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# Grey-theory based algorithm for impact assessment of green design

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**Abstract:** Life cycle assessment (LCA) is an important content of green design; the major phase of LCA is impact assessment. After classifying the impact factors, with grey-system theory, the evaluating grey-groups and their whitening weighing functions are defined; the grey-cluster analysis of each classified impact is performed; based on analyzing results, the calculating method of classified impact index is given. By range of action, the impact classes are grouped to three groups — global impact, regional impact, and local impact; the calculating methods of grouped and overall impact index are presented. Finally, an application example of comparative choice of a category of products — three materials, steel, aluminum and engineering plastics is given.

**Key words:** green design; impact assessment; grey-theory; algorithm; impact index

Green design and manufacturing are the only ways to ensure the sustainable development of human society. Through green technology, the whole life cycle (design, manufacture, sale, recycle and disposal) of products can be forwardly controlled, minimizing waste emission, improving products' green degree and enhancing market competitive ability[1].

The method of life cycle assessment (LCA) is a process to assess the environmental impact of product, production technology and activity; in LCA, the energy used, material consumed and environmental waste discharged are identified and quantified. The assessment runs through the whole life cycle of the product, production technology and activity. As the most important phase and the most difficult segment, impact assessment (IA) performs a qualitative and quantitative assessment of the environmental impact of various emissions got in LCA. Commonly, IA is divided into three phases: classification, characterization and valuation[2].

Classification takes emission, having accordant and similar environmental impact, as a class. With classification, the tracks, through which impact factors affect environment, can be proved; the magnitude of impact range can be known, determining the next object assessed.

Characterization quantifies the impact intensity and degree of impact factors. The impact degrees of most factors change greatly depending on environmental conditions and occurring time; the changes are usually non-linear. At present, there exists no feasible method for characterization.

Valuation sums up every classified and quantified impact factor to an index to act as an overall assessment index of the environmental impact. However, there is no acceptable assessment method for environmental impact so far.

Impact assessment can provide more valuable information to both designer and enterprise decision maker to make effective decisions. But because of the complexity of LCA, the existing LCA assessment rarely refers to impact assessment. So far no acknowledged scientific solution exists[3,4]. Schulz gave the analyzing model framework of life cycle inventory of machine parts[5]; Domkundwar put forward an analytic hierarchy process (AHP) based impact assessment method for cutting processes[6].

## 1 Impact Assessment Model of Green Design

### 1.1 Classification of environmental impact

Through a large amount of investigation, the product life cycle inventory (LCI) can be obtained. LCI includes energy consumption, atmosphere emission, water emission, material usage, and solid waste, etc.; each item contains some corresponding impact factors.

The environmental impact of all impact factors was classified into eight classes: ① GWP (global warming); ② OD (ozone destroying); ③ EC (energy consumption); ④ AF (acidification); ⑤ NF (nitrification); ⑥ HT (human toxicity); ⑦ ET (ecological toxicity); ⑧ RD (resource depletion).

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Based on the above classification, the emissions having accordant and similar environmental impact were put into the same class, the ones having no or minimal impact were ignored.

At the same time, the impact classes were grouped by impact range, the grouping result is as follows:

1) Global impact includes GWP, OD, EC, RD;

2) Regional impact includes AF, NF;

3) Local impact includes HT, ET.

### 1.2 Environmental impact assessment model

After the classification of impact factors, the impact indices can be calculated through a weighing algorithm, then the impact indices of three groups, through definite algorithm rule, can be given; with a similar process the overall index can be gained.

The environmental impact assessment model is shown in Fig.1.

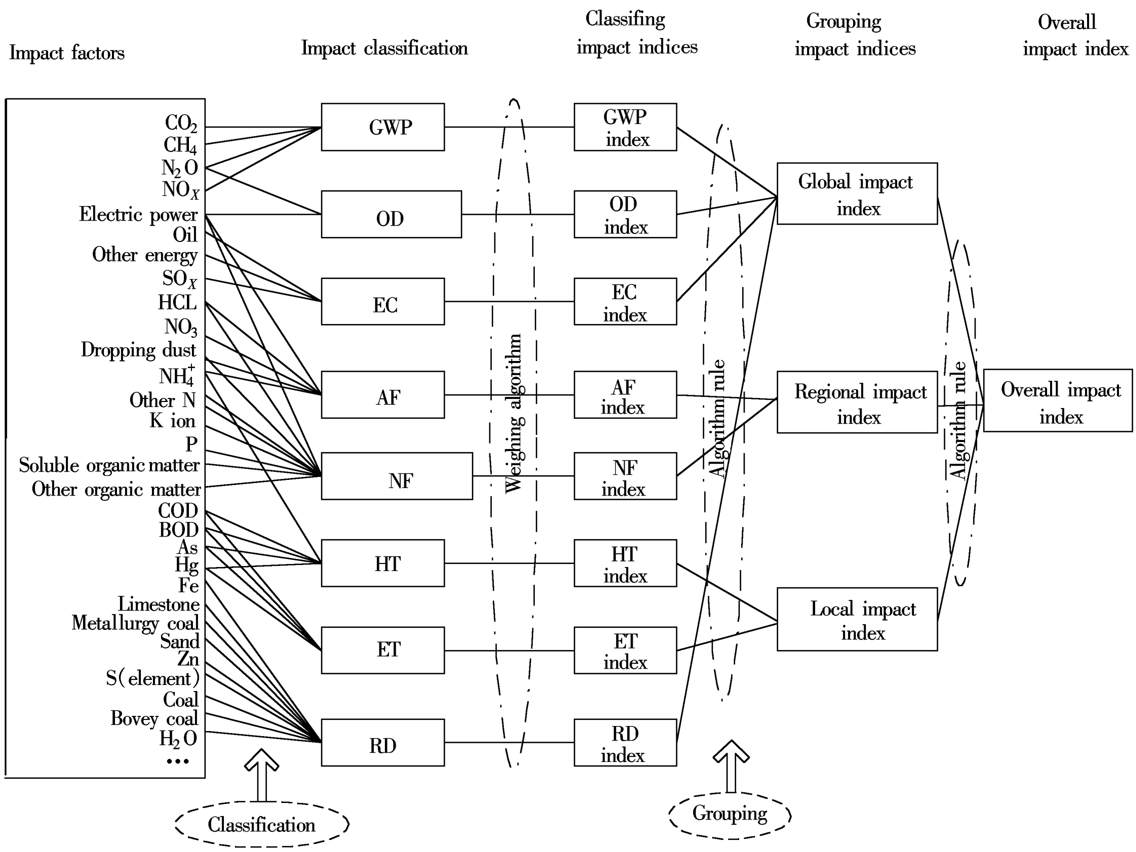


**Fig.1** Environmental impact assessment model

## 2 Grey-Theory Based Algorithm for Impact Assessment

Starting from incompleteness of information, Grey system theory studies and treats a complex system. It studies systems not based on the internal special regularity of a system, but through mathematical treatment of a certain level of observational material of the system, understanding the mechanisms, internal changing tendency and interdependence of the system, from higher level. In case of insufficient system data and conditions not meeting demand, the mathematical method of grey-theory, as a non-statistical method, is a more practical tool[7].

### 2.1 Standard quantification of impact factors

Standard quantification of impact factors can use the following methods.

**Method 1** Assessment of one product

Taking the emission value as a sample value, appointing a standard value for every factor according to standards concerned or empirical value, then defining the whitening weighing function based on the standard value for every factor and doing cluster analysis.

**Method 2** Assessment of one category of products

For $n$ products, the sample value of one of impact factors of a product (for instance $CO_2$) is $y_i$ ($i = 1, 2, \cdots, n$), the standard quantified value $Y_i$ of factor $i$ can be calculated by

$$Y_i = \frac{y_i}{\sum_{j=1}^{n} y_j} \times 100\% \qquad i = 1, 2, \cdots, n \tag{1}$$

## 2.2 Defining of evaluating grey-groups and their whitening weighing functions

### 2.2.1 Evaluating groups

To evaluate the severity of environmental impact, evaluating groups were grouped under five classes: severe impact, deep impact, medium impact, mild impact and slight impact.

### 2.2.2 Whitening weighing functions of evaluating groups

Given the order number of evaluating group $s$, for the second method of standard quantification, the threshold value of each grey-group is defined as follows.

The first grey-group severe impact $s = 1$. Grey value $\otimes_1 \in [75, \infty]$, the whitening weighing function is defined as $f_j^1[75, 90, -, -]$,

$$f_j^1(x) = \begin{cases} 0 & x < 75 \\ \dfrac{x-75}{15} & 75 \leqslant x \leqslant 90 \\ 1 & x \geqslant 90 \end{cases}$$

where $j$ represents the number of impact factors of each impact class. The function graph is shown in Fig. 2.

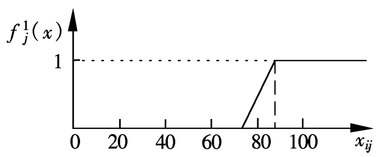


**Fig.2** $f_j^1(x)$ function graph

The second grey-group deep impact $s = 2$. Grey value $\otimes_2 \in [60, 80]$, the whitening weighing function is defined as $f_j^2[60, 70, -, 80]$,

$$f_j^2(x) = \begin{cases} 0 & x \notin [60, 80] \\ \dfrac{x-60}{10} & 60 \leqslant x \leqslant 70 \\ \dfrac{80-x}{10} & 70 \leqslant x \leqslant 80 \end{cases}$$

The function graph is shown in Fig.3.

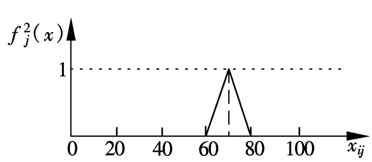


**Fig.3** $f_j^2(x)$ function graph

The third grey-group medium impact $s = 3$. Grey value $\otimes_3 \in [45, 65]$, the whitening weighing function is defined as $f_j^3[45, 55, -, 65]$,

$$f_j^3(x) = \begin{cases} 0 & x \notin [45, 65] \\ \dfrac{x-45}{10} & 45 \leqslant x \leqslant 55 \\ \dfrac{65-x}{10} & 55 \leqslant x \leqslant 65 \end{cases}$$

The function graph is shown in Fig.4.

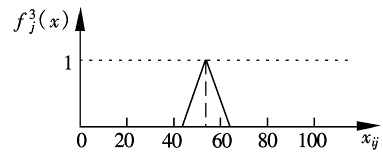


**Fig.4** $f_j^3(x)$ function graph

The fourth grey-group mild impact $s = 4$. Grey value $\otimes_4 \in [30, 50]$, the whitening weighing function is defined as $f_j^4[30, 40, -, 50]$,

$$f_j^4(x) = \begin{cases} 0 & x \notin [30, 50] \\ \dfrac{x-30}{10} & 30 \leqslant x \leqslant 40 \\ \dfrac{50-x}{10} & 40 \leqslant x \leqslant 50 \end{cases}$$

The function graph is shown in Fig.5.

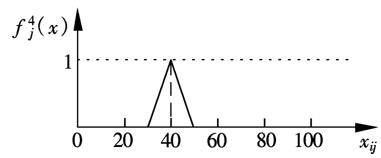


**Fig.5** $f_j^4(x)$ function graph

The fifth grey-group slight impact $s = 5$. Grey value $\otimes_5 \in [0, 35]$, the whitening weighing function is defined as $f_j^5[-, -, 25, 35]$,

$$f_j^5(x) = \begin{cases} 0 & x \notin [0, 35] \\ 1 & 0 \leqslant x \leqslant 20 \\ \dfrac{35-x}{15} & 20 \leqslant x \leqslant 35 \end{cases}$$

The function graph is shown in Fig.6.

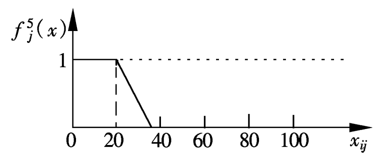


**Fig.6** $f_j^5(x)$ function graph

## 2.3 Decision-making weight, decision-making coefficient and decision-making vector

Given $n$ decision-making objects, $m$ decision-making targets, $s$ grey-groups, $x_{ij}$ ($i = 1, 2, \cdots, n$; $j = 1, 2, \cdots, m$) is the standard quantified value about decision-making target $j$ of decision-making $i$, $f_j^k(*)$ ($j = 1, 2, \cdots, m$; $k = 1, 2, \cdots, s$) is whitening weighing function about grey-group $k$ of target $j$, $\eta_j$ ($j = 1, 2, \cdots, m$) is general weight of target $j$, $\sum \eta_j$

= 1, then the decision-making coefficient about grey-group $k$ of object $i$ is calculated as

$$\sigma_i^k = \sum_{j=1}^{m} f_j^k(x_{ij})\eta_j \qquad (2)$$

The decision-making vector of object $i$ is defined as

$$\boldsymbol{\sigma}_i = \{\sigma_i^1, \sigma_i^2, \cdots, \sigma_i^s\} \qquad i = 1, 2, \cdots, n \quad (3)$$

Decision-making weight can be determined according to experience and standards documents; for instance, the endothermal capacity of factor $CH_4$ exceeds that of $CO_2$ greatly, so the weight value of $CH_4$ should be greater than that of $CO_2$.

### 2.4 Impact index

#### 2.4.1 Classified impact index

Against impact class "*", the impact index of decision-making object $i$ is calculated as

$$I_i^* = 5\sigma_i^1 + 4\sigma_i^2 + 3\sigma_i^3 + 2\sigma_i^4 + \sigma_i^5 \qquad (4)$$

#### 2.4.2 Grouped impact weighing vector and grouped impact index

For an impact group of $n$ impact classes, the contributing-degree to group of an impact class was divided by 10 grades, from great to small, 9, 8, 7, 6, 5, 4, 3, 2, 1 and 0. Through pairwise comparison, a contributing-degree matrix could be constructed, whose element $y_{ij} = y_i / y_j$, where $y_i$ is the contributing-degree of impact class $i$. Naming $\boldsymbol{C} = \{C_1, C_2, \cdots, C_n\}$ as the weighing vector of the impact group, where

$$C_i = \frac{x_i}{\sum_{j=1}^{n} x_j} \qquad x_i = \sqrt[n]{\prod_{j=1}^{n} y_{ij}};\ i = 1, \cdots, n \quad (5)$$

The grouped impact index is calculated as

$$I^* = \sum_{k=1}^{n} C_k I_k^* \qquad k = 1, 2, \cdots, n \qquad (6)$$

#### 2.4.3 Overall impact index

Through the same procedure as above, the overall environmental impact could be treated as an impact group; each group was taken as an impact factor, the overall impact index could be calculated with the same method as the grouped impact index.

## 3 Assessment Example

Recently, the main flow of mechanical manufacturing development is light weight and environmentally-conscious manufacturing. Among many materials used by manufacturing, steel, aluminum and engineering plastics were thought as the most competitive materials. Under the precondition of meeting the performance demand, which material is more favorable to the environment?

Life cycle inventories of the three materials can be got through life cycle investigation. The data handling procedures and results using the above method are related as follows.

### 3.1 Standard quantification and decision-making weight determination of impact factor

Based on method 2 of standard quantification, the standard qualified result and decision-making weight determining result are shown in Tab.1.

**Tab.1** Standard quantified value and decision-making weights of nitrification impact factors

| Factors | Steel | Aluminum | Engineering plastics | Decision-making weight $\eta_j$ |
|---|---|---|---|---|
| $SO_X$ | 96.81 | 1.44 | 1.75 | 0.05 |
| $NO_X$ | 95.59 | 2.55 | 1.86 | 0.10 |
| $NO_3$ | 0 | 8.56 | 91.44 | 0.10 |
| $NH_4$ + | 84.44 | 1.30 | 14.25 | 0.10 |
| Other N | 54.84 | 0.55 | 44.62 | 0.10 |
| Other organic matter | 0 | 1.34 | 98.66 | 0.05 |
| K ion | 0 | 32.65 | 67.35 | 0.10 |
| P | 0 | 5.91 | 94.09 | 0.30 |
| Soluble organic matter | 2.59 | 5.44 | 91.97 | 0.10 |

### 3.2 Decision-making coefficient and vector

The decision-making coefficient and vector are shown in Tab.2.

**Tab.2** Decision-making coefficients and vectors of nitrification impact factors

| Steel $\boldsymbol{\sigma}_1$ | | | | | Aluminum $\boldsymbol{\sigma}_2$ | | | | | Engineering plastics $\boldsymbol{\sigma}_3$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\sigma_1^1$ | $\sigma_1^2$ | $\sigma_1^3$ | $\sigma_1^4$ | $\sigma_1^5$ | $\sigma_2^1$ | $\sigma_2^2$ | $\sigma_2^3$ | $\sigma_2^4$ | $\sigma_2^5$ | $\sigma_3^1$ | $\sigma_3^2$ | $\sigma_3^3$ | $\sigma_3^4$ | $\sigma_3^5$ |
| 0.213 | 0.000 | 0.098 | 0.000 | 0.650 | 0.000 | 0.000 | 0.000 | 0.027 | 0.916 | 0.550 | 0.074 | 0.000 | 0.054 | 0.250 |

### 3.3 Grouped impact weighing vector and grouped impact index

After determining the contributing-degree of each impact class, the grouped weighing vector can be calculated as

$$\boldsymbol{C}_{\text{global impact}} = \{0.166\,7, 0.233\,3, 0.300\,0, 0.300\,0\}$$
$$\boldsymbol{C}_{\text{regional impact}} = \{0.714\,3, 0.285\,7\}$$
$$\boldsymbol{C}_{\text{loacal impact}} = \{0.571\,4, 0.428\,6\}$$

Tab.3 shows the grouped impact indices.

**Tab.3** Grouped impact indices

| Materials | $I_{global\ impact}$ | $I_{regional\ impact}$ | $I_{local\ impact}$ |
|---|---|---|---|
| Steel | 2.492 3 | 3.859 7 | 1.403 9 |
| Aluminum | 1.211 1 | 0.991 4 | 2.608 0 |
| Engineering plastics | 2.006 1 | 1.972 6 | 1.417 9 |

### 3.4 Overall impact index

The followings are the overall impact weighing vector and overall impact indices calculated.

$$\boldsymbol{C}_{impact} = \{0.333\,3, 0.428\,6, 0.238\,1\}$$
$$I_{steel\ impact} = 2.819\,2$$
$$I_{aluminum\ impact} = 1.449\,5$$
$$I_{engineering\ plastics\ impact} = 1.851\,7$$

## 4 Conclusion

After classifying the impact factors of emissions, with grey-system theory, the evaluating grey-groups and their whitening weighing functions are defined; the grey-cluster analysis of each classified impact is performed; based on analyzing results, the calculating method of classified impact index is given. By range of action, the impact classes are grouped to three groups — global impact, regional impact, and local impact; the calculating methods of grouped and overall impact index are presented. Finally, to illustrate the application of above method in comparative choice of a category of products, an example of three materials, steel, aluminum and engineering plastics is given. With the result, it is intuitionistic that the environmentally-conscious performance of aluminum is the best, engineering plastics takes the second place, and steel is the last one.

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# 基于灰色系统理论的绿色设计影响评估算法研究


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**摘要**: 生命周期评估(LCA)是绿色产品设计的一项重要内容, 影响评估是 LCA 的重要阶段.本文将各种排放物影响因子进行分类后, 应用灰色系统理论, 提出了影响评估灰类划分及其白化权函数, 对各影响类别进行了灰色聚类分析, 然后根据分析结果给出了分类影响指数的计算方法.根据各影响类别的作用范围, 将影响类别按全球影响、区域影响、本地影响进行了分组, 并给出了分组影响指数以及总体影响指数的计算方法.最后, 以设计中的 3 种材料钢、铝、工程塑料为例, 说明了以上方法在一类产品比较选择中的应用.



**关键词**: 绿色设计; 影响评估; 灰色理论; 算法; 影响指数

**中图分类号**: TB497