzy AHP

After the evaluation framework is developed, it is essential to know how important one criterion is over another. In other words, assessors have to determine the weights between the evaluation criteria. Analytic Hierarchy Process (AHP) is one well known and widely used MCDA approach to estimate the comparative weights. AHP, developed by Saaty (1980), considers a hierarchical model which gives the ability of taking into consideration of more information and provides superiority to solve such complex decision problems. AHP has been extensively applied by academics and professionals and the literature. Nevertheless, AHP has difficulty to compare different factors due to the lack of adequate information. To address this limitation, some scholars have made use of fuzzy logic. Since Van laarhoven and

Pedrycz (1983) and Buckley (1985) present their preliminary work in fuzzy AHP, many studies on fuzzy AHP are proposed in different problem environments. Studies that apply fuzzy AHP (e.g. Weck et al. 1997; Huang et al. 2008; Wang et al. 2012) leverage the benefits of Fuzzy set theory and make use of linguistic terms (e.g. high, very high) or a fuzzy number *in lieu* of a precise numerical value when conducting pairwise comparison,.

Here, the importance of a decision criterion in relation to others was evaluated using Fuzzy AHP in line with Hsieh et al. (2004) as follows:

Step 1: Construct pairwise comparison matrices from a panel of experts. Linguistic variables could be used so the following matrix (per expert) is constructed as shown Equation (7). For simplicity, reference to different experts is omitted (see Step 2):

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & & \tilde{a}_{2n} \\ \vdots & & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n1} & \cdots & 1 \end{bmatrix} \qquad (7)$$

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

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

Step 2: Since the evaluation of different experts would lead to different matrices, the opinions of different experts are integrated 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 (1985):

$$\tilde{a}_{ij} = (\tilde{a}_{ij}^{1} \otimes \tilde{a}_{ij}^{2} \otimes \ldots \otimes \tilde{a}_{ij}^{E})^{1/E} \qquad (8)$$

The superscript in Equation (8) to different experts where there is a 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 (9) and Equation (10) respectively:

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \ldots \otimes \tilde{a}_{in})^{1/n} \qquad (9)$$

$$\widetilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \ldots \oplus \tilde{r}_n)^{-1} \qquad (10)$$

Step 4: Since the calculation so far involves linguistic variables, the next step involves defuzzifying the different weights from Step 3 to form meaningful values for analysis (e.g. ranking). Again, the COA method is used for defuzzification.

Assume the fuzzy weights of each criterion (w_i) can be expressed in the following form:

$$\widetilde{w}_i = (Lw_i, Mw_i, Uw_i) \quad (11)$$

where Lw_i, Mw_i, Uw_i represent the lower, middle and upper values of the fuzzy weight of the ith criterion. Then, the non-fuzzy (i.e. defuzzified) weight value of the i^{th} criterion (w_i) is given as:

$$w_i = [(Uw_i - Lw_i) + (Mw_i - Lw_i)]/3 + Lw_i \quad (12)$$

3.4 Evaluation for eco-packaging solution

In this section, the fuzzy AHP method discussed above is used to evaluate the performance of the alternative packaging options in each attribute of performance assessment. Ratings of performance for different packaging design alternatives are calculated for each criterion identified during the whole packaging life cycle with respect to the four assessment attributes illustrated in Figure 1. Using criterion C_{11} as an example, Table 1 shows the fuzzy elevation of criterion C_{11} with respect to the assessment attribute A_1.

Table 1. The fuzzy elevation of criterion C_{11} with respect to the assessment category P_1

Criteria C_{11}	Design 1	Design 2	…	Design *n*	R_{111}
Design 1	(1, 1, 1)				$R_{111}(X_1)$
Design 2		(1, 1, 1)			$R_{111}(X_2)$
…			…		…
Design *n*				(1, 1, 1)	$R_{111}(X_n)$

The procedure discussed in Section 3.3 is then repeated for other assessment attributes. For each eco-packaging design, the performance assessment output for criterion C_{11} have to incorporate evaluation results of all four assessment attributes as shown in Equation (13):

$$R_{11}(X_1) = R_{111}(X_1) + R_{112}(X_1) + R_{113}(X_1)+R_{114}(X_1) \quad (13)$$

Using the same approach, the ratings of performance assessment for criterion C_{lc} can be obtained as:

$$R_{lc}(X_i) = \sum_{a=1}^{4} R_{lca}(X_i) \quad (14)$$

where *i* is the index of the life cycle stages; *c* is the index of the criteria in each life cycle phase (from 1 to c_l for phase *l*, i.e. , there are c_l criteria for stage *l*); *a* is the index of assessment attributes in the environmental impact evaluation; and *i* is the index of the alternative designs.

However, even with the performance ratings for each criterion with respect to the different packaging options, selecting the best design is a challenging task due to conflicting nature of the objectives. It is necessary to consider the weightings between main phases and associated criteria. To make the final decision, it requires a systematic approach to incorporate all the elements in the decision framework into consideration. Here, an eco-packaging index (EPI) is introduced here that considers all the ratings of performance assessment for the identified criteria throughout the life cycle stages and the importance in the estimation.

$$\mathrm{EPI} = \sum_{\mathrm{l}=1}^{5} \mathrm{W_l} \sum_{c=1}^{\mathrm{c_l}} W_{lc} R_{lc}(X_i) \quad (15)$$

According the EPI value, the alternative packaging options can be ranked from the most preferred to the least preferred feasible options.

4. Discussion and conclusion

Green packaging is increasingly playing an important role in moving towards a greener economy. The concept of eco-design can be deemed as a competitive strategy for manufacturers to satisfy diverse requirements from customers as well as policy makers. Built on the concept of life cycle assessment, this study proposes an eco-packaging evaluation framework. In addition, fuzzy Delphi is applied to selected important evaluation criteria. Fuzzy AHP is then used to calculate the importance weights of life cycle phases and associated evaluation criteria, and fuzzy hierarchical TOPSIS is applied to evaluate alternative packaging design options. The research advances the use of MCDA approaches as an effective and realistic modelling approach for eco-packaging evaluation. The application of the proposed methodology can support rational decision making process for eco-packaging selection. The novelty of this research lies in the fact that an analytical methodology enables the essential business preferences concerning eco-packaging to be taken into consideration in making the decision.

Despite the benefits outlined above, the research has its own limitations which could lead to future research opportunities. One limitation of the proposed methodology is that decision makers have to make subjective decisions in the pair-wise comparisons and conduct performance assessments for alternative packaging options. Using reliable data sources instead of subjective assessment could lead to more accurate decisions. Therefore, one future research direction is to consider a more objective weighting technique such as entropy method or Data Envelopment Analysis (DEA). Furthermore, an empirical case study that offers insights into how the findings from the application of the proposed methodology can support companies to adopt green packaging solutions will be useful.

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