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ORIGINAL ARTICLE

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Environmentally conscious design by using fuzzy multi-attribute decision-making

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Abstract Products affect the environment at many points in their life cycles. Once a product moves from the drawing board into the production line, its environmental attributes are largely fixed. Many researchers have focused on developing intelligent systems to provide a variety of design and manufacturing information to help designers make environmentally conscious decisions. However, in the early design stage, not all the information available is precise. A large amount of information, especially those that are based on designer experience, is fuzzy in nature. This paper presents an innovative method, namely green fuzzy design analysis (GFDA), which involves simple and efficient procedures to evaluate product design alternatives based on environmental consideration using fuzzy logic. The hierarchical structure of environmentally conscious design indices was constructed using the analytical hierarchy process (AHP), which include five aspects: (1) energy, (2) recycling, (3) toxicity, (4) cost, and (5) material. After weighting factors for the environmental attributes are determined, the most desirable design alternative can be selected based on the fuzzy multi-attribute decision-making (FMADM) technique. The benefit of using such a technique is to effectively solve the design problem by capturing human expertise.

Keywords Analytical hierarchy process · Environmental conscious design · Fuzzy multi-attribute decision-making

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1 Introduction

Products affect the environment at many points in their life cycle. Once a product moves from the drawing board into the production line, its environmental attributes are largely fixed. During the design process, the uncertainty and qualitative nature of environmental variables makes the task of evaluating design and process alternatives difficult. Environmentally conscious design and manufacturing (ECDM) is a view of manufacturing which includes the social and technological aspects of the design, synthesis, processing, and use of products in continuous or discrete manufacturing industries [1]. It is a proactive approach to environmental protection by virtue of the fact that product life cycle environmental impacts are addressed in the product design stage. Based on a McKinsey's survey [2], 92% of CEOs and top executives agreed that the environmental challenge is one of the central issues of the 21st century, while 83% highlighted that companies need to assume responsibility for the products they manufacture. Since decisions made during the design process play the most dominant role in determining the environmental impact of a product, many researchers have focused on developing intelligent systems to provide a variety of design and manufacturing information to help designers make decisions.

As can be seen from the literature survey, most of the research focuses on a particular product and require precise information for design evaluation. However, in the early design stage, not all the information available is precise. A large amount of information, especially those that are based on designer experience, is fuzzy in nature. Decision-making could be characterized a process of choosing among alternative courses of action for the purpose of attaining goals. One of the most important aspects for a useful decision aid is to provide the ability to handle imprecise and vague information [3]. Therefore, it is necessary to develop a method that can utilize non-exact information to evaluate design alternatives.

This paper presents an innovative method, called green fuzzy design analysis (GFDA), which involves simple and efficient procedures to evaluate product design alternatives based on environmental consideration using fuzzy logic. A brief background is provided in Sect. 2; the GFDA method is presented in Sect. 3; an example is used to illustrate the application of GFDA in Sect. 4; and Sect. 5 summarizes the results of this paper.

2 Background

Fiksel [4] defined the life cycle cost (LCC) of a product as "the total cost that a firm incurs, from the time of purchase until the disposal of any wastes or by-products and beyond, as long as liabilities may remain." Several researchers have studied product life cycle cost in design [5, 6]. Product life cycle assessment (LCA), developed by the Society of Environmental Toxicology and Chemistry [7], is divided into three stages:

1. Inventory analysis: using quantitative data to establish the levels and types of energy and material inputs to a system and to result to the environmental analyses.
2. Impact analysis: relating the outputs of a system to their impacts on the external world.
3. Improvement analysis: explicitly describing the needs and opportunities for reducing environmental impacts.

Watkins and Kleban [8] developed the EcoSys system that integrates design information and expert system to perform environmental impact analyses during product design and manufacturing processes. The goals of EcoSys are: (1) to identify and quantify within the manufacturing process between product design and material consumption and waste generation; and (2) to apply these relationships to compare the environmental consequences of competing product designs or processes. Results of EcoSys analyses provide decision support in a number of areas including comparative process and product assessments, process optimization, and environmental needs assessments. Chen et al. [9] used knowledge-based rules to select suitable materials for green products. The authors used procedural programming with built-in heuristic rules serving as a control engine to match the design requirements and material properties, to calculate the environmental cost of the material, determine the minimum total cost of a product made from a material, and to select materials based on the design requirements, manufacturing process, and environmental life cycle consideration.

Presley and Sarkis [10] developed a pervasive methodology focusing on the justification of strategic integrated enterprise technology. The methodology is based on a management approach and meets the elemental requirement by the Environmental Protection Agency's (EPA) cost assessment. These elements include expanded cost inventories, extended time horizons, use of long-term indicators, and allocation of costs by activities. More specifically, the analysis is accomplished through a series of documentation and analysis matrices in which the pervasive impact of the technology on the enterprise is determined. Financial analysts and external funding sources integrate these impacts into a cash flow matrix for the calculation. Graedel et al. [11] developed an overall system assessment approach using a target plot that includes manufacturing and design information. To construct the target plot, the value of the data of the environmental product matrix are plotted as sequentially increasing angles in multiples of 360(degree)/24 = 15(degree)°. The results are graphical displays that can help a corporation in producing competitive, timely, and environmentally benign product.

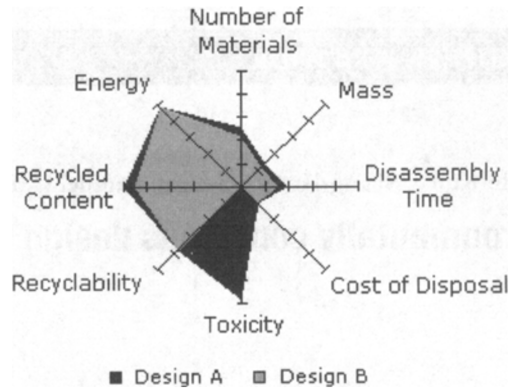


Fig. 1. Design comparison using GDA

Costic et al. [12] estimated the environmental performance of conventional lead-based solders and their substitutes using LCA. Donaldson et al. [13] conducted a life cycle assessment of a telecommunications semiconductor laser. Terho [14] carried out LCA for telecommunication cables including improvement assessment. Van Mier et al. [15] discussed the application of two life-cycle methods (LCC and LCA) on a 17-inch Philips-branded monitor showing that there is a strong positive correspondence between economical and environmental aspects. Sarkis [16] presents a model that considers the systematic and hierarchical relationships among a number of decision and environmental factors facing organization.

An analytical approach for environmentally conscious machining has been developed [17]. The environmental impact was analyzed along the dimensions of process energy, mass flow of primary and catalytic waste streams, and process time. Evaluation of different waste was accomplished through integration of analytical hierarchy process (AHP) ranking methods with simple weighting schemes; including toxicity, flammability, and mass flow characteristics of the waste streams. At Motorola, engineers use the Green Design Advisor (GDA) to design green products. The GDA enables the product designers to compare different materials and processes that could be used to create a product. This gives design engineers the ability to choose and compare different materials and processes based on their potential environmental impact. For example, in the GDA-generated chart presented below, the environmental impact of two competing designs for a test product are compared, illustrating that design B has a lower overall environmental impact (Fig. 1).

3 Fundamentals of the analytical hierarchy process (AHP)

AHP [18] has been proven to be an effective method to analyze multi-attribute decision-making problems. In the AHP, a deci-

Table 1. Numerical scale of relative judgment proposed by Satty [18]

Description	Relative importance
w_i is extremely more important than w_j	9
w_i is very strongly more important than w_j	7
w_i is strongly more important than w_j	5
w_i is moderately more important than w_j	3
w_i is equally important than w_j	1
Intermediate values between	2,4,6,8

sion process is modeled as a hierarchy. At each level in the hierarchy, the decision maker is required to make pairwise comparisons between decision alternatives and criteria using a ratio scale. This allows the decision maker to focus on the comparison of just two alternatives, which makes the observation as free as possible from extraneous influences. The crux of AHP is the determination of the relative weights. Assuming we are dealing with n criteria at a given hierarchy, the procedure establishes a $n \times n$ pairwise comparison matrix, P, from which the relative weights of all the alternatives can be extracted. Eq. 1 is a pairwise comparison matrix from which one can see that for n criteria, the pairwise comparison of element i to element j has one of the numerical values form Table 1 called w_{ij}. For consistency, $w_{ij} = k$ should automatically imply that $w_{ji} = \frac{1}{k}$. Also, all the diagonal elements a_{ii} of A must equal 1 because they rank a criterion relative to itself.

$$P = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ w_{n1} & w_{n2} & \cdots & w_{nn} \end{bmatrix} \tag{1}$$

Based on the pairwise comparison matrix, P, the principal eigenvector, is computed and normalized. The relative weights are determined from P by dividing the elements of each column by the sum of the elements of the same column. The geometric means of the ith row, called M_i, is calculated as follows:

$$M_i = \prod_{j=1}^{n} w_{ij} \text{ for } i, j = 1, 2, \ldots, n \tag{2}$$

where w_{ij} is the element in the comparison matrix standing for the comparison of the ith to the jth criterion, and n is the total number of criteria. The desired relative weights are then computed as the row average of the resulting normalized matrix (Eqs. 3–5).

$$\bar{W}_i = (M_i)^{1/n} \tag{3}$$

$$b_i = \frac{\bar{W}_i}{\sum_{j=1}^{n} \bar{W}_j} \tag{4}$$

In the AHP, consistency means that the decision is exhibiting coherent judgment in specifying the pairwise comparison of the criteria or alternatives. In Eq. 5, PW is the resultant vector, n is the number of criteria, and w_{ij} is the relative weight of priority for the ith criterion with respect to the jth criterion. To verify the consistency of the result, the maximum or principal eigenvalue called $\lambda_{\max}$ is calculated as follows:

Table 2. The value of RI [18]

n	2	3	4	5	6	7	8
RI	0.00	0.58	0.90	1.12	1.24	1.32	1.41

$$PW = \begin{bmatrix} PW_1 \\ PW_2 \\ \vdots \\ PW_n \end{bmatrix} = P \times W = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ w_{n1} & w_{n2} & \cdots & w_{nn} \end{bmatrix} \bullet \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{bmatrix} \tag{5}$$

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(PW)_i}{nb_i} = \frac{1}{n} \sum_{i=1}^{n} \frac{(PW)_i}{b_i} \tag{6}$$

Next, the "consistency index" (CI) is calculated from $\lambda_{\max}$ using the following equation, where n is the number of criterion being compared.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{7}$$

From the above discussion, the CI value depends greatly on the number of criterion being compared. Therefore, the value is standardized and divided by a random index (RI) (Table 2). Based on CI and RI, the consistency ratio, CR, is calculated as follows:

$$CR = \frac{CI}{RI}, \quad \text{where } RI \text{ is listed in Table 2} \tag{8}$$

According to Eq. 8, the higher consistency ratio means the comparison of design alternatives is less consistent. In general, if $CR \leq 0.1$, the decision makers are relatively consistent. That means the weighting set $W = \{b_1, b_2, \ldots, b_n\}$, $\sum_{i=1}^{n} b_i = 1$ could be the weighting factor.

3.1 Fuzzy multi-objective decision-making

The design team then seeks a decision function D that simultaneously satisfies all of the environmental criteria. Here, they need to combine the weighting objectives into an overall decision function to reduce subjective bias. Based on the AHP, the preferences will be attached to each objective to quantify the designer's feeling about the influence that each objective could have on the chosen alternative. Now, a universe of m alternatives, $A = \{a_1, a_2, \ldots, a_m\}$ and a set of n objectives (criteria), $O = \{O_1, O_2, \ldots, O_n\}$, are defined. Let the parameter b_i be contained on the set of weighting preference, $W = \{b_1, b_2, \ldots, b_m\}$. Then, the function is represented as the interaction of n-factors, denoted as a decision measure, $M(O_i, b_i)$, involving objectives and preferences, as follows:

$$D = M(O_1, b_1) \cap M(O_2, b_2) \cap \cdots \cap M(O_n, b_n) \tag{9}$$

In Eq. 9, the most important problem is what operation should relate each objective O_i and its importance b_i, such that the linear ordering required of the preference set is preserved, and at the same time relates the two quantities in a logical way, where negation is also accommodated. A particular alternative, a, can be replaced with a classical implication in the following form:

$$M(O_i(a), b_i) = b_i \rightarrow O_i(a) = C_i(a) \tag{10}$$

where

$$C_i(a) = \bar{b}_i \cup O_i(a)$$

hence

$$\mu_{C_i}(a) = \max\left[\mu_{\bar{b}_i}(a), \mu_{O_i}(a)\right]$$

Equation 10 indicates a unique relationship between a preference and its associated objective. As the ith objective becomes more important in the final decision, b_i increases, causing $\bar{b}_i$ to decrease, which in turn causes $C_i(a)$ to decrease. This increases the likelihood that $C_i(a) = O_i(a)$, where $O_i(a)$ will be the value of the decision function $D(a)$ representing alternative a.

A reasonable decision model for the alternative a will be the joint intersection of n decision measures,

$$\begin{aligned} D(a) &= M(O_1(a), \bar{b}_1) \cap M(O_2(a), \bar{b}_2) \cap \cdots \cap M(O_n(a), \bar{b}_n) \\ &= \bigcap_{i=1}^{n} M(\bar{b}_i \cup O_i(a)) \end{aligned} \tag{11}$$

Therefore, the optimum design, D^*, is the alternative a that maximizes $D(a)$ based on the calculation of Eq. 11.

3.2 Problems solving

From the discussion above, the design team needs to evaluate how well each alternative satisfies each environmental criterion, and must combine the weighting objectives into an overall decision function in the most plausible way. The GFDA is provided to assist designers in evaluating design alternatives based on fundamentals of the AHP method and fuzzy logic analysis [19]. Three steps are included in the GFDA.

1. Environmental impact analysis hierarchy construction. This step develops the hierarchy of the problem in terms of the overall goal, the criteria to be used and the decision alternatives.
2. Environmental analysis evaluation. Select proper design guidelines based on environmental consideration.
3. Fuzzy multi-objective decision-making. To prevent bias in the data, fuzzy logic is used to evaluate design alternatives based on the AHP weighting factor and environmentally impact analysis, energy, recycling, toxic, cost, and material usage.

The system architecture of the proposed methodology is illustrated in Figs. 2 and 3. The input of the system is information about the product's environmental impact. The multi-objective decision-making process, based on recycling, energy, cost, toxicity, and material considerations, can generate a better alternative to green products.

3.2.1 Energy

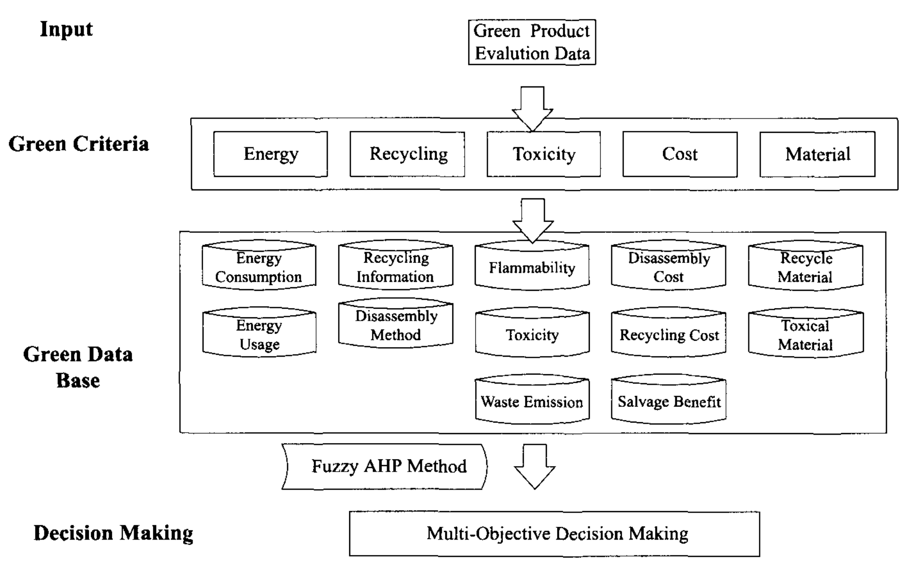
Energy saving can result from reducing power from extraneous energy sources within a product, or from reducing total energy consumption of the entire product during periods of non-use. The energy usage index is calculated as follows:

$$E_u = \frac{Output_E}{Input_E} \tag{12}$$

where

$$\begin{cases} Output_E : \text{total energy of output} \\ Input_E : \text{total energy of input} \end{cases}$$

Fig. 2. The GFDA model



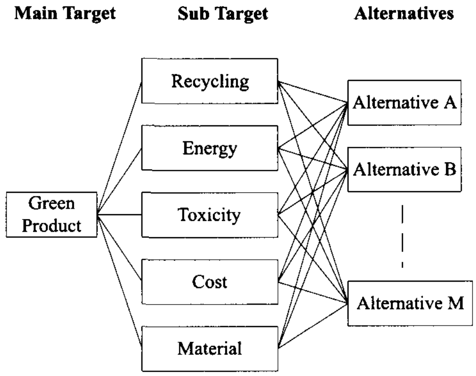


Fig. 3. Green fuzzy design criteria hierarchy

3.2.2 Recycling

Recycling includes recycling and disassembling planning. Current environmental efforts are focused on waste management and pollution control. A change in focus to pollution prevention is required to lessen the impact of manufacturing operations on the environment. This lessening of impact will be accomplished through reuse, recycling, and waste minimization. Thus, indices to measure these impacts are necessary. They are shown as follows:

$$REC_R : \frac{\text{Total Reused Component Weight}}{\text{Total End of Life Product Weight}} \tag{13}$$

$$REC_C : \frac{\text{Total Recycled Component Weight}}{\text{Total End of Life Product Weight}} \tag{14}$$

$$REC_L : \frac{\text{Total Landfill Component Weight}}{\text{Total End of Life Product Weight}} \tag{15}$$

Disassembling ability refers to the ease in which product can be disassembled at minimum cost. Whether a unit, component, module, or assembly should be disassembled not only depends on the costs of disassembly and separation, but also on its reuse, resale, or salvage values. For example, it may not be cost-effective to disassemble products that contain many different and difficult to identify materials. Similarly, if components, modules, and assemblies cannot be reused or refurbished, or if they contain largely non-recyclable materials, disassembly is unnecessary. The index used in this research is the disassembly time.

3.2.3 Toxicity

Hazardous material includes toxic and flammable materials. The materials and chemicals used in the production of manufactured products play an important role in determining the products' environmental impact. The concerns about end of life products are mainly hazardous waste disposal, the cost of which has increased dramatically over the past decade. It is better to reduce the environment impact by reducing the use of hazardous material.

$$Mat_H(\%) = \frac{\text{Total hazardous material weight}}{\text{Total product weight}} \times 100\% \tag{16}$$

3.2.4 Material

Material containment is a serious problem for the environment. An important aspect of sustainable development is the conservation of non-renewable resources. To sustain the environment, manufacturers are encouraged to use more environmentally conscious material (25 to 100%) or recycled content. This is feasible to the extent that substitution of recycled material with potential impurities is cost effective and does not compromise the quality of the final product. One of the approaches to reducing the environmental impact of the EOL product is source reduction. The best method of source reduction is to reduce the weight of major components. Thus, the total product weight will be a good index for the measurement of environmental impact:

Mat_W : Total product weight

With the advent of environmental consciousness, elegance and simplicity of form are required. Simplicity usually leads to lower manufacturing cost, lower material mass, greater durability, and easier disassembly for maintenance and recovery. It is measured using the following index:

Mat_D : Total distinct material type

3.2.5 Cost

Some costs are fixed, such as on-site labor, and thus do not vary significantly by different recycling scenarios. Other costs, such as off-site treatment and disposal costs, need to be considered. However, the cost analysis is not the focus of this research. Therefore, a simple equation is used as follows:

$$\text{Cost} = C_{\text{disassembly}} + C_{\text{transportation}} + C_{\text{recycling}} + S_{\text{salvage}} \tag{17}$$

4 Case study

To verify the validity of the model, three computer models (PIII-150 MHz, PIII-350 MHz, and PIII-550 MHz) were disassembled and evaluated by the design team. The pairwise comparison matrix P was constructed according to the five environmental criteria as follows:

$$P = \begin{array}{c} \\ \text{R} \\ \text{E} \\ \text{T} \\ \text{C} \\ \text{M} \end{array} \begin{array}{c} \begin{array}{ccccc} \text{R} & \text{E} & \text{T} & \text{C} & \text{M} \end{array} \\ \begin{bmatrix} 1 & \frac{1}{5} & 7 & 5 & 7 \\ 5 & 1 & 9 & 5 & 7 \\ \frac{1}{7} & \frac{1}{9} & 1 & \frac{1}{3} & \frac{1}{3} \\ \frac{1}{5} & \frac{1}{5} & 3 & 1 & 2 \\ \frac{1}{7} & \frac{1}{7} & 3 & \frac{1}{2} & 1 \end{bmatrix} \end{array} \tag{18}$$

R: Recycling, E: Energy, T: Toxicity, C: Cost, M: Material.

By using Eqs. 1–8 of the AHP process, the weighting factor was obtained as $W = \{0.2699, 0.5403, 0.0349, 0.0932, 0.0617\}$, which provides the relative weights with respect to the five criteria. The value $CR = 0.0978 \leq 0.10$ shows that the pairwise comparisons are consistent (Table 3).

Using fuzzy logic, the design team sets up the problem as follows:

$$A = \{PIII150, PIII350, PIII550\} = \{a_1, a_2, a_3\}$$
$$O = \{Recycling, Energy, Toxicity, Cost, Material\}$$
$$W = \{b_1, b_2, b_3, b_4, b_5\} \rightarrow [0, 1]$$

The engineer investigated three decision scenarios for recycling, energy, toxicity, cost, and material criterions. The results are shown in Table 4 and plotted in Fig. 4, which can be used to help the designer to choose the desired design alternative to achieve minimum environmental impact. However, the weighting factor is not considered.

To consider the weighting factor, the problem is transformed into a multi-attribute decision-making problem. The membership functions for the alternatives are calculated by using Eq. 9. The engineer combines the weighting objectives into an overall decision function to determine the sensitivity of the optimum solutions to the preference rating as follows:

$$\begin{aligned}
D(a_1) &= \bigcap_{i=1}^{n} M(\bar{b}_i \cup O_i(a)) \\
&= (0.7301 \vee 0.35) \wedge (0.4597 \vee 0.55) \wedge (0.9551 \vee 0.65) \\
&\quad \wedge (0.9068 \vee 0.7) \wedge (0.9383 \vee 0.6) \\
&= 0.55 \\
D(a_2) &= (0.7301 \vee 0.55) \wedge (0.4597 \vee 0.6) \wedge (0.9551 \vee 0.7) \\
&\quad \wedge (0.9068 \vee 0.5) \wedge (0.9383 \vee 0.7) \\
&= 0.6 \\
D(a_3) &= (0.7301 \vee 0.5) \wedge (0.4597 \vee 0.8) \wedge (0.9551 \vee 0.6) \\
&\quad \wedge (0.9068 \vee 0.7) \wedge (0.9383 \vee 0.5) \\
&= 0.7301
\end{aligned}$$

Therefore, the optimal design alternative, $D*$, will be a_3, since it maximizes the objective function as shown in the following:

$$\begin{aligned}
D^* &= \max\{D(a_1), D(a_2), D(a_3)\} = \max\{0.55, 0.6, 0.7301\} \\
&= 0.7301
\end{aligned}$$

Since the energy reduction and recycling rate environmental criterions have the higher weightings in the computer design process, it can be concluded that the higher the energy and recycling requirements preferences, the higher the value of D_3.

Table 3. AHP results for the computer cases

	1.00	0.20	7.00	5.00	7.00
	5.00	1.00	9.00	5.00	7.00
$P =$	0.14	0.11	1.00	0.33	0.33
	0.20	0.20	3.00	1.00	2.00
	0.14	0.14	3.00	0.50	1.00
	49.00		2.177906		0.2699
	1575.00		4.359695		0.5403
$M_i =$	0.00	$\bar{W}_i =$	0.281374	$W_i =$	0.0349
	0.24		0.751696		0.0932
	0.03		0.497942		0.0617
	1.519906		$\lambda_{max} =$	5.438344	
	3.101607		$CI =$	0.109586	
	0.185095		$CR =$	0.097845	
$PW =$	0.483258				
	0.328663				

Table 4. The results of fuzzy calculation

	Weighting	a_1	a_2	a_3
Recycling	0.2699	0.35	0.55	0.5
Energy	0.5403	0.55	0.6	0.8
Toxicity	0.0349	0.65	0.7	0.6
Cost	0.0932	0.7	0.5	0.7
Material	0.0617	0.6	0.7	0.5

5 Conclusion

Entering the 21st century, environmental consideration have become a critical aspect in the design stage. This paper presents

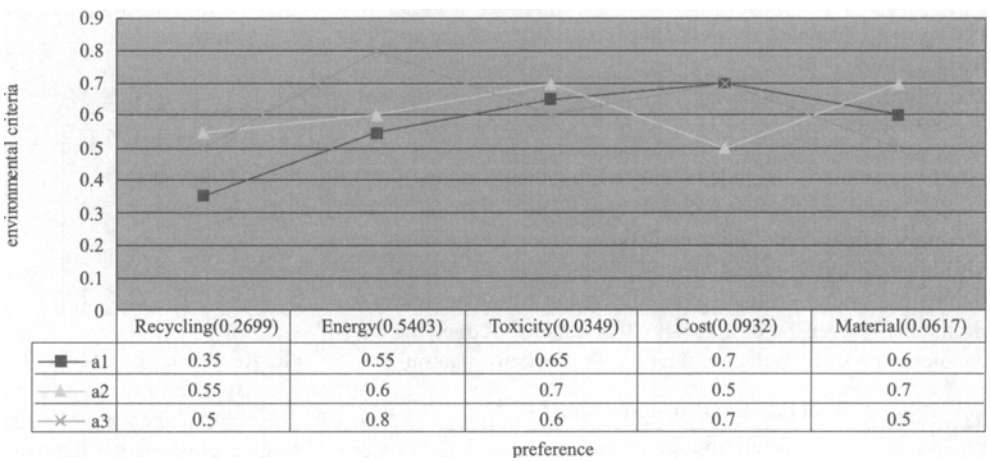


Fig. 4. The diagram of objectives and weights for the three design alternatives

an efficient green fuzzy analysis method to allow designers evaluate different design alternatives and come up with an environmentally benign product design. Fuzzy analysis is used to reduce the bias caused by weighting factor, design attributes and people. The hierarchical structure of environmental conscious design indices were constructed by using AHP with four aspects, namely inventory analysis, impact analysis, life cycle cost analysis, and improvement analysis. The fuzzy multi-attribute decision-making model was used to select the best design alternative. The benefits of the method are:

1. It is intuitive and captures the expertise of experienced designers.
2. It can reduce biases associated with the preferences of different experts.
3. It can be easily input into computers to serve as a decision-making tool to assist designers in designing environmentally benign products.
4. It can be generalized to deal with a variety of situations effectively.

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