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Evaluation and Implementation of Environmentally Conscious Product Design by Using AHP and Grey Relational Analysis Approaches

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Abstract

With the increasing societal awareness of environmental conservation and laws of environment protection are rolling on and on by governments around the world. Green design become a critical consideration in new product development for more and more companies. However, there are still companies that give up implementing green initiatives because the increasing cost of manufacture or materials. This study proposed that green design need to base on comprehensively consideration of environmental performance and the market value. The rough-cut life cycle assessment, which is more feasible for small and medium enterprises, replaced traditional full life cycle assessment Trade-off model was then applied to evaluate the market implementing value with benefits, opportunities, costs and risks as criteria. For green design alternatives, Gray Relational Analysis (GRA) integrated with Analytical Hierarchy Process (AHP) was used to rank the priority order, which provides an optimized decision-making tool for small and medium enterprises to implement green initiatives in new product design processes.

Keywords: green design, rough-cut LCA, AHP, GRA

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INTRODUCTION

With the increasing societal awareness of environmental conservation and strict scrutiny from environmental regulatory requirements, manufacturers are required to integrate environmental aspects into product design and development with the aim of reducing adverse environmental impacts throughout a product's life cycle (Ihobe 2000). Many prominent regulatory requirements for manufacturers have been enacted. For example, the European Union (EU) formulated Directive on Waste of Electronic and Electronic Equipment (WEEE) and Extended Producer Responsibility (ERP). Some states in the USA passed laws to mandate the use of environmental friendly products. Also in China, the government proclaimed "The Management Regulation on the Recycling and Treatment of Disposed Appliances and Electronic Products". In many countries, if a product cannot comply with the law of environment protection, it's not allowed to entrance and trade in the localmarket.

Life Cycle Assessment (LCA) is always used to evaluate the environmental impact of commercial products. Environmental impact is quantified along an entire product's life, which ranges from raw materials, production, transportation, use to end-of-life treatment and final disposal (Tillman et al. 1994). A completely LCA needs a great amount of data, but small-and-medium enterprises always don't have the ability to collect available Life Cycle Inventory (LCI) data, therefore hinders them to use LCA in practice (Ng and Chuah 2011). Even some large enterprises that have the Life Cycle Inventory data, while might be inaccuracy due to calibrated differently among equipment and inconsistency existed in experts' judgment for system boundaries of LCA. All of these make the LCA too complicated to apply for the new product development in actual operation, hence product designers always refuse to adopt this tool in new product development (Lindahl 2006). Generally, the application of LCA based on trivial details of different phases, facing with amount of uncertain or vague information. Small-and-medium entrepreneurs need an "end-of-pipe solution" (Filho et al. 2007), which should be simpler and more practical to make appropriate design judgments to optimize the environmental performance of green design alternatives.

The rough-cut LCA as a simplified version of a full LCA includes all the same important environmental data and the same critical steps with a standard LCA. Although the rough-cut LCA is not so trivial as one

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standard LCA, it is also a systematic and comprehensive tool to evaluate the environmental performance of products. Same with standard LCA, its' phases also include materials, production, transportation, use to end-of-life treatment, but rough-cut LCA is more easy to conduct in actual operation. Even if there is a lack of available LCI data for one specific process(es), LCI data belong to the similar processes could be used to substitute or just not include it. Eco-indicator 99 is a methodology of LCIA, which always used in rough-cut LCA to represent the environmental burden in the entire life cycle phases (Goedkoop and Spriensma 1999).

Although rough-cut LCA is an executable method for evaluate environmental impact of green product design alternatives, whether to implement green initiative is another problem needs to be considered. Undoubtedly, implementation of green design not only brings benefits and opportunities but also accompanied with costs and risks. For example, the environmental friendly product, which complies with regulatory requirements, can open more export market and attract more customer preference with environmental product. On the other hand, selection of environmental materials increases manufacturing costs, also maybe decreases the product's quality and service life. Many studies only focus on design alternatives' environmental performance, but neglected the costs and risks of adopting green design initiatives. For example, Hsueh, and Lin (2015) proposed to combine structured LCA with fuzzy analytical hierarchical process to select best green design; Ng (2018) integrated analytic hierarchy process with Evidential Reasoning to evaluate the environmental performances and prioritization of design alternatives; Ng (2016) also used a simplified LCA to quantify the environmental impacts of design options, then ant colony optimization is applied to search for the best assembly sequences.

Above studies and other researches mainly focus on the environmental impacts and rank the prioritization of design alternatives, but ignored that adoption of green product designs not only have benefits, but also potentially have many negative effects. Before implementing a new product needs to tradeoff among a series of competitive capabilities (e.g. quality, production cost, risks) (Skinner 1996). Tradeoff models have been explored and debated empirically or theoretically by a considerable of papers (Avella et al. 2011, Cai and Yang 2014, Sarmiento et al. 2013, Shih et al. 2014). Especially Roberto and Karla proposed a model to evaluate whether to adopt a green initiative based on the tradeoff among the benefits (B), opportunities (O), costs (C) and risks (R) in the implementation of a green initiative (Sarmiento et al. 2018). This BOCR model can help decision makers to decide whether to implement a green initiative, which can be combined with methods that evaluate environmental impact (e.g. rough-cut LCA), provides a more comprehensive assessment for the implementation and evaluation of green product design.

In order to achieve this goal, the environmental performances and the worthiness of implementation must be evaluated together. This paper presents an integrated approach for the optimization of design alternatives based on the considerations of environmental performances and the BOCR trade off model. Specifically, this study posited that rough-cut LCA is a more practical method compared to a standard LCA for small-and-medium entrepreneurs or product designers. When considered whether the design is worthy to put into the market, a BOCR tradeoff model is used to weight the benefits or opportunities and costs or risks in the implementation processes. This integrated approach helps decision makers to broaden the realm of their analysis by taking implemental factors into account as the traditional approach usually dealt only with environmental factors.

METHODOLOGY USING AHP AND GRA

In this study, Analytical Hierarchy Process (AHP) is used to compare the weights between any two evaluation items, then the correlations between various components of design alternatives are determined by a further calculation. Grey Relational Analysis (GRA) is adopted to obtain the final rank of all design alternatives.

Analytical Hierarchy Process (AHP)

The selection of the design alternatives is considered as a multi-criterial decision making (MCDM) problem with uncertainty by taking into account of the environmental and implemental analysis together. Analytical Hierarchy Process is a well-known technique used to solve MCDM problems. AHP was originally proposed by Satty (1980), which decomposing complex multi-criteria problems into simple hierarchical structures include a goal, criteria and alternatives. Criteria are pairwise compared for their importance relative to the main goal, and then the total priority vector of the overall hierarchy is calculated, which is the weighting of each evaluation criteria (Saaty 2013). The basic steps can be divided into five steps as below (Tian et al. 2016).

Step 1: Define the decision-making problem: Overall goal of the problem.

Step 2: Construct a hierarchical structure: Arrange the objectives, criteria, and alternatives similar to a family tree.

Step 3: Create a pairwise comparison evaluation matrix: use the pairwise values and a k-order evaluation matrix A in which every element a_{ij} (i, j∈ {1, 2, ..., k}) expresses the individual preference of experts regarding alternative A_i compared to alternative A_j, as shown below:

$$A = [a_{ij}], (i, j \in \{1, 2, \cdots, k\}) \quad (1)$$

$$a_{ij} = 1, a_{ij} > 0, a_{ij} = \frac{1}{a_{ij}}, (i, j \in \{1, 2, \cdots, k\}) \quad (2)$$

Step 4: Derive criterion weights: The vector of weights $w = (w1, w2, \cdots, wk)$ belonging to elements $i \in \{1, 2, \cdots, k\}$ can be derived from A by the eigenvector method.

$$A_w = \lambda_{max} w \quad (3)$$

where w is the eigenvector corresponding to the maximal eigenvalue λ_{max} of matrix A.

Step 5: Check consistency: The consistency is defined by the relation among the entries of A:$a_{ij} \times a_{jk} = a_{ik}$. The final consistency ratio (C_R) is calculated as the ratio of C_I to γ, that is

$$C_R = C_I/\gamma = (\lambda_{max} - k)/\gamma(k - 1) \quad (4)$$

where C_I is the consistency index. Its use allows one to conclude whether the evaluations are sufficiently consistent.

If $C_R < 0.1$, the judgment matrix is acceptable. Otherwise, it is considered inconsistent. To obtain a consistent matrix, judgments should be reviewed and improved till $C_R < 0.1$.

Grey Relational Analysis (GRA)

Grey relational analysis is an evaluation model that applied to quantify the degree of relationship (similarity or difference) between two sequences based on the grade of relation (Deng 1989). GRA has one merit like point set topology that allow global comparison between two sets of data instead of local comparison between two points (Deng 2002). Also, one another merit of GRA is without the side effect caused by subjective settings of parameters, always having a consistent result with qualitative analysis of that model. In this paper, we advised to combine rough-cut LCA and BOCR altogether to rank green design alternatives, in the which rough-cut LCA is used to evaluate environmental domain and BOCR is used to measure the implementation domain. GRA model is appropriate for this domain-combination condition (Chan and Tong 2007).

Generally, the perform of GRA contains five steps to rank the alternatives by generating the global comparison.

Step 1: Derivate the standard sequence and the reference sequences from the original decision-making matrix D.

Step 2: Normalize the original decision making matrix D.

Step 3: Calculate the grey relational distance.

Step 4: Calculate the grey relational coefficient.

Step 5: Determinate the grey relational grade.

A decision-making matrix D is formulated by a set of alternatives ($x_1, x_2, \ldots, x_m$) and criteria ($k_1, k_2, \ldots, k_m$). Each criterion is weighted with a value and assigned to a preference index (PI) by decision maker. When the value of criterion is higher, PI would be closer to 1andit means the alternative would be better.

$$D=\begin{bmatrix} x_1(k_1) & \ldots & x_i(k_1) & \ldots & x_m(k_1) \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ x_1(k_j) & \ldots & x_i(k_j) & \ldots & x_m(k_j) \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ x_1(k_n) & \ldots & x_1(k_n) & \ldots & x_m(k_n) \end{bmatrix}$$

where

$$PI_j = \begin{cases} 1, \text{increasing} \\ 0, \text{decreasing} \end{cases}$$

Normalize the original decision-making matrix *D* to a new matrix *D'*

$$D=\begin{bmatrix} x_1(k_1)' & \ldots & x_i(k_1)' & \ldots & x_m(k_1)' \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ x_1(k_j)' & \ldots & x_i(k_j)' & \ldots & x_m(k_j)' \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ x_1(k_n)' & \ldots & x_i(k_n)' & \ldots & x_m(k_n)' \end{bmatrix}$$

where

$$x_i(k_j)' = \frac{x_i(k_j) - \min_{\forall j}\{x_i(k_j)\}}{\max_{\forall j}\{x_i(k_j)\} - \min_{\forall j}\{x_i(k_j)\}}$$

The pre-reference sequence $y_0 = \{y_0(k_j);\ k = 1,2,3, \ldots, m\}$ is calculated by

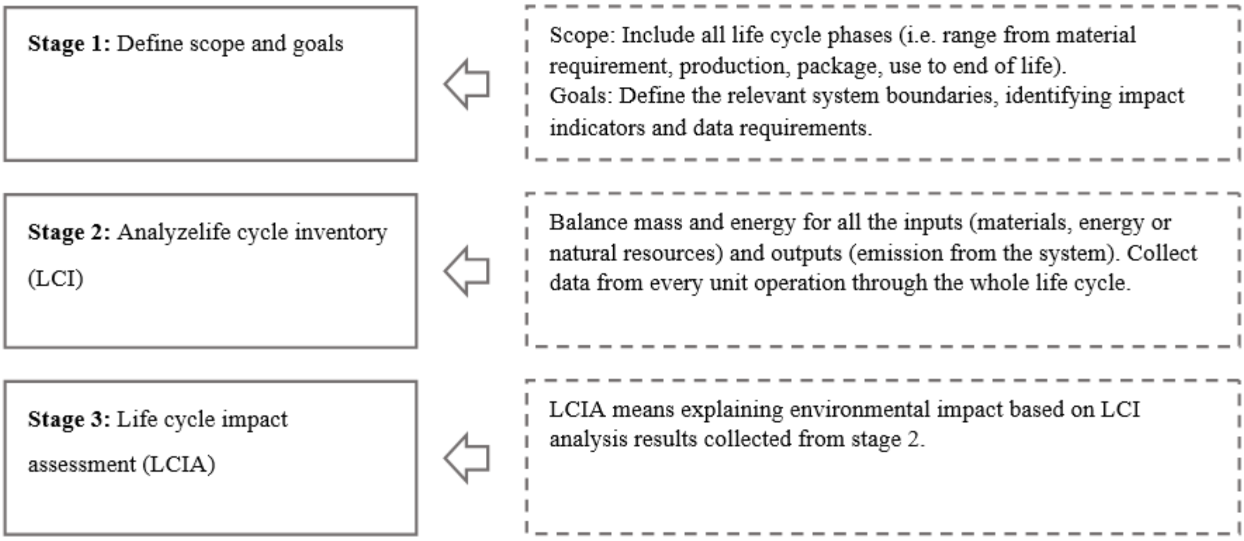

Fig. 1. Rough-cut LCA Procedures

$$y_0(k_j) = \begin{cases} \min\limits_{\forall j}\{x_i(k_j)\}, \ \mathrm{PI_j} = 0 \\ \max\limits_{\forall j}\{x_i(k_j)\}, \ \mathrm{PI_j} = 1 \end{cases}$$

Then, the reference sequence $y'_0 = \{y_0(k_j)'; \ k = 1,2,3, \dots, m\}$ can be determined by

$$y_0(k_j)' = \begin{cases} 1 - y_0(k_j), \text{if } \mathrm{PI_j} = 0 \\ \ \ y_0(k_j), \ \text{if } \mathrm{PI_j} = 1 \end{cases}$$

Finally, grey relational coefficient is calculated by comparing each sequence with the reference sequence.

$$\gamma\left(y_0(k), \ x_j(k)\right) = \frac{\Delta min + \zeta \Delta max}{\Delta_{0j}(k) + \zeta \Delta max}$$

where $y_0(k)$denotes the reference sequence, $x_i(k)$ denotes a specific comparative sequence, and j=1, …, n, k=1,…, m.

$\Delta_{0j}(k) = |y_0(k) - x_j(k)|$, ($\Delta_{0j}(k)$ is termed as the "the grey relational distance".)

$$\Delta\min = \min_{\forall j \in i} \min_{\forall} |y_0(k) - x_j(k)|$$

$$\Delta\max = \max_{\forall j \in i} \max_{\forall} |y_0(k) - x_j(k)|$$

"ζ" is referred to as the "distinguished coefficient", which value is between 0 and 1. Here the value of 0.5 is applied as a rule (Ng and Chuah 2014).

The grey relational grade is used to obtain the superior order of design alternatives, which can be calculated with the equation as below.

$$\gamma(y_0, \ x_i) = \sum_{j=1}^{n} \beta_k \gamma\left(y_0(k), \ x_j(k)\right) \tag{5}$$

where β_k represents the normalized weight of criterion k, and the summation equals to 1.

Proposed Approaches

Aims to obtain the superior order of design alternatives, both AHP and GRA as decision-making methodology are applied in this paper. Concurrently, all the criteria and sub-criteria to formulate hierarchical structures in AHP stem from dimensions of rough-cut LCA and BOCR. More precisely, criteria origin from rough-cut LCA is used to evaluate the environmental performances and criteria derived from BOCR is used to evaluate the worthiness of implementation.

Although rough-cut LCA is a simplified version of full LCA, it includes all the key environmental data. So the criteria of rough-cut LCA can be defined by materials (M), production (Pr), packaging (Pa), use (U) and end-of-life (EOL) treatment. The procedure of executing rough-cut LCA is also similar with conventional LCA methodology like **Fig. 1** (Roy 1990).

To evaluate the worthiness of implementation for new product design alternatives, aspects (i.e. criteria) of BOCR model is specifically described as below.

Benefits: Positive outcomes derived from adoption of green initiatives except the environmental benefits, which has been already evaluated by rough-cut LCA. The quality of product and manufacture speed is mainly considered here. For example, the quality of product might be improved by the analysis of green design elements.

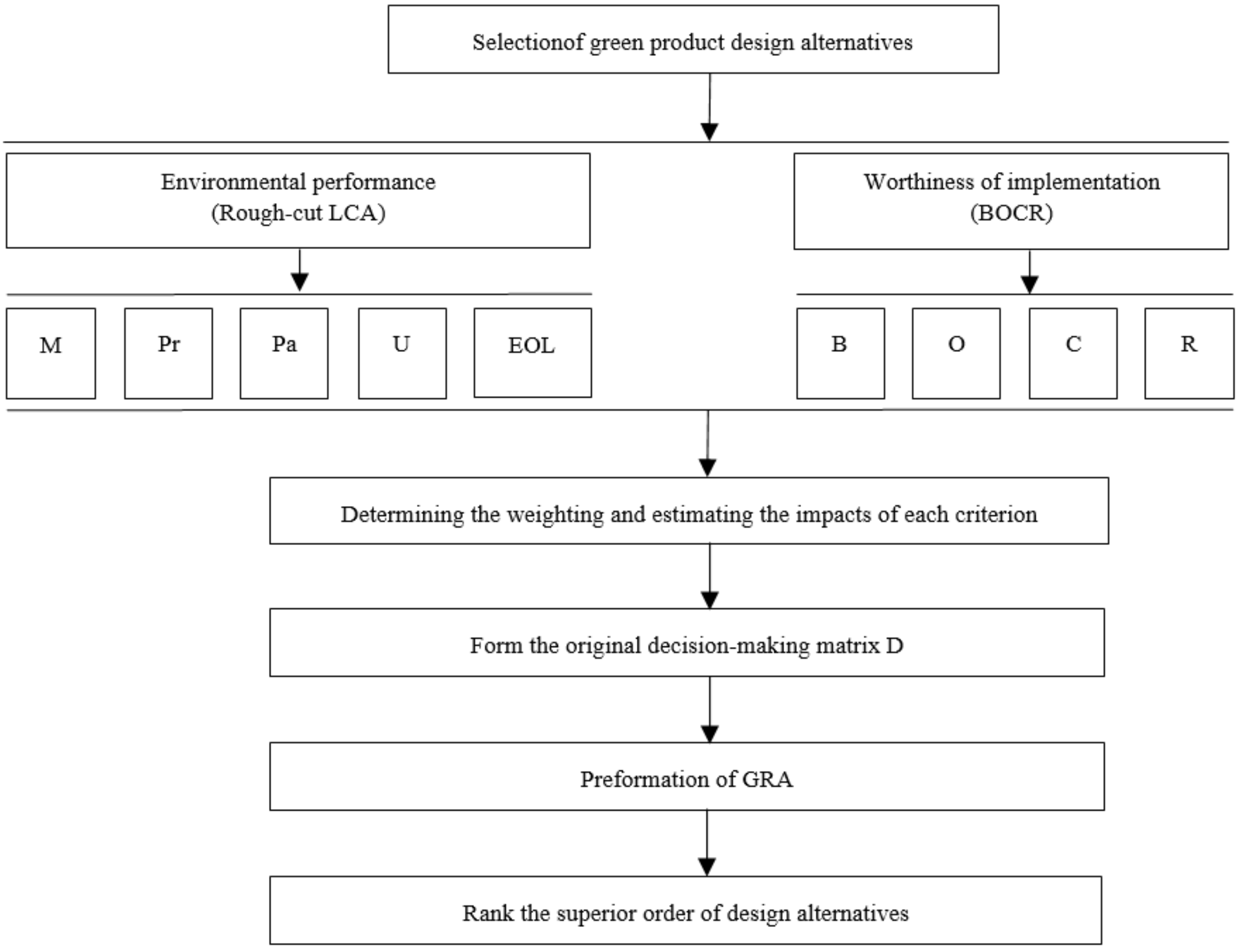

Fig. 2. Research framework

Opportunities: All potential opportunities come from the market attribute to the adoption of green initiatives. For example, due to invest in developing environmental conscious products that the reputation of manufacturer is increasing, which might attract more customers.

Costs: All negative outcomes associated with the adoption of green initiatives mainly include cost of material, cost of manufacture, deterioration of product quality, etc.

Risks: Potential punishment from the government for the reason of environment pollution.

The BOCR model provides a better understanding for the implementation of green initiatives, but the evaluation criteria should be carefully selected according to practical situation. Moreover, the decision-maker should be familiar with all the phases of life cycle and skilled in developing new products.

After the structure of criteria through rough-cut LCA and BOCR, a whole research framework is presented in **Fig. 2**. Initially, decision maker determines the impacts of environmental performance and implementation worthiness according to the criteria. Also the importance of each aspect is weighted by AHP. As the above executed, the original decision-making matrix D is formulated. Then, the superior order of design alternatives is derived by using GRA methods.

ILLUSTRATIVE EXAMPLE

A simulated example is used for the proposed approach. The overall goal of this study is to select the best green design alternatives. There are two decision domains, i.e., environmental performance and implementation worthiness. The former is evaluated by using rough-cut LCA, and the latter is evaluated by using BOCR model.

In order to judge the relative importance between criteria and sub criteria, a nine-point linguistic scale (1-9) as shown in **Table 1** to represent the relative importance during pairwise comparison is always used in the AHP. After decision makers marked the linguistic scale, the corresponding decision matrices are

Table 1. Relative importance ratio scale

Importance Degree	Relative importance ratio scale																	
	9:1	8:1	7:1	6:1	5:1	4:1	3:1	2:1	1:1	2:1	3:1	4:1	5:1	6:1	7:1	8:1	9:1	
C1					X													C2
C1											X							C3
C2																X		C3

Table 2. Comparison matrix for the sub criteria of environmental performance

Criteria	M	Pr	Pa	U	EOL	Geometric mean	Sub weight	Priority weight
M	1	2	4	1/2	3	1.64	0.26	0.09
Pr	1/2	1	3	1/3	2	1	0.16	0.05
Pa	1/4	1/3	1	1/5	1/2	0.38	0.06	0.02
U	2	3	5	1	4	2.61	0.42	0.14
EOL	1/3	1/2	2	1/4	1	0.61	0.10	0.03

Table 3. Comparison matrix for the sub criteria of implementation worthiness

Criteria	B	O	C	R	Geometric mean	Sub weight	Priority weight
B	1	1/5	1/3	3	0.67	0.12	0.08
O	5	1	3	7	3.20	0.56	0.37
C	3	1/3	1	5	1.50	0.26	0.17
R	1/3	1/7	1/5	1	0.39	0.07	0.05

Table 4. The input table of design alternatives

Index	Environmental performance					Implementation worthiness			
	M	Pr	Pa	U	EOL	B	O	C	R
I/O	1	1	1	1	1	1	1	0	0
Weight	1/3					2/3			
Sub weight	0.26	0.16	0.06	0.42	0.10	0.12	0.56	0.26	0.07
Final priority weight	0.09	0.05	0.02	0.14	0.03	0.08	0.37	0.17	0.05
Design alternative 1	0.7	0.5	0.5	0.3	0.6	5	7	US$ 1500	US$ 1200
Design alternative 2	0.5	0.7	0.7	0.6	0.5	7	4	US$ 2000	US$ 1000
Design alternative 3	0.6	0.4	0.3	0.7	0.4	6	9	US$ 2500	US$ 800

Table 5. The grey relational coefficient for each design alternative

	M	Pr	Pa	U	EOL	B	O	C	R
Design alternative 1	1	0.4	0.5	0.33	1	0.33	0.56	1	0.33
Design alternative 2	0.33	1	1	0.67	0.5	1	0.33	0.5	0.5
Design alternative 3	0.5	0.33	0.33	1	0.33	0.5	1	0.33	1

constructed. Here, the importance of environmental performance compared to implementation worthiness is 1:2, which means the weight of environmental performance and implementation worthiness respectively are 1/3 and 2/3. **Table 2** and **Table 3** respectively shows the comparison matrix for the sub criteria of environmental performance and implementation worthiness. The weight of each sub criteria is calculated by the geometric mean of column vectors and normalized. Priority weight of each sub criteria is obtained by multiplying sub criteria weight with criteria weight.

The consistency test is executed to make sure the evaluation results are consistent when decision makers are conducting pairwise comparison. Both the consistency index for environmental performance and implementation worthiness are below 0.1, which means the decision makers' preference is transitive and compiled into **Table 4**. **Table 4** presents the original decision-making matrix.

Table 6. The grey relational grades for each design alternative

Design alternatives	Grey relational grade	Ranking
1	0.6163	2
2	0.5206	3
3	0.7341	1

In this example, the reference sequence is described as $y_0' = \{1,1,1,1,1,1,1,0,0\}$, for j=1-9. The grey relational coefficients $\gamma(y_0, x_i)$ for nine sub criteria are computed as shown in **Table 5**.

According to the Eq. (5), the grey relational grade $\gamma(y_0, x_i)=\sum_{j=1}^{n}\beta_k\gamma\left(y_0(k), x_j(k)\right)$ for each design alternative is obtained. **Table 6** shows the relational grades and the priority of these three alternatives.

DISCUSSION

Different with traditional green design only focus on environmental protection, this study based on a more comprehensive view, which applied rough-cut LCA that is practical for small and medium enterprises to evaluate the environmental performance and utilized trade-off model BORC to evaluate the market value. Considering environmental performance and market value as a whole provides a theoretical and practical decision-making tool for small and medium enterprises to implement green initiatives in new product design processes. Two issues raised as below:

1. Although full LCA is always used in traditional green design, it is difficult to conduct due to data missing or bias. The rough-cut LCA as simplified LCA can cover these shortages, therefore can provide a practical method for enterprises or designers.

2. A comprehensive evaluation from both environment protection and market value needs to consider the aggregation effect, then the priority order is ranked. The commonly used multi-criteria decision-making models include ELECTRE (Roy 1990), TOPSIS (Huang 2011), SIR (Xu 2001), GRA (Deng 1985) and entropy (Shannon and Weaver 1949). Among of these measures, ELECTRE, TOPSIS, SIR are based on preference thresholds and indifference thresholds within each other, but the setting of those thresholds are always subjective. The entropy decision model cannot evaluate uncertainties and is inappropriate for multiple criteria decisions. GRA possesses the merit of global comparison between sets of data, which avoids the side effect of subjective setting of parameters. GRA is suitable for two or more domain-combination conditions.

CONCLUSION

Environmental protection as becoming a critical consideration for manufacturers related with whether product comply with environment laws of export country, and determines whether can be allowed to access the local market. As a company implements green design, the environmental performance is not the only consideration, the trade-off between benefits and costs also should be considered. Synthesizes these two domains, this study provides a more practical green design measures for companies to implement green design in new product development.

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