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Greenness Assessment of Products in PLCA by DEA Approach*

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How to assess the greenness of products from the viewpoint of LCA (Life Cycle Assessment) is one of the important issues in PLCA (Products Life Cycle Analysis). In this report, we present a non-uniform assessment method for greenness assessment of products based on DEA (Data Envelopment Analysis) model after analyzing the shortcomings of the existing comprehensive assessment methods for green products. This method not only assesses the greenness of given products with regard to technical reference product constructed by means of the information of products, but also illustrates how to improve the greenness of products quantitatively by utilizing the project theory on DEA efficient frontier of DMU (Decision Making Unit). Finally we take a numerical example concerning greenness assessment of refrigerators to show how to use the established method and prove its availability.

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1. Introduction

Since 1990s, series of problems concerning environment and resources have emerged with the development of industry. The adjustment of global industrial structure shows a tendency to a new green strategy. Under the impact of the green movement, the products produced by green design and green manufacturing, gradually spring up. Green manufacturing is a modern manufacturing pattern developed in recent years, which considers much on the effects of the manufacturing process on environment and resources, and whose goal is to minimize the negative effects on the environment and maximize the utilization ratio of resources in the product life cycle which contains designing, manufacturing, packaging, transporting, using and disposing.[1)] Since the concept of green manufacturing was put forward in the blue-covered book on green manufacturing by ASME in 1996, green manufacturing is paid much closer attention by the developed countries increasingly. Especially after International Standard Organization issued its No. 14000 series standards on the environmental management, green manufacturing is regarded as an advanced manufacturing model to realize the sustainable development of industries. At present, there are many decision-making problems on green manufacturing such as standards of green design, assessment model of green products, multi-objective optimization and decision support system (DSS). They are rather complex problems to be settled urgently.

PLCA (Products Life Cycle Analysis) is a process to evaluate the environment burdens associated with a product by identifying and quantifying energy and materials used, and the wastes released to the environment; to assess the impact of those energy and materials used and released to the environment; and to identify and evaluate opportunities to affect environment improvements.[2)] The assessment includes the entire life cycle of the product, encompassing extracting and processing raw materials, manufacturing, use, re-use, maintenance, recycling, and final disposal. Green product is the final embodiment of green design and ecodesign, and the carrier of the product greenness. Therefore, how to assess the greenness of a product from the viewpoint of LCA is one of the important issues in PLCA.

The assessment of green products can not only differentiate whether the greenness of the product is good, but also have very important functions to direct the development of green manufacturing. This problem of assessment is actually that of decision-making with multicriteria. The existing mathematical models adopted by many assessment systems, are generally based on optimization theory and satisfied principle, which leave no stone unturned to decide a prior weight for each index by some methods beforehand, and then array the priority of projects or alternatives according to the sum of each index value with multiplying its weight.[3)] They are called uniform assessment methods because they use the same weight admeasure for all assessment projects and alternatives. They have two shortcomings at least. First, it is difficult to decide the weighing and to avoid the subjectivity; Secondly, the partiality results from the uniformity of the weighing for different assessment objects. In fact, the differences of the importance and observability between each pair of indexes may be very large.

Each assessment index of green products reflects their greenness, and the differences exist between each pair of different indexes. It is shown that the greenness of products is not determined by some phases or some index of products in the practice research.[4–6)] Thus there are some shortcomings in using uniform assessment methods to appraise green products and we should choose a suitable non-uniform method. That is, for each project or object, we need to find its own optimum weighing for each index; Hence, we get different weighing admeasures for different objects and reasonable assessment results. At present, the most representative non-uniform assessment method is DEA (Data Envelopment Analysis), put forward by the famous operation

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researchers, A.Charnes *etc.* in 1978.[7] It is a decision-making method for multiobjective problem based on the concept of relative comparative efficiency. It determines the weight vector and prior order by solving the mathematical programming corresponding to each alternative that is called decision-making unit (DMU) in DEA. The weights differ from one DMU to another and are all relatively optimal. Hence, DEA is a non-uniform evaluation method with objectivity and optimality. Since its presence, it has been developed well in theory and applied more and more extensively.

This paper establishes the non-uniform assessment model of green products according to the principle and method of DEA after constructing a virtual product as a technical reference product firstly in accordance with the requirements of the greenness assessment of products. It not only assesses the greenness of given products with regard to technical reference product constructed through the information of products, but also illustrates how to improve the greenness of products quantitatively by utilizing the project theory on DEA efficient frontier of DMU. Finally a numerical example concerning greenness assessment of refrigerators is taken to show how to use the established method as well as to prove its availability.

2. The Concept of Green Products And The Assessment Index System

2.1 The concept of green products

Green product is the final embodiment of green design, and the carrier of the product greenness. So far, it hasn't a universally accepted and authoritative definition because the describable and quantifiable characteristics of its greenness are not very specific. It can be defined as follows: Green product is a kind of products that meet the need of the given requirements for the environmental protection, and do no harm to or minimize the impact on the environment, maximize the utilization ratio of resources and reduce the consumption of the energy resources in its life cycle. Its connotation mainly contains the following point: (1) Excellent environmental performance: The product can do no harm to or minimize the impact on the environment. (2) Fully utilizing the material resources: It reduces the sort and quantity of the material, especially rarity or costly material and poisonous or harmful material. And when the basic functions are satisfied, the structures of the product can be predigested to great extent, meanwhile different kinds of material with good combinable characteristics can be reused as far as possible. (3) Efficiently utilizing the energy resources: It makes full use of the resources and reduces the consumption of the energy resources in its life cycle. Therefore, the product's greenness isn't embodied in some part or in some phase of the product life cycle, but in every phase during its life cycle.

2.2 The assessment index system of green products

Since green product is the ultimate outcome of green design and green manufacturing, we assess green manufacturing by assessing green products. In fact, green manufacturing is based on the traditional manufacturing by adopting the advanced production mode or technology to improve some performances or renovate some functions of traditional products, and bring forth many kinds of the so-called green products. There are no strict, uniform and exact industrial standards up to now. Therefore, in order to appraise their greenness, we should follow the following principles such as purposefulness, systematicness and completeness, scientificness, comparableness, manipulability and independence to build up green assessment system and assess their greenness synthetically. According to the standards of the green assessment, its index system usually contains four main attributes such as environment, energy, resource and economic phase. For each attribute, under the framework of the environmental standards system issued by ISO, we can divide it into much hierarchy and many indices, until every index of the sub-hierarchy can be quantifiable or comparably describable. At the same time, we divide the indexes into two kinds according to the need of DEA. The bigger its value is, the better it is thought to be. Then the index is called a positive one, for example, the utilization ratio of the energy. On the other hand, if the worse it is thought to be while the bigger its value is, the index is called a negative one just like the investment of production and the consumption of the energy. This may be illustrated by the greenness assessment system such as an inverse tree-shape shown in Fig. 1.

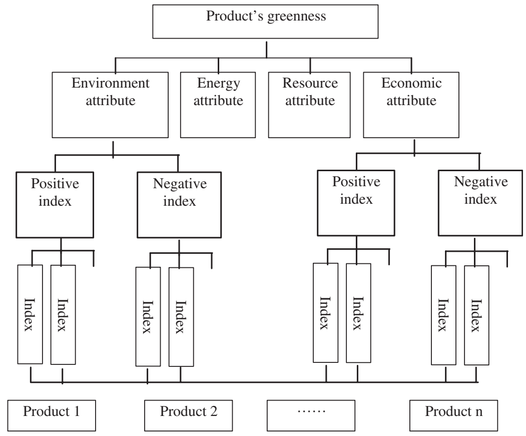

Fig. 1 The assessment system of green products.

3. Greenness Assessment of Products by DEA Approach

Green products are the environmental efficient products. But in the face of multitudinous indexes, it is very difficult to build the function between the indexes and the greenness of products to assess products. However, DEA only has such advantages that there is no need to assume the function between inputs and outputs, but appraise DMUs by constructing their mathematical programming models. The input data is the values of the negative indexes, and the output data is that of the positive indexes. We determine whether the greenness of a product is good or bad according to its efficient degree of DEA.

We list the procedure to build the non-uniform assessment model for greenness assessment of products by DEA approach as follows:

a) Decide the DMU (Decision-making unit) set: Suppose there are n products to be appraised, each product is called one DMU.

b) Select the negative indexes and positive indexes: Suppose that each product has m negative indexes as its inputs and s positive indexes as its outputs. Let x_{ij} denote the value of the i-th input of the j-th DMU and y_{rj} denote the value of the r-th output of the j-th DMU, where $i = 1, \dots, m$; $j = 1, \dots, n$; $r = 1, \dots, s$. Let

$$X_j = (x_{1j}, \dots, x_{mj})^T \geq 0, \quad Y_j = (y_{1j}, \dots, y_{sj})^T \geq 0$$

Then (X_j, Y_j) can represent the j-th DMU.

c) Construct the technical reference product as the $n+1$-th DMU: the value of each input of the so-called technical reference product is defined as follows: the value of each input is the minimum value of the correspond input values of n products while the value of each output is the maximum value of the correspond output values of n products. Hence, we have $n+1$ products to be appraised.

d) Adopt C^2R model of DEA approach to assess the technical efficiency and the scale efficiency of products. That is, the greenness of the j_0-th product is determined by the following linear programming:

$$(D)\begin{cases} \min \theta = V_D \\ s.t. \sum_{j=1}^{n} X_j \lambda_j + s^- = \theta X_{j_0} \\ \sum_{j=1}^{n} Y_j \lambda_j - s^+ = Y_{j_0} \\ \lambda_j \geq 0, \quad j = 1, \dots, n+1 \\ s^+ = (s_1^+, \dots, s_m^+) \geq 0 \\ s^- = (s_1^-, \dots, s_s^-) \geq 0 \end{cases} \tag{1}$$

If the optimal value V_D of (D) is equal to 1, then the j_0-th DMU is weak DEA efficient. If under the above condition, its optimal solution $\lambda^0 = (\lambda_1^0, \lambda_2^0, \dots, \lambda_n^0)^T$, s^{+0}, s^{-0}, θ^0 satisfy that $s^{+0} = 0$, $s^{-0} = 0$, then the j_0-th DMU is DEA efficient.

The optimal value of (D) is actually the assessment index of the greenness of the j_0-th product. Therefore, we can get the assessment indexes of the greenness of n products by solving n linear programming, and put the products into order according to their assessment indexes of the greenness. If the assessment index of the greenness of the j_0-th product is 1, then the product is a green efficient one.

e) The direction to improve the greenness of products:

The project of each DMU on DEA efficient frontier of DMUs gives the direction of each product to improve its greenness. If the green assessment index of the j_0-th product is less than 1, its project on DEA efficient frontier of DMUs can be calculated by the following formulae:

$$\hat{X}_{j_0} = \theta^0 X_{j_0} - s^{-0} = \sum_{j=1}^{n} X_j \lambda_j^0 \tag{2}$$

$$\hat{Y}_{j_0} = Y_{j_0} + s^{+0} = \sum_{j=1}^{n} Y_j \lambda_j^0 \tag{3}$$

It can be proved that the project is DEA efficient.[3,7] In this way, according to the project of the j_0-th product on DEA efficient frontier, we can optimize its input and output quantitatively. In the light of this standard, the product produced by this input-output production scheme, must be DEA efficient. Consequently, it can realize the purpose of bettering its greenness.

The established model in accordance with the above DEA approach above for greenness assessment of products possesses the following features:

(1) It can avoid such things happen as more than one product are all DEA efficient simultaneously.[8)]

(2) It can reflect how to adjust the production schemes to make sure that the considered product attain DEA efficient.

(3) It not only makes full use of the existing information of products, but also uses the information of the technical reference product. This is much more suitable for the need of the assessment theory of green products.

4. Example

We adopt the assessment example of refrigerators in Ref. 6), and assume the assessment indexes system in Table 1. All of indexes are divided into two groups according to the standards of the input and output index, shown in Table 2. All index values of three kinds of refrigerators and the technical reference one are also given in Table 2. By employing the internet application of software DEA 4.0, we calculate the assessment indexes of the greenness of three refrigerators with regard to the reference product and their projects on DEA efficient frontier shown in Table 3.

We can analyze the greenness of refrigerators according to the projects on DEA efficient frontier. Although CFCs is the main air pollution factor in refrigerator sector, and its emission from No. 1 is more than that of No. 2 and No. 3, No. 1 reaches DEA weak efficiency. It shows that the greenness of product is not determined by one of indexes or one of the phases of the production process. The differences between the index values of the projects and the practical values of No. 2 and No. 3 are very large. There are still some problems existing in these two kinds of refrigerators, such as too large scale inputs or lower technical efficiency. As far as No. 2 is concerned, the practical value of the noise index in the usage progress is 45, while its project value is just 40.13. It shows us that the input is too large, that is to say, the noise pollution is too heavy. We must reduce the noise pollution in order to improve its greenness and make the noise value of this kind of product be 40.13. On the other hand, the value of the utilization ratio of the energy must be improved to 56% while its practical value is only 50%. It shows that the

Table 1 The green assessment index system and hierarchical structure of refrigerators.

The Objective level	The greenness of product														
	Environment attribute							Energy attribute		Resource attribute				Economic attribute	
	Air pollution			Water pollution		Noise pollution									
Index level	Co_2	So_2	Fluoride	Pb	Cd	Noise in the production process	Noise in the usage process	The amount of the electricity consumption	The utilization ratio of energy recourses	The utilization ratio of material	The recycle ratio of material	The ratio of poisonous material	The ratio of harmful material	The user cost / the production cost	The environment expense / the production cost

Table 2 The index values of refrigerators.

Refrigerators	The input index												The output		
	CFCs(mg/m^3)	CO_2(mg/m^3)	SO_2(mg/m^3)	P(mg/L)	Suspended substances (mg/L)	Noise in the usage process(dB)	Noise in the production process (dB)	Ratio of poisonous material	Ratio of harmful material	User / product cost	Environment / product cost	Efficiency rate	Utilization ratio of energy resource	Utilization ratio of material	Recycle ratio of material
1	0.006	0.003	0.11	0.12	0.008	43	62	0.1%	0.8%	6.5%	2%	0.86	60%	75%	42%
2	0.005	0.005	0.15	0.10	0.01	45	65	1.5%	2%	7%	4.5%	0.9	50%	70%	35%
3	0.0045	0.004	0.13	0.09	0.007	46	66	1.4%	2.1%	6.4%	4.2%	0.94	45%	65%	40%
4	0.0045	0.003	0.11	0.09	0.007	43	62	0.1%	0.8%	6.4%	2%	0.86	60%	75%	42%

Table 3 The assessment indexes of the greenness of three refrigerators and their projects on DEA efficient frontier.

Refrigerator	Greenness	The input index												The output		
		CFCs (mg/m^3)	CO_2 (mg/m^3)	SO_2(mg/m^3)	P (mg/L)	Suspended substances (mg/L)	Noise in the usage process (dB)	Noise in the production process (dB)	Ratio of poisonous material	Ratio of harmful material	User / product cost	Environment / product cost	Efficiency rate	Utilization ratio of energy resource	Utilization ratio of material	Recycle ratio of material
1	1	0.0045	0.003	0.11	0.09	0.007	43	62	0.001	0.008	0.064	0.02	0.86	0.6	0.75	0.42
2	0.8919	0.0042	0.0028	0.1027	0.084	0.00654	40.13	57.87	0.0009	0.0075	0.0597	0.0187	0.8027	0.56	0.7	0.392
3	0.9524	0.0043	0.029	0.1048	0.0857	0.0067	40.95	59.05	0.001	0.0076	0.61	0.019	0.819	0.57	0.7143	0.4
4	1	0.0045	0.003	0.11	0.09	0.007	43	62	0.001	0.008	0.064	0.02	0.86	0.6	0.75	0.42

utilization ratio of energy resource of this kind of refrigerator is too low, and one of main measures need to be taken for improving the greenness is to increase the utilization ratio of energy resource. The project value also presents how much it need to increase. The other indexes can be analyzed by the same way. Through analyzing the projects, we can apply the specific improvement and adjustment of the schemes for practical production progresses. However, sometimes the project value may be only result in theory and difficult to put into practice. Thus, this is just considered as a target to realize in the future by reforming the production technique of refrigerators to better the greenness of products. These measures contain both decreasing the input such as *CFCs* emission, and increasing the output such as the utilization ratio of energy resource.

5. Conclusions

The paper presents a non-uniform assessment method for greenness assessment of products with the aid of DEA approach, and it proves available by the assessment example. From the assessment results, we can find the established model and procedure have many advantages such as the followings while DEA method is employed to appraise green products comprehensively and synthetically.

(1) It doesn't need to suppose the weighing vector in advance because DEA adopts mathematical programming to realize the non-uniform assessment. And the assessment results are much more impersonal, impartial and reasonable;

(2) It not only assesses whether the greenness of product is good or bad, but also gives the approach to reform the technique of product by calculating the project on DEA efficient frontier of DMUs.

(3) It does work with getting reasonable assessment result even when the number of products is quite few.

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