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Integrated Assessment of Environmental and Economic Performance of Chemical Products Using Analytic Hierarchy Process Approach*

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Abstract With the increasing public consciousness on environmental issues, chemical products and process designs require simultaneous satisfaction and compromise of environmental and economical requirements. To fulfill the two conflicting while complementary objectives, a systematic approach for life cycle design of a chemical product is proposed in this article. Multiattribute decision-making is adopted in a trade-off consideration of both technical economical evaluation and environmental impacts assessment using the analytic hierarchy process (AHP) approach. On the basis of an evaluation of the relative importance of the criteria multicriteria decision making is performed. In this study, an AHP model is used to derive single a criteria score by analyzing the environmental impact and life cycle cost of a product, respectively. And a fluctuant weight analysis is put forth to calculate the integrated index of the product to enable products to be ranked or selected intuitionally and conveniently. The proposed AHP model has been applied to a case study, a comparative study on chamber cleaning with NF_3 and C_2F_6. The results show that the proposed AHP model is capable of providing a rational and relevant evaluation.
Keywords life cycle assessment, life cycle cost, analytic hierarchy process, chemical product

1 INTRODUCTION

Traditional approaches for chemical product development pay attention to the methodology of increasing financial benefit. With the improvement of living standards and the enhancement of environmental awareness, the impact of environment should be taken into consideration at the initial stage of the product design. In order to meet the conception of sustainable development, there is a potential pressure for contemporary chemical entrepreneurs or engineering researchers to adopt whole life cycle thinking to product design[1,2]. Consequently, the new challenges that arise for chemical engineering researchers are: to devise methodologies to shorten the product-process development cycle to meet the market demands and to develop the products that are friendly to the mankind and the environment.

In this article, the procedures and results that lead to the evaluation of the performance of cleanings for chemical vapor deposition chamber are discussed in detail. Initially, the main ideas and process of implementation of life cycle assessment (LCA) in the chemical product design are briefly described in Section 2, and then the conception of life cycle cost (LCC) is introduced in Section 3, which is used as a criterion for assessing the product. An analytic hierarchy process (AHP) model for integrating the assessment of the economical and environmental performance is presented in detail in Section 4. Described in Section 5 is the case study used to illustrate the availability of this model, and finally a conclusion is drawn.

2 LIFE CYCLE ASSESSMENT OF CHEMICAL PRODUCT DESIGN

In view of the environmental impact, reduction of pollution by implementing cleaner technologies or processes has received attention in the chemical industries, and the end-of-the-pipe technologies, such as filtering or cleaning solutions, aimed at reducing the amount of harmful emission and substances released from manufacturing facilities, have been applied widely. It has been observed that although efforts have been made to optimize the wastes discharge in one unit, this has increased the total environmental burden and impacts[3]. Therefore, it is very important and necessary to consider the environmental burden and adverse impact caused by any change or modification in the process and allied facilities in a holistic way. As a systematic analysis technology, LCA has been identified as a powerful tool to estimate the environmental impacts associated with the whole life cycle of products. The LCA methodology is still under development. At present, the methodological framework comprises four phases, as shown in Fig.1: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment, and (4) interpretation[4].

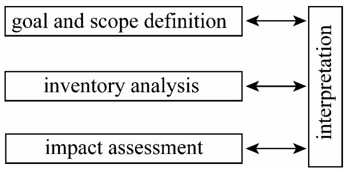

Figure 1 Life cycle assessment framework[4]

In the last decade, the use of LCA as a tool for assessing the environmental impacts of products and processes has gained wide acceptance, and in the chemical industry LCA has been applied comprehensively in the process of modification, selection, and optimization of products design. Kniel *et al*.[5] presented the LCA case study of a nitric acid process

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considering the environmental and economic constraints. By further studies, Hernandez *et al*.[6] proposed a mathematical model to minimize the environmental impacts that are subsequently used for deciding the optimal degree of pollution abatement. Azapagic[7] appreciably advocated in favor of the LCA based design and decision-making and have discussed the LCA application in the evaluation of the process performance for various Boron products. Spath and Mann have demonstrated the successful application of the LCA in evaluating different stages of natural gas combined with the cycle power generation system. This report clearly emphasized the strength of the LCA in identifying and screening environmental burdens at various life stages of the plant, which enabled development of targeted remedial goals[8]. In China also, many attempts also have been made in the application of LCA, but the efforts mainly focused on life cycle inventory analysis and the erection of assessment indices to evaluate the environmental performance of products, processes or services[9—12], whereas there was little research on the means of using LCA to optimize product processes or product designs.

3 LIFE CYCLE COST OF CHEMICAL PRODUCT DESIGN

LCA has the ability to focus on information with regard to the environmental releases, burdens, or impacts of the system under study. However, besides satisfying the important requirements of environmental performance, cost, or economic aspects that are usually included in any company's decision making activities, should also be considered at the early stage of product development to judge whether it is economically feasible to improve or develop a product system. Lundie argued that no design project should proceed to the final stages before costs are considered, and cost estimates should be made throughout the early stages of the design project, even when complete specifications are not available[13]. Kniel *et al*.[5] attempted accommodating both economic and environmental considerations in the design and operation of a process. Qian *et al*.[14] put forth LCC to provide useful information for rational chemical product designs. In this perspective, it will be pointed out that estimating the cost of a product system is much more complex than estimating the cost of a new piece of equipment because many variables and intangibles are involved in it. However, cost consideration is necessary in deciding whether the development of new product system is worth pursuing and whether further capital should be invested in the product improvement project.

Throughout the whole life cycle of the product, there are many decision requirements for decision-making that are both technical and non-technical in nature. In most cases, especially in the earlier stages, these decisions have life-cycle implications and definitely affect LCC, which refers to all costs associated with the system or products as applied to a defined life cycle[15—17]. The framework of LCC is shown in Fig.2. It is the total cost that a firm incurs, from the time of raw material extraction to the disposal of any

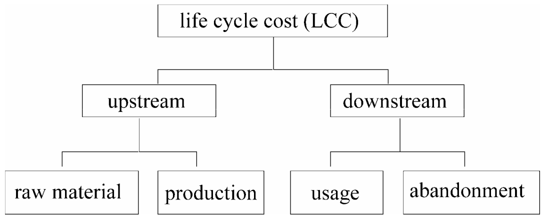

Figure 2 Framework for life cycle costing of a chemical product design[2]

wastes or by-products and beyond, as long as liabilities or other costs can remain. It is determined by identifying their cost in each phase of the life cycle, applying the appropriate estimate approach, and ultimately accumulating the costs for the entire span of the life cycle.

Many researchers argue that the main option for expanding the domain of LCA seems to be in the combined analysis of environmental effects and costs. Several attempts have been made to try and combine the results of environmental evaluations with economic consideration. However, there appears to be no established methodology in the literature for integrating environmental and economic assessments. In this article, AHP with fluctuant weight analysis is adopted for an integrated assessment of the environmental and economical performance of chemical products to screen the environmental friendly alternatives.

4 AN AHP MODEL FOR INTEGRATED ASSESSMENT OF ECONOMIC AND ENVIRONMENTAL PERFORMANCE

4.1 The structure of the AHP model

The AHP is a powerful and flexible multicriteria, decision-making method for complex problems, and it has been used in many governmental and industrial applications[18,19]. These applications include multicriteria decision-making problems in the areas of environmental protection, scheduling, project evaluation, and strategic planning[20]. The AHP combines both qualitative and quantitative aspects of complex problems by means of a hierarchical structure. The AHP is used to break down a complex and unstructured problem into its component parts, and at the same time uses the facts and judgments of key individuals to relate and prioritize the components, and synthesizes the results[21,22].

In the construction of the AHP model, the selection of criteria is very essential for the reliability and rationality of the assessment results. Many environmental indices are available in the literature to evaluate the environmental performances of products[23,24]. On the basis of the theoretic framework of LCA, some impact categories, which has received considerable attention, such as global warming potential (GWP), ozone depletion potential (ODP), photochemical oxiden creation potential (POCP), acidification potential (AP), cancer hazard potential (CHP), non-cancer hazard potential (nCHP), and ecotoxicity potential (ETP), are used in this article.

The structure of the AHP model for the integrated assessment of environmental and economic performances of chemical products for the scenarios alternatives is shown in Fig.3. In the AHP model, the top level of the hierarchy specifies the goal, and intermediate levels specify criteria and subcriteria, which reflect successive categorizations of environmental performance and economic performance. The lowest level corresponds to the inputs associated with chemical product alternatives. Based on the different levels, criteria and subcriteria are prioritized.

In the formulated AHP model, the alternatives under evaluation are denoted as A_i ($i=1, 2,\cdots, n$). The criteria used for the comparative analysis are LCC and environmental impact (EI). The subcriteria are denoted as S_j and E_j ($j=1, 2,\cdots, m$) from left to right, where m is the number of subcriteria. The value of the contribution of alternative A_i on subcriteria E_j is denoted as u_{ij}.

4.2 Determining the priority of each subcriteria

Constructing the comparison matrix: Each of the criteria has m number of subcriteria. To determine the priority of the subcriteria, a pair-wise comparison matrix, $\boldsymbol{B}$, needs to be constructed according to their individual relative importance, as showing in Table 1. For the relative model of comparison, entries b_{ij} are determined by the relative importance of subcriteria i and j (the numerical values are shown in Table 2) and $b_{ij}=1/b_{ji}$.

Table 1 The structure of the judgment matrix

	$\boldsymbol{B}_1$	$\boldsymbol{B}_2$	$\cdots$	$\boldsymbol{B}_j$
$\boldsymbol{B}_1$	b_{11}	B_{12}	$\cdots$	b_{1j}
$\boldsymbol{B}_2$	b_{21}	B_{22}	$\cdots$	b_{2j}
$\vdots$	$\vdots$	$\vdots$		$\vdots$
$\boldsymbol{B}_j$	b_{j1}	b_{j2}	$\cdots$	b_{jj}

Determination of the weight of each subcriterion: After the comparison matrix has been determined, the vector of weight, $\boldsymbol{W}_l$ for $\boldsymbol{B}_j$, is computed. The initial step to obtain $\boldsymbol{W}_l$ is to change matrix $\boldsymbol{B}$ into matrix $\boldsymbol{C}$, that is, every entry in $\boldsymbol{B}$ is standardized by normalizing every column one after the other. Then all the elements in each row in $\boldsymbol{C}$ are summed up, resulting in a column vector. This column vector is normalized to obtain the vector of weight, $\boldsymbol{W}_l=(w_{1l}, w_{2l},\cdots, w_{jl})^{\mathrm{T}}$. Finally, the consistency index (CI), which indicates the deviation from consistency, is calculated to judge the rationality of weight. It should be pointed out that if the CI doesn't meet consistency requirement, the comparison matrix $\boldsymbol{B}$ needs to be constructed again. CI is determined using Eq.(1)

$$\mathrm{CI}=\frac{\lambda_{\max}-j}{j-1} \tag{1}$$

where $\lambda_{\max}$ is the principle eigenvalue of $\boldsymbol{B}$.

Table 2 Comparison scale used to complete the weighting matrices

Numerical values	Verbal scale
1	both criteria equally important
3	left is slightly more important than top
5	left is moderately more important than top
7	left is much more important than top
9	left is extremely more important than top
2, 4, 6, 8	intermediate values

4.3 Evaluating alternatives

Determination of $\mathbf{MA}_l$: For m number of subcriteria, there are m number of matrices, $\mathbf{MA}_l$ ($l=1, 2, \cdots, m$), each being a comparison matrix of the alternatives with respect to each other's contribution. The matrix is determined as follows:

$$\mathbf{MA}_l=(a_{ij})\ (i, j=1, 2)$$

In this comparison matrix, entries a_{ij} are determined by u_{ij}. For example, given subcriteria, E_2, and two alternatives, A_1 and A_2, the value of the contribution of alternatives to E_2 are u_{12} and u_{22}, respectively. The

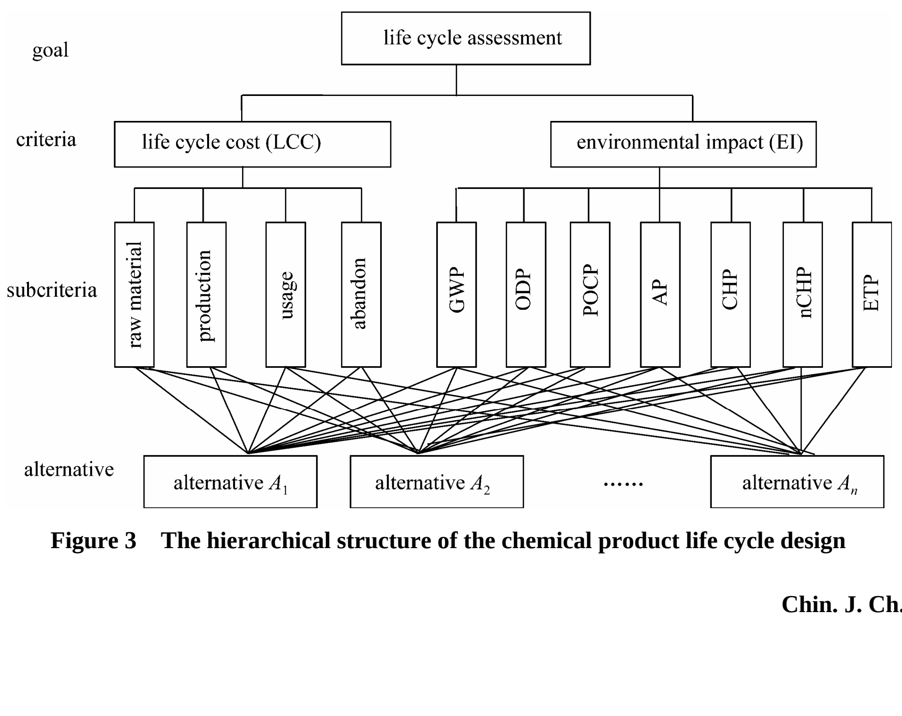

Figure 3 The hierarchical structure of the chemical product life cycle design

Table 3 Environmental impacts potential for the two chamber cleanings

	E_1	E_2	E_3	E_4	E_5	E_6	E_7
NF_3	243150	52	2984	0	8263	1472188	2383
C_2F_6	79157577	7349	6103	0	21803	548490	47483

numerical value of a_{ij} is given by Eq.(2).

$$a_{ij} = \frac{u_{i2}}{u_{j2}} \quad (i,\ j=1,\ 2) \tag{2}$$

So the matrix $\mathbf{MA}_2$ is determined as follows:

$$\mathbf{MA}_2 = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} u_{12}/u_{12} & u_{12}/u_{22} \\ u_{22}/u_{12} & u_{22}/u_{22} \end{bmatrix}$$

Determination of $\mathbf{WA}_l$. Once the comparison matrix is determined, the vector of weight, $\mathbf{WA}_l$ for $\mathbf{MA}_l$, is computed. The initial step to obtain $\mathbf{WA}_l$ is to sum up all the elements in each row in $\mathbf{MA}_l$, resulting in a column vector. This column vector is normalized to obtain the vector of weight, $\mathbf{WA}_l=(w_{1l}, w_{2l},\cdots, w_{nl})^{\mathrm{T}}$.

4.4 Determine the score of single criteria

The performance of the product in the aspect of different criteria can be evaluated by comparing their score. For this purpose, the initial step is to construct a matrix $\boldsymbol{M}$ with $\mathbf{WA}_l$. Then the vector of weight $\boldsymbol{W}_l$ is multiplied by $\boldsymbol{M}$, resulting in the score of single criteria for alternatives. For alternative products, hereto, designers can choose a promising alternative with respect to an ascertain criteria based on its score. In contrast to conventional AHP, however, here fluctuant weight analysis technology is adopted to calculate the score of single criteria. The weights are not constant but fluctuant and are based on the decision-maker's preference or knowledge, so the decision-maker can select more competitive alternatives in a perspective view.

5 CASE STUDY

In the manufacture of integrated circuits, multiple thin film depositions are carried out by processes that employ plasma enhanced chemical vapor deposition (PECVD). Periodic cleaning of the internal surfaces of the deposition reactors is necessary to maintain production yield. Chamber cleaning is usually carried out by utilizing fluorine chemistry to convert solid residues into volatile gaseous by-products that can be pumped out of the CVD reactor using vacuum pumps. Perfluorocarbon (PFC), such as C_2F_6, and NF_3 are often employed as the source of reactive fluorine in PECVD chamber cleaning. The alternative cleaning gases have their respectively merits. For a comprehensive understanding and to illustrate the applicability of the formulated AHP C_2F_6 and NF_3 are used as case objects. The selection of etch gases for the chamber cleaning processes depends on the result of AHP.

5.1 Life cycle inventory

Having defined the goal and scope, life cycle inventory is performed from raw material extraction to production, usage, and abandonment. However, in the process of using NF_3 and C_2F_6 for CVD chamber cleaning, some harmful materials and nonreaction raw materials are released in the form of gas. To facilitate LCA study, some simplifications are made: (1) the treatment of wastes in the abandonment stage is integrated into usage stage; (2) LCC in abandonment stage is also omitted; (3) the benchmark function is the production of $1000\mathrm{kg\cdot h^{-1}}$ NF_3 and C_2F_6. Life cycle inventory data mostly refer to Ref.[25] and are partly assembled from the industrial and governmental statistic data. After carefully gathering and analyzing data, the environmental impact potential of the wastes emitting from the two product life cycles are summarized in Table 3, whereas Table 4 represents the LCC in each stage.

Table 4 LCC for the two chamber cleanings (dollar)

	S_1	S_2	S_3	S_4
NF_3	12000	6800	4800	—
C_2F_6	8000	3500	2900	—

5.2 Life cycle assessment

The selection process of a CVD chamber cleaning is achieved through evaluating its economical and environmental performances. The economic and environmental hierarchies are constructed as shown in Fig.3, and the number of alternatives is two in this case. The comparison matrix for LCC and EI are constructed according to the method described in section 4.2, and their relative weight (RW) against the individual weight as well as the relative weight score of each subcriteria, are calculated as shown in Tables 5 and 6. Their relative CI are also calculated to ensure the consistency of the comparison matrix. The column, RW, in Tables 5 and 6 show the vector of weight, $\boldsymbol{W}_1$ for LCC and $\boldsymbol{W}_2$ for EI, respectively. From the Table 5, it can be judged that the cost relative to raw material acquirement and product manufacture accounts for the maximum proportion of the cost of LCC (75% of the total cost), and therefore reducing this cost to a large extent can decrease LCC remarkably. In the same way, CHP and nCHP of materials released from the product life cycle are worth being paid more attention to, as they are the main subcriteria in evaluating the environmental performance of a product, as shown in Table 6.

Table 5 Relational score and relative weight for LCC against individual score and weight

LCC	S_1	S_2	S_3	S_4	RW
S_1	1	1	3	3	0.375
S_2	1	1	3	3	0.375
S_3	1/3	1/3	1	1	0.125
S_4	1/3	1/3	1	1	0.125

Table 6 Relational score and relative weight for EI against individual score and weight

EI	E_1	E_2	E_3	E_4	E_5	E_6	E_7	RW
E_1	1	1	1	3	1/3	1/3	1/2	0.086
E_2	1	1	1	3	1/3	1/3	1/2	0.086
E_3	1	1	1	3	1/3	1/3	1/2	0.086
E_4	1/3	1/3	1/3	1	1/6	1/6	1/4	0.043
E_5	3	3	3	6	1	3	2	0.269
E_6	3	3	3	6	1	1	2	0.269
E_7	2	2	2	4	1/2	1/2	1	0.160

On the basis of the results from the inventory analysis, relative score and relative weight of CVD chamber cleanings with respect to LCC and EI were computed, respectively, and their details are shown in Tables 7 and 8. The column, RW, in Tables 7 and 8 express the vector of relative weight of C_2F_6 and NF_3, $\mathbf{WA}_l$, with respect to LCC and EI. As far as the financial issue is concerned, the RW of NF_3 at three stages of the life cycle (raw material extraction, production, and usage) is greater than that of C_2F_6. In contrast, with regard to environmental performance, the RW of C_2F_6 at the environmental category (GWP, ODP, and POCP) is greater than that of NF_3 because there is discharge of a great deal of material during the life cycle of C_2F_6, such as $C_2Cl_2F_4$ and $C_2Cl_3F_3$, which have a great impact on GWP, ODP, and POCP. In addition, F_2, which have a high numerical value of nCHP, is emitted during the production and usage of NF_3, which causes the RW at nCHP to be high. Therefore, to protect human health, it is imperative to implement some protective measures during the production and usage of NF_3.

Table 7 Relative score and relative weight of CVD chamber cleaning with respect to LCC

Stage		NF_3	C_2F_6	RW
S_1	NF_3	1	1.5	0.60
	C_2F_6	0.667	1	0.40
S_2	NF_3	1	2.057	0.67
	C_2F_6	0.486	1	0.34
S_3	NF_3	1	1.533	0.64
	C_2F_6	0.652	1	0.36
S_4	NF_3	1	1	0.50
	C_2F_6	1	1	0.50

Table 8 Relative score and relative weight of CVD chamber cleaning with respect to EI

Category		NF_3	C_2F_6	RW
E_1	NF_3	1	0.031	0.030
	C_2F_6	32.25	1	0.970
E_2	NF_3	1	0.007	0.007
	C_2F_6	142.8	1	0.993
E_3	NF_3	1	0.489	0.328
	C_2F_6	2.045	1	0.672
E_4	NF_3	1	1	0.50
	C_2F_6	1	1	0.50
E_5	NF_3	1	0.378	0.275
	C_2F_6	2.646	1	0.725
E_6	NF_3	1	2.684	0.729
	C_2F_6	0.373	1	0.271
E_7	NF_3	1	0.050	0.048
	C_2F_6	19.93	1	0.952

From the above analysis, it may be confusing to note that product alternatives have excellent performance in one subcriterion, but not so good in other criteria. Therefore, to obtain an overall and objective evaluation, the calculation of the score of single criterion, LCC and EI, for alternatives is carried out. The score of single criterion (see Table 9) is obtained by multiplying $\boldsymbol{W}_l$ by $\boldsymbol{M}$ (the detailed procedure of computation is shown in Section 4.4). By calculating the emission impact on the environment in various categories and analyzing the LCC in each phase, it is not difficult to conclude that C_2F_6 is worse in terms of environmental performance than NF_3, but not in terms of economical performance.

Table 9 The score of single criterion for alternatives

	LCC	EI
NF_3	0.619	0.328
C_2F_6	0.381	0.672

5.3 Result and discussion

The hierarchy results show that, based on environmental criteria, NF_3, as a CVD chamber cleaner, is a more environment friendly product when compared with C_2F_6. However, in terms of economical performance, C_2F_6 is more competitive because of its low LCC. In fact, the knowledge of the importance of economy, society, and environment in product development is not an achieved consensus in the chemical industry. So a scientific assessment needs some trade-offs in the aspect of economy and environment based on the designers' preference. Being a general decisive tool, a fluctuant weight analysis is put forth to calculate the integrated index of the product. Once the weight of economy is defined, it is found that lower the integrated index, the more excellent the product is. Integrated index is determined by using the following equation.

$$\text{Integrated index} = \beta_1 \times \psi_1 + \beta_2 \times \psi_2 \quad (\beta_1 + \beta_2 = 1) \tag{3}$$

where β_1 and β_2 indicate the weight factor in economical and environmental terms, respectively, bounding from 0 to 1, and they can be used to reflect the preference tendency of a decision-maker. ψ_1 and ψ_2 denote the score of the single criterion, LCC and EI, for alternatives, respectively.

By changing the numerical value of β_1, the relatively integrated index of each product is obtained as shown in Fig.4. So it can intuitively be deduced from Fig.4 that when the weight factor of economy, β_1, is less than 0.6, the production of NF_3 is more feasible than that of C_2H_6.

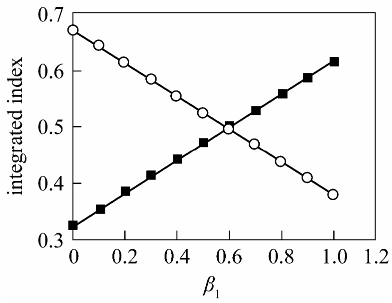

Figure 4 Integrated indexes of two products under different criteria
■ NF_3; ○ C_2F_6

6 CONCLUSIONS

Product alternatives can be compared using the formulated AHP model with a fluctuant weight analysis, based on the result of LCA and LCC. The results obtained can serve as some initial guidelines for judging the feasibility of using a certain product. In addition, these alternatives are compared on a common basis (the same set of criteria) with respect to their environmental and economic merits. This solves the frequent, but difficult question of how to interpret and compare the results of separate LCA analyses that have been performed on these alternatives. What is more fascinating is the fact that the relative comparison as well as the absolute comparison modes can be used in the proposed AHP mode. The formulated AHP model with fluctuant weight analysis for product evaluation has a general character because it can be applied for the comparison of any type of or any number of products.

NOMENCLATURE

E_1 green warm potential
E_2 ozone depletion potential
E_3 photochemical oxiden creation potential
E_4 acidification potential
E_5 cancer hazard potential
E_6 noncancer hazard potential
E_7 ecotoxicity potential
S_1 raw material stage
S_2 production stage
S_3 usage stage
S_4 abandonment stage

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