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A mathematical model for environmental risk assessment in manufacturing industry①

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[Abstract] Environmental conscious manufacturing has become an important issue in industry because of market pressure and environmental regulations. An environmental risk assessment model was developed based on the network analytic method and fuzzy set theory. The "interval analysis method" was applied to deal with the on-site monitoring data as basic information for assessment. In addition, the fuzzy set theory was employed to allow uncertain, interactive and dynamic information to be effectively incorporated into the environmental risk assessment. This model is a simple, practical and effective tool for evaluating the environmental risk of manufacturing industry and for analyzing the relative impacts of emission wastes, which are hazardous to both human and ecosystem health. Furthermore, the model is considered useful for design engineers and decision-maker to design and select processes when the costs, environmental impacts and performances of a product are taken into consideration.

[Key words] environmental risk assessment; mathematical model; fuzzy set theory; network analysis

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1 INTRODUCTION

"Green" product and design for environment (DFE) have become important issues in manufacturing industry because of market pressure (eco-label products) and environmental regulations (e. g. ISO 14000). This has spurred recent research to develop a reliable environmental risk assessment model for analyzing the environmental impact potentials of wastes generated in manufacturing a product.

Currently, several impact analysis and evaluation methods are available, such as the health hazard scoring (HHS)[1,2], the Swiss eco-point (SEP) method, the sustainable process index (SPI)[3], the life-cycle assessment (LCA, defined by SETAC)[4], and the other assessment models[5~9]. Anyway, to varying degrees, those readily available methods are narrow in assessment scope (only considering human health risk, or ecosystem risk), or too complicated (too many assessing procedures or very complex data system), or lack of sufficient consideration of the uncertain information in environmental impact assessment[10]. Therefore, a simple and feasible environmental risk assessment (ERA) model, which considers both ecosystem and human health risk, is desired. To meet this requirement, an ERA model has been developed by Wenger and Rong[11] and applied to study the environmental risk of the Green Bay, Lake Michigan, USA[12] and the St. Croix National Scenic Riverway[13]. This model is based on a data matrix $\boldsymbol{X} = (x_{ik})$, which provides the basic information for assessment. However, the information of this data matrix is determined by the judgment of experts. The judgment of experts is a kind of vagueness and uncertainty information, which may result in unsatisfied assessment or even result in unexpected misleading assessment results. This is because the information depends on individual and regional factors. The data information may vary with the background of individual experts (their knowledge on the system being assessed) and manufacturing region being considered. To overcome this limitation, in this paper, we propose a mathematical model for environmental risk assessment by modifying Wenger and Rong's model with the "interval analysis method".

2 METHODOLOGY

In processes of manufacturing a product, each process may generate some kinds of wastes (S_1, S_2, …, S_m). These wastes may to some degree (weighting factors, w_{mn}) be hazardous to human or ecosys-

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tem health (potential impact categories, Y_k). The overall environmental risk (EI) can be assessed by combining the amounts of these potential impact categories with their weighting factors (β_k). The flow chart of the environmental risk assessment model proposed in this paper is illustrated in Fig. 1. Therefore, the methodology of this ERA model will focus on three aspects: 1) to determine the impact scales of various stressors based on different impact categories, 2) to rank the impact scales of different stressors, and 3) to evaluate the overall environmental risk in manufacturing a product.

2.1 Determining impact scales of various stressors

The objective of impact scaling is to characterize the inherent or potential hazards associated with a particular stressor (waste). As indicated above, the starting point in the Wenger and Rong's methodology is a set of alternatives, S_1, S_2, …, S_m, and a set of criteria or decision factors, C_1, C_2, …, C_n. These determine the rows and columns, respectively, of a data matrix $\boldsymbol{X} = (x_{ik})$, as shown in Fig. 2. The entry x_{ik} is a number, which represents the level or value of a decision factor for a given alternative. In case that information for the criteria is qualitative, data on a semantic scale can be transformed to a scale from 0 to 1. x_{ik} in the data matrix is determined by persons with scientific expertise relevant to the system being assessed. In our environmental risk assessment model, the sets of alternatives and criteria are environmental stressors (wastes) and impact categories, respectively. The data matrix is thus an impact matrix, in which x_{ik} measures the level of the stressor i contributing to a loss of ecosystem health and human health integrity based on the category k. However, the determination of x_{ik} is based on the on-site monitoring data instead of subjective opinions. The determination of x_{ik} is described below in detail.

Assuming that a manufacturing process generates a set of wastes, $S = \{S_1, S_2, \cdots, S_i, \cdots, S_m\}$, and the on-site monitoring emission amounts of these wastes can be expressed as a set $E = \{E_1, E_2, \cdots, E_i, \cdots, E_m\}$. The set of the international/national allowed maximum emission standards for the corresponding wastes is $V = \{V_1, V_2, \cdots, V_i, \cdots, V_m\}$. To determine x_{ik} ($i = 1, 2, \cdots, m$; $k = 1, 2, \cdots, n$), we employ a so called "interval analysis method" and eco-indicator method. We define that the impact scale of waste i (stressor i) is 10 when the emission amount E_i of the waste i is equal to or more than V_i. When the emission amount E_i of the waste i is less than V_i, we partition the interval $[0, V_i)$ into ten subintervals, and define that their corresponding impact scales range from 1 to 10 as shown in Table 1. Given a kind of waste i, its emission amount, E_i, is practically measured on the manufacturing sites by the sampling method. Practically speaking, the value E_i is in fact a random variable in an interval of $[a_i, b_i]$ and its probability density function $f_i(x)$ can be obtained by the statistical method. The probability of E_i belonging to one of the ten intervals can be obtained by computing

$$P_{i1} = \int_0^{V_i/10} f_i(x)\,dx \tag{1}$$

$$P_{i2} = \int_{V_i/10}^{2V_i/10} f_i(x)\,dx \tag{2}$$

$$P_{i10} = \int_{V_i}^{\infty} f_i(x)\,dx \tag{3}$$

The expected impact scale of the stressor i, A_i, is the sum of the products of the impact scales and their corresponding probabilities, i. e. $A_i = 1P_{i1} + 2P_{i2} + \cdots + 10P_{i10}$. The values of A_i for each stressor

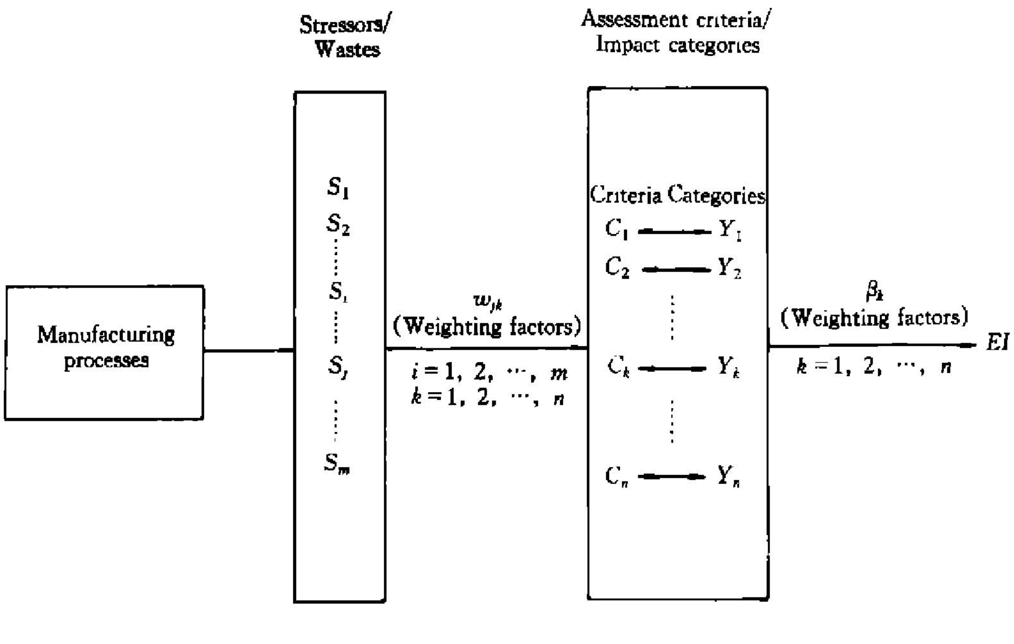

Fig. 1 Schematic illustration of environmental assessment model

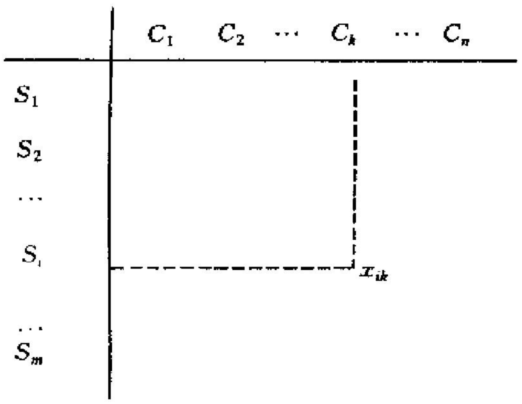

Fig. 2 Data matrix

Table 1 Impact scale of waste i by isometric interval analytic

Interval	Impact scale
$[0 \quad V_i/10)$	1
$[V_i/10 \quad 2V_i/10)$	2
$[2V_i/10 \quad 3V_i/10)$	3
$[3V_i/10 \quad 4V_i/10)$	4
$[4V_i/10 \quad 5V_i/10)$	5
$[5V_i/10 \quad 6V_i/10)$	6
$[6V_i/10 \quad 7V_i/10)$	7
$[8V_i/10 \quad 9V_i/10)$	8
$[9V_i/10 \quad V_i)$	9
$\geqslant V_i$	10

are given in Table 2. Since the stressor i has different contributions to different impact categories, the final data x_{ik} of the impact matrix will be obtained by assigning weighting factors w_{ik} of different categories to the expected impact scales, i. e. $x_{ik} = A_i \times w_{ik}$. For the determination of w_{ik}, we employed the method developed by the Danish Environmental Design of Industry Products (EDIP)[14]. In the EDIP method, these weighting factors take values with a specific reference material related to an impact category according to the rules of Eco-Indicator'95, RIVM (NL Environmental Ministry):

GWP (Global Warming Potential) for wastes: weight ratio (WR), compared to CO_2= 1;

Table 2 Impact scale of stressors in manufacturing process

Stressors	S_1	S_2	...	S_i	...	S_j	...	S_m
Impact scale	A_1	A_2	...	A_i	...	A_j	...	A_m

ODP (Ozone Depletion Potential) for wastes: (WR), compared to CFC-11= 1;

POCP (Photochemical Ozone Creation Potential) for wastes: (WR), compared to ethene= 1;

AP (Acidification Potential) for wastes: (WR), compared to SO_2= 1;

NEP (Nutriment Enrichment Potential) for wastes: (WR), compared to phosphate= 1;

TP (Toxicogenic Potential) for wastes: (WR), compared to lead= 1;

CP (Carcinogenic Potential) for wastes: (WR), compared to PAH= 1.

Finally, an environmental impact scale matrix of the environmental assessment for the stressor $i(S_i)$ based on the potential impact category $k(C_k)$ is obtained as shown in Table 3.

2.2 Ranking impact scales of different stressors

The ranking purpose is to identify dominance

Table 3 Environmental impact matrix for environmental impact assessment

Stressors	Impact categories (assessment criteria)					
	C_1	C_2	...	C_k	...	C_n
S_1	x_{11}	x_{12}	...	x_{1k}	...	x_{1n}
S_2	x_{21}	x_{22}	...	x_{2k}	...	x_{2n}
...	...	...	...	...	...	...
S_i	x_{i1}	x_{i2}	...	x_{ik}	...	x_{in}
...	...	...	...	...	...	...
S_j	x_{j1}	x_{j2}	...	x_{jk}	...	x_{jn}
...	...	...	...	...	...	...
S_m	x_{m1}	x_{m2}	...	x_{mk}	...	x_{mn}
$Y_k = \sum_{i=1}^{m} x_{ik}$	$Y_1 = \sum_{i=1}^{m} x_{i1}$	$Y_2 = \sum_{i=1}^{m} x_{i2}$	...	$Y_k = \sum_{i=1}^{m} x_{ik}$	...	$Y_n = \sum_{i=1}^{m} x_{in}$
Weighting factors	β_1	β_2	...	β_k	...	β_n

relationships between pairs of environmental impact potentials of stressors. The analytic method of this assessment work in our model is the same as that in Wenger and Rong's environmental risk assessment methodology, which is based on a fuzzy dominance relation as described in Ref. [15].

For a pair of stressors i and j, $D_k(i, j)$ expresses the relative dominance measure of the stressor i to the stressor j and is defined as follows:

$$D_k(i, j) = \begin{cases} 1 & (x_{ik} - x_{jk} > 0) \\ 0 & (x_{ik} - x_{jk} < 0) \\ 0.5 & (x_{ik} - x_{jk} = 0) \end{cases} \quad (4)$$

where $k = 1, 2, \cdots n$; $i = 1, 2, \cdots, m$; and $j = i + 1, i + 2, \cdots, m$.

Then construct a matrix $\boldsymbol{R} = (r_{ij})$, where

$$r_{ij} = \begin{cases} \sum_{k=1}^{n} D_k(i, j) & (i \neq j) \\ 0 & (i = j) \end{cases} \quad (5)$$

where $i, j = 1, 2, \cdots m$.

The matrix $\boldsymbol{R} = (r_{ij})$ is displayed in Table 4. The row sum, $\sum_{j=1}^{m} r_{ij}$, is a measure of the degree to which the stressor i dominates the other stressors. If the row sum of the stressor s, $\sum_{j=1}^{m} r_{sj}$, is the largest one among $\sum_{j=1}^{m} r_{ij}$ $(i = 1, 2, \cdots, s, \cdots, m)$, then the top rank is given to the stressor s and defined as 1. The rank numbers of the other stressors are determined by R_i, the ratio between $\sum_{j=1}^{m} r_{ij}$ $(i \neq s)$ and $\sum_{j=1}^{m} r_{sj}$, i. e.

$$R_i = \frac{\sum_{j=1}^{m} r_{ij}}{\sum_{j=1}^{m} r_{sj}} \quad (i = 1, 2, \cdots, m \text{ and } i \neq s) \quad (6)$$

In this environmental impact assessment process, it is appropriate to rank the stressors in the order of descending values of $R_i (i = 1, 2, \cdots, m)$.

Table 4 Matrix $\boldsymbol{R}$ together with sum of entries in row i of matrix $\boldsymbol{R}$

	S_1	S_2	…	S_i	…	S_j	S_m	$\sum_{j=1}^{m} r_{ij}$
S_1	r_{11}	r_{12}	…	r_{1i}	…	r_{1j}	r_{1m}	$\sum_{j=1}^{m} r_{1j}$
S_2	r_{21}	r_{22}	…	r_{2i}	…	r_{2j}	r_{2m}	$\sum_{j=1}^{m} r_{2j}$
…	…	…	…	…	…	…	…	…
S_i	r_{i1}	r_{i2}	…	r_{ii}	…	r_{ij}	r_{im}	$\sum_{j=1}^{m} r_{ij}$
…	…	…	…	…	…	…	…	…
S_j	r_{j1}	r_{j2}	…	r_{ji}	…	r_{jj}	r_{jm}	$\sum_{j=1}^{m} r_{jj}$
…	…	…	…	…	…	…	…	…
S_m	r_{m1}	r_{m2}	…	r_{mi}	…	r_{mj}	r_{mm}	$\sum_{j=1}^{m} r_{mj}$

$i, j = 1, 2, \cdots, k, \cdots m$

$\sum_{j=1}^{m} r_{ij}$ —The sum of the environmental impact potential of stressor $i (i = 1, 2, \cdots, m)$

2.3 Evaluating overall environmental risk

The total environmental risk can be obtained by combining the network analysis method with the fuzzy set theory[16]. The overall environmental risk is defined as EI, which is given by

$$EI = \sum_{k=1}^{m} Y_k \beta_k \quad (7)$$

$$Y_k = \sum_{i=1}^{m} x_{ik} \quad (k = 1, 2, \cdots, n) \quad (8)$$

where Y_k denotes environmental impact potential of category k contributed by m kinds of hazardous materials from a process. Y_k is the column sum, $\sum_{i=1}^{m} x_{ik}$ $(i = 1, 2, \cdots, m$, and $k = 1, 2, \cdots, n)$ as shown in Table 3. β_k is the weighting factor of the impact category k. It considers the relative contribution of impact category k to the overall environmental risk and can be calculated by a methodology proposed by HUI et al[17].

3 CONCLUSION

Environmentally friendly manufacturing can not be overlooked by manufacturers and designers. In this paper, an environmental risk assessment model is developed based on combining a so-called "interval analysis method" with the network analytic method and fuzzy set theory. Compared to Wenger et al's method, this "interval analysis method" of determining data information in an impact matrix has an advantage of objectiveness and accuracy. This is because the data information is on-site monitoring data instead of human judgment. Furthermore, the data information is gotten from production sites of a system being considered. This unquestionably avoids the flaws, which may be introduced by expert individuals when they consider different systems of manufacturing the same type of products with different production scales, different recycling facilities, or different raw materials used in production. Consequently, this model improves the data quality in the data matrix and thus supports a better environmental risk assessment. It is believed that this model provides simple, practicable and effective methodology on evaluating the overall environmental risk of manufacturing processes and analyzing the relative importance of emission wastes, which are hazardous to human and ecosystem health.

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