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An integrated approach for risk-based life cycle assessment and multi-criteria decision-making: selection, design and evaluation of cleaner and greener processes

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ABSTRACT

Cleaner and greener technologies for process and product selection and design have gained popularity in recent years. Life cycle assessment (LCA) is a systematic approach that enables selection of cleaner and greener products and processes. Recently, significant progress has been made for the use of LCA for product/process evaluation and selection, however, its use in process design and environmental decision-making has not been fully exploited. There are challenging activities which require trade-offs among conflicting attributes like cost, technical feasibility and environmental impacts. These attributes can be analysed at the early design stage by considering the full life cycle of a process (and/or a product). A cleaner and greener process referred economical, technically feasible and environmental friendly alternative. This paper proposes an integrated methodology for design by combining LCA with multi-criteria decision-making. This methodology is simple and applicable at the early design stage and guide decision-making under uncertainty. Application of the methodology is demonstrated through a case study of urea production.

Key words: LCA, cleaner and greener, fuzzy, risk-based and multi-criteria decision-making.

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1. Introduction

Life Cycle Assessment (LCA) is a systematic approach to evaluate the environmental impacts associated with products, processes and/or services. LCA is a process of *estimating environmental burdens for energy and materials used and wastes released into the environment, and identifying opportunities for environmental improvements*. The assessment includes the entire life cycle of the product, process or an activity starting from extraction (or excavation), processing, manufacturing, transportation, distribution, use, recycle, and final disposal (Fava *et al.*, 1991; USEPA, 1995; Tukker, 2000; Widiyanto *et al.*, 2003; Benetto *et al.*, 2004). The LCA guides regulatory agencies and other stakeholders for decision-making in design, selection and evaluation of a process. It may be used to evaluate the environmental impacts of a segment within a product or process's life cycle where the greatest reduction in resource requirements and emissions can be achieved.

Traditionally the LCA is a product-centered approach but recent efforts have been towards process design, where economic, technological and environmental constraints control decision-making. Earlier efforts were mainly economic driven and focused on cost-benefit or cost-effective analyses, which traded-off environmental and economic assets with an objective to maximize differences between socioeconomic benefits of an activity against the financial and environmental liabilities (Bhander *et al.*, 2003).

The LCA overcomes many problems faced in the conventional approaches and establishes links between the environmental impacts, operation, and economics of the process (Kniel *et al.*, 1996; Choong and Sharratt, 2000; Angelini *et al.*, 2003; Suh *et al.*, 2004). According to the ISO 14040, the LCA should assess the potential environmental issues and aspects associated with a product or service by compiling an inventory of relevant inputs and outputs; evaluating the potential environmental impacts; and interpreting the results of the inventory and impact phases in relation to the objectives of the study.

1.1 Literature review

Many attempts have been made by chemical industries to reduce pollution by implementing cleaner technologies (and/or processes). Frequently, it has been observed that the optimization of treatment process reduces the quantity of waste discharge at the end-of-the-pipe, but increases the overall environmental burden and impacts. Therefore, it is important to consider the adverse environmental impacts caused by any change or modification in the process and associated facilities as a whole. It is possible only when there is clarity in understanding relationships among design/operating parameters and associated environmental impacts.

El-Halwagi and Manousiouthakis (1989; 1990) and later Wang and Smith (1994) have introduced the concept of *mass pinch* as a tool to derive cost optimal mass exchange networks with minimum emissions. They have proposed an interval based targeting procedure for the waste minimization considering energy and mass inputs. The waste minimization was achieved through recycling of the target stream or replacing with less harmful process. Pistkopoulos *et al.* (1994) proposed a methodology to estimate various environmental impacts by minimizing a

particular process through a cost function, which describes a relationship between impacts and process model.

Hernandez *et al.* (1998) proposed a model for pollution abatement. Kniel *et al.* (1996) presented an LCA case study for nitric acid. Though the article emphasizes the use of LCA in a design stage but lacks in providing details for the steps involved in the methodology. Azapagic and Clift (1999) demonstrated the application of the LCA in various processes and product selection. Azapagic (1999) and Azapagic and Clift (1999) have discussed the LCA application in the evaluation of process performance for various Boron products. Young and Cabezas (1999) have also proposed a methodology for sustainable design by waste reduction. Their methodology focused on minimizing the waste across the process boundary. Bhander *et al.* (2003) have presented a general discussion on the use of LCA in product design. Xian et al. (2003) have discussed development GPLCD (LCA tool) for electromechanical products green design. Widiyanto *et al.* (2003) studied life cycle inventory data for electric generation system in Indonesia. Bennetto *et al.* (2004) used LCA for coal based electric power generation system. Phekar and Ramachandran (2004) presented state-of-the-art review of LCA and MCDM for sustainable energy planning.

Spath *et al.* (1999) and Mann and Spath (1997) have used LCA for evaluating various options of a power plant. Later, Spath and Mann (2000) have demonstrated application of LCA in evaluating different stages of natural gas combined cycle power generation system. This report emphasized the strength of an LCA in identifying and screening the environmental burdens at various life stages of the plant, which enables development of targeted remedial goals. In order to streamline the LCA approach, a workgroup (SETAC North America LCA streamline workgroup) has been formed which discussed various steps of LCA and environmental parameters (Todd and Curran, 1999). Kohler and Lutzkendorf (2002) have presented development of new tool LEGOE based on integrated life-cycle-analysis.

The impact of any corrective or remedial measure may be beneficial for the process viewpoint, but modification required to achieve may cause severe environmental impacts outside the boundary of process. Khan *et al.* (2001) proposed *GreenPro* a design methodology for cleaner and greener process, which comprised of four steps. The first two steps deals with design problem formulation and the last two steps involved a design problem solution with multi-objective optimization and MCDM. Application of this methodology was demonstrated through selection of vinyl chloride monomer process. The *GreenPro* was effective in design, however it application is restricted at early design stage due to extensive computational load and large data requirements. Later, Khan *et al.* (2002) have tried to overcome earlier limitations and proposed a revised methodology *GreenPro-I*, which is more efficient, robust (less sensitive to the reliability of the data) and is applicable to early design stage. A detailed description of the *GreenPro-I* for greener and cleaner process selection and design is discussed here with the help of a case study.

2.   *GreenPro-I*

The *GreenPro-I* comprises of two major steps - risk-based life cycle assessment (RBLCA) and risk-based multi-criteria decision-making (RBMCDM). These steps further consist of many sub-steps as shown in Figure 1.

2.1. Risk-based life cycle assessment (RBLCA)

The application of risk management tools aid in selection of discreet, technically feasible and scientifically justifiable actions that will protect environment and human health in a cost-effective way. The RBLCA is a process of weighting policy alternatives and selecting the most appropriate action by integrating the environmental risk assessment with social, economic, and political attributes to reach a decision. The RBLCA will choose the alternatives, which cause minimum environmental damages and evaluate the costs and benefits of proposed risk reduction programs. The RBLCA may integrate sociopolitical, legal and engineering factors to manage risks and environmental burdens of a process. The RBLCA considers human health, ecological, safety and economical risks information, which may involve preferences and attitudes of decision-makers.

Process design has two main objectives: 1) evaluating environmental performance of a process using *cradle-to-gate* approach and 2) selecting the best process design combinations. The RBLCA identifies the options for the improvement of environmental performance and considers the material and energy supply chains within the system boundary. It includes material and energy flows into the system, outflows from the system and what have been used within the system. It classifies the environmental burden for all activities within the system boundary as material extraction/excavation, refining, transportation, construction and commissioning of the plant, production and decommissioning, and final disposal.

2.1.1 Defining the scope and boundary

The scope of RBLCA must be clearly articulated and system boundaries are defined objectively to ensure that no relevant elements of the system are missed. It requires backtracking from the conventional process system to the natural state of pure raw materials, which are available at no environmental liability. The global system boundary includes inputs and their routes with output emissions which form an aggregated waste vector. Although this definition is consistent with the conventional LCA for products, but it does not include the routes and stages of the product after leaving the process (i.e. *cradle-to-gate* instead of *cradle-to-grave* approach).

2.1.2 Life cycle inventory (LCI)

Energy and material inputs, wastes and emissions data must be collected and environmental load should be quantified in order to accomplish the RBLCA goals. The LCI analysis is used for collecting data and quantifying environmental load based on material and energy balances. LCI analysis should be comprehensive to make the final decision, but in instances where rough estimates have to be made, they must be conservative and clearly noted. Data quality will likely vary depending upon its source therefore to ensure that the data used are in the best available form and the sources are contemporary, an extreme care must be taken.

The LCI analysis starts with the identification of environmental hazards expected at various units. These hazards are due to the chemical compounds involved in the process that upon release adversely affect to humans or to the environment. It also includes hazard due to severity

of operating conditions like temperature and pressure. The chemical hazards are not limited to process chemistry, rather they include cleaning solvents, heating and cooling agents, and all other chemicals involved in any part of the process.

2.1.3. *Environmental impact and risk assessment (EIRA)*

Environmental impact and risk assessment (EIRA) examines the potential and actual environmental and human health effects from the use of resources (energy and materials) and environmental releases. An EIRA includes classification, characterization, and valuation.

Classification is the process of assigning and aggregating results from the inventory into relatively homogeneous impact categories. This process involves identifying stressors and organizing them with respect to impact on the ecosystem. For example, carbon monoxide, chlorine and methane are all stressors with the potential to impact the environment under the category of global warming. Classification includes the creation of complex stressor/impact chains, because a single pollutant can have multiple impacts, and a primary impact can result in secondary (or greater) impacts through cascading impact chain process. The general categories are: ozone depletion (*OD*), acid rain potential (*AP*), photochemical oxidant impact (*POI*), global warming potential impact (*GWPI*), controlled toxic water mass (*CTWM*), solid mass disposal (*SMD*), safety risk (*SR*), human health risk (*HHR*), ecological risk (*ER*), and natural resource depletion (*RD*).

Characterization assesses the magnitude of impacts for each of the stressor categories in order to translate LCI into impact descriptors. Characterization methods of few categories are depicted below.

CTWM is a controlled toxic mass flow rate of water pollutant (kg pollutant/h);

SMD is a solid mass disposal rate (kg solids/h);

GWPI is a mass of pollutant (kg/h) × global warming potential (kg CO_2 equivalent/h); (Global warming potential for each pollutant is defined by equivalent of CO_2)

POI is estimated in terms of equivalent of ethylene (kg ethylene/h);

OD is expressed by their ozone depletion potential in terms of CFC-11 equivalent/h;

AP is based on the contributions from SO_2, NO_x, HCl, NH_3, and HF due to their potential of acidic deposition i.e. potential to give H^+ ions;

HRR is characterized by a concentration of contaminant at specified location exposed to human population (using reference dose *RfD*);

SR is quantified by individual risk factor at the study area due to any eventuality in the operation and determined by divided a factor of 1.0×10^{-6}; and

ER is characterized as a concentration of contaminant at specified location as exposed to ecological community (using No-observed-effect-concentration, *NOEC*).

Valuation is assigning relative values or weights to different impacts, economic and performance measures to determine the total impact. An analytic hierarchy process (AHP) is used for this purpose, which involves a structured description of the hierarchical relationships among various decision attributes. Assigning weights is a group exercise, where experts are asked to reach on a consensus. The experts may include cost estimator, process specialist, environmental engineer, and/or ecologist/toxicologist.

2.1.4 Design problem formulations

Development and designing of a process involves consideration of number of constraints (see Figure 2), which guide to the decision-making. Many researchers have argued consideration of environmental performance and safety in design, which may lead to cost effective cleaner and greener process. Cabezas *et al.* (1997, 1999) incorporated environmental impacts into process design model through mass balance equations. It is necessary to relate the environmental impacts to measurable quantities. A generalized linear theory proposed by Mallick *et al.* (1996) and Cabezas *et al.* (1999) has been adopted in this study. In order to analyze the relationship between environmental impact and process cost, a mathematical framework has been used. The process is represented by a set of mathematical equations, which describe the properties of the inlet stream, waste stream, and equipment specifications, cost functions and the degree of pollutant removal. The details of the mass and energy balance equations and the derivation of environmental function can be seen in Khan *et al.* (2001).

2.2 Risk-based multi-criteria decision-making (RBMCDM)

Various MCDM approaches are available in literature which use either fuzzy or crisp numbers. Many research attempts have been made for decision-making under uncertainty using probability theory and fuzzy set theory (Pohekar and Ramachandran, 2004). Fuzzy composite programming (FCP) and AHP are used in proposed RBMCDM. A traditional MCDM problem can be expressed in a matrix form:

$$
\begin{array}{c}
A_1 \\
A_2 \\
\vdots \\
A_m
\end{array}
\begin{bmatrix}
X_{11} & X_{12} & \cdots & X_{1n} \\
X_{21} & X_{22} & \cdots & X_{2n} \\
\vdots & & & \\
X_{m1} & X_{m2} & \cdots & X_{mn}
\end{bmatrix}
\qquad (1)
$$
$$
\quad\;\; X_1 \quad X_2 \quad\;\; \cdots \quad X_n
$$

where

$A_i = 1, 2,..., m$ are possible actions or alternatives;

$X_i = 1, 2,..., n$ are attributes, reference to alternative performance; and

X_{ij} = Performance rating of an alternative A_i with respect to an attribute X_i.

In real life, it is common that X_{ij} may not be assessed precisely due to unquantifiable, incomplete, and non-obtainable information. The unquantifiable information means subjective attributes e.g., *good*, *poor*, *high*, *low*, etc. The examples of incomplete information are *about* one million, *less than* 10 miles per hour. Sometimes crisp data are obtainable but need lot of resources, but approximation can be achieved with less effort and time. Linguistic descriptions are employed due to unavailability of information or lack of resources. The fuzziness is also attributed to ignorance from factual conditions. These limitations make fuzzy-based approach a strong candidate for RBMCDM. The FCP (an approach selected for RBMCDM) involves following two steps:

- The *aggregation* of the performance scores of all the attributes for each alternative; and

- The *rank ordering* of the alternative according to aggregated scores.

MCDM methods require information about relative importance of attributes or criteria. It is usually established by set of preference weights, which are normalized to a sum of 1. In case of n criteria, a set of weights can be written as

$$\underline{W}^T = (\, w_1, w_2, \ldots, w_j, \ldots, w_n\,) \quad \text{and} \tag{2}$$

$$\sum_{j=1}^{n} w_j = 1 \qquad \text{(for a given } i\text{)} \tag{3}$$

Therefore MCDM problem becomes

$$D = \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1n} \\ X_{21} & X_{22} & \cdots & X_{2n} \\ \vdots & & & \\ X_{m1} & X_{m2} & \cdots & X_{mn} \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \tag{4}$$

Saaty (1988) proposed analytic hierarchy process to estimate the relative weights of attribute in a group based on a pair-wise comparison. To compare attribute "i" with "j" the decision-maker can assign importance values from Table 1 and determine weights.

2.2.1. *Converting qualitative items into fuzzy numbers*

In cases where we deal with linguistic terms, a numerical approximation is proposed to convert linguistic terms into corresponding fuzzy numbers. Chen and Hwang (1992) have defined eight scales to convert linguistic terms into fuzzy numbers. One of the most important scales is shown in Figure 3. This scale has 5 levels. The linguistic terms used to describe this scale are *very low*, *low*, *medium*, *high* and *very high*. Same linguistic terms contain different meaning in different scales. The *high* in this scale means [(0.6, 0), (0.75, 1), (0.9, 0)], i.e. most likely value (i.e. when

membership function $\mu(x)$ is 1) is 0.75 and the largest likely interval is in between 0.6 and 0.9 (when membership function, $\mu(x)$ is 0).

2.2.2.   *Grouping of attributes*

It is difficult to select an appropriate MCDM strategy when the values of input variables (such as ecological, safety and human health risks, cost, and qualitative terms like technical feasibility) are uncertain or qualitative in nature. The FCP is used to assist decision-makers in solving problems of multiple attributes and conflicting objectives.

The first step in FCP is the normalization of the basic indicators. This is necessary because all basic indicators have non-commensurate units and are difficult to compare in their respective units. At the first level, human health, ecological, and safety risks are grouped into environmental risk reduction index (*RI*). Similarly, global warming potential and ozone depletion are grouped to get the warming reduction index (*WI*). At level 2, the warming reduction, acidification reduction (*AI*), pollution reduction (*PI*) and risk reduction (*RI*) indices are grouped as sink depletion - improvement index (*SDI*). The same procedure is repeated for other basic indicators, e.g., technical feasibility index of any alternative is developed from ease of operation (*EO*), efficiency (*EF*), status of technology (*ST*) and control measures requirements (*CM*). The Level-3 sink depletion (*SDI*) and resource depletion (*RDI*) improvement indices are grouped to form the environmental - improvement index (*EI*). The same procedure is repeated for cost saving index (*CI*). The grouping for different attributes is performed in steps, until we get the environmental, cost saving and technical feasibility indices to make a trade-off analysis among these conflicting objectives. This trade-off analysis for different alternatives can be made at all hierarchy levels. The system improvement index (*SI*) value at Level 5 represents the contribution of environment, cost saving and final technical feasibility of operations (see Figure 4).

The values of the basic indicators are designated by fuzzy numbers to characterize their uncertainties. By defining $Z_i(x)$ as a fuzzy number of the ith basic indicator with a trapezoidal membership function of $\mu[Z_i(x)]$, various management alternatives under uncertainty can be evaluated. Since units of basic indicators are different, the actual value of each basic indicator should be transformed into an index, $S_{i,h}(x)$, using the best (BES) or the worst (WOR) value of the indicator as shown in Figure 5 (see Lee *et al*., 1991 for details). Using the normalized index values of basic indicators, the Level 2 index values, $L_{j,h}(x)$, of composite indicators can be defined by

$$L_{j,h}(x) = \left\{ \sum_{i=1}^{nj} w_{i,j} \left[S_{i,h,j}(x) \right]^{pj} \right\}^{(1/pj)} \tag{5}$$

where

n_j =   Number of elements in second-level group j;

$S_{i,h,j}(x)$ = Basic value for i^{th} basic indicator in the second level group j of basic indicators with membership of h;

$w_{i,j}$ = Weight reflecting the importance of each of basic indicator ($\sum w_{i,j} = 1$); and

p_j = The balancing factor for group j.

Further, the index values $L_{k,h}(x)$, of third level composite indicators can be calculated by the index values for second level composite indicators. This procedure is repeated till the final step, which compares three indices - environment, cost saving and technical feasibility.

2.2.4. Ranking method

When fuzzy data are incorporated into MCDM problem the final ratings are no longer crisp number rather they are fuzzy numbers. The fuzzy numbers are not straightforward to compare. Chen's ranking method (1985) for *defuzzification* is extensively used for risk-cost trade-off analysis (Sadiq *et al.*, 2003). The alternative, which has the highest ordering value, is selected as the best alternative. Khan *et al.* (2002) and Sadiq (2001) have described this method in detail. Chen (1985) has generalized the results for trapezoidal fuzzy numbers as following:

$$U_T(x) = \frac{1}{2}\left[\frac{(d_i - L_{min})}{(L_{max} - L_{min}) - (b_i - d_i)} + 1 - \frac{(L_{max} - c_i)}{(L_{max} - L_{min}) + (a_i - c_i)}\right] \tag{6}$$

3.   Selection of Urea Production Processes

Being the cheapest source of nitrogen, urea is the most common fertilizer. India has 41 urea plants of total capacity 20.1 metric ton, 19 out of them are based on natural gas (alternative 1), 14 on naptha (alternative 2), 6 on fuel oil (alternative 3) and 2 on coal, as feedstock (alternative 4) (Roy, 2001). Percentage contributions of each feedstock to the total installed capacity are: natural gas 54.2%, naptha 26.1%, fuel oil 18.2%, and coal 1.5%. The cost of urea production is more than $ 168/ton in India while the cost of importing urea from US is about $116 per ton. The higher cost of production is due to costlier inputs in the form of feedstock of petroleum origin (Roy, 2001).

3.1   Urea production process

Ammonia, the raw material for the urea is synthesized from hydrocarbon feedstock. Urea is produced from a chemical reaction involving ammonia and CO_2. Production of ammonia accounts for more than 80% of the total energy consumed in urea production. Ammonia production involves feed treatment, steam and air reforming of hydrocarbons, gas purification, and synthesis. The major reactions involve in the production of urea are:

$$\left.\begin{array}{l} CH_4 + H_2O \rightarrow CO + 3H_2 \\[2mm] CH_4 + air \rightarrow CO + 2H_2 + N_2 \\[2mm] CO + H_2O \rightarrow CO_2 + H_2 \end{array}\right\} \tag{7}$$

$$N_2 + 3H_2 \rightarrow 2NH_3 \tag{8}$$

Ammonia is then further converted into urea

$$CO_2 + 2\ NH_3 \rightarrow NH_4CO_2NH_2 \rightarrow NH_2CONH_2 + H_2O \tag{9}$$
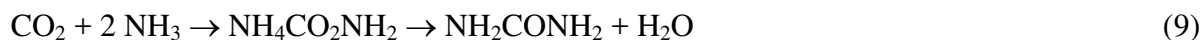
In the above process, hydrogen is chemically separated from the hydrocarbon feedstock and combined with nitrogen to produce NH_3. A chemical solution (scrubber) is added which absorbs some of the CO_2 produced in this reaction. The remaining CO_2 is converted into methane in a methanator because methane is more inert as compare to CO_2. The CO_2 percentage on dry mole basis in synthesis gas varies from 28.6% (Lurgi process) to 6.2% (Koppers-Totzec process) but in Winkler process it is 20.5% .The sulfur and CO_2 are removed from the synthesis gas before it is methanated. The scrubbing solution is then passed through a process of re-generation. This process releases the absorbed CO_2 into the atmosphere. Emissions of CO_2 depend upon the type of hydrocarbon used for the production of ammonia. SO_2, NO_X, CO and non-methane volatile organic compound may also be emitted in addition to CO_2. In the urea production there is not significant gas emissions because 99 % of CO_2 and NH_3 are converted into urea (Holmstrom and Comer, 1999). Details of different process can be seen in Mavrovic *et al*. (1998).

3.2   Application of RBLCA

Boundaries and scope of the problem have been defined in Figure 6. Nine environmental indicators for six main processes are considered. Among various environmental indicators *RD*, *GWPI* and environmental risks are of major concern. It must be noticed that CO_2 is used as one of the basic raw material in urea production thus causing a positive impact on environment. This effect is duly accounted in GWPI ad SDI computation for urea plant.

Resource consumption is large in case of coal-based process, which is then followed by fuel oil and naptha. Though *RD* for natural gas option is also high but this value is comparatively lower than the other three alternatives. Detailed results of environmental impacts for various activities are given in Table 2. Natural gas production and transport, ore mining and processing and energy production are three major activities contributing to the *RD*. Ammonia production and energy production are the two major processes contributing to *GWPI*. Energy production is contributing about 30% while ammonia production about 25% of the total *GWPI*. Among various sources, CO_2 is a major pollutant contributing about 78%, followed by methane 12%, and oxides of nitrogen and others about 4% of the total *GWPI*. The *POI* and *OD* are the other indicators of concerns. They occur due to light hydrocarbons release in various processes. For *OD*, natural gas production, transportation and ammonia production approximately 45%, 25% and 15% contribute energy production, respectively. In case of *POI* natural gas production and transport, energy production, and ammonia production are contributing with the same order of magnitude.

For three risk factors - *HHR*, *SR*, and *ER* - ammonia and urea process operations are major contributors to these risks. These processes contribute about 38% (average) of the total risk, followed by natural gas production, transport and energy production. Mining process is the next most significant contributor (20%). The results are shown in Table 2.

Ammonia and urea productions are the major contributors to the total environmental burden therefore these processes are studied in-depth. The results of this analysis are presented in Table 3. The reforming unit is the main contributor (about 35%) to the total *GWPI* due to ammonia and urea plant which is then followed by Hydro-desulfurrization and ammonia reactor. In case of *OD* and *POI*, reforming unit is the main contributor. The CO converter unit and urea reactor are major contributors to *SMD* and *CTWM*. Ammonia reactor is of concern to human health, safety and ecological risk, contributing 25%, 30% and 30%, respectively. A meticulous study of safety risk reveals that ammonia reaction unit is the most vulnerable (contributes 30% of the total risk). It is followed by hydro desulfurizing (15%), reforming unit (15%) and urea reactor (15%) (Table 4). For safety risk the hazards including fire, explosion, and toxic release are rated equally important. The *HHR* analysis shows that the fuel oil based process poses a maximum *HHR* followed by naptha, coal and natural gas based process. Among various exposure routes, air exposure route is of major concern, which contributes about 55% to the total *HHR* followed. It is followed by exposures through water (35%) and soil (10%). The chemicals of concern and their respective contributions through different exposure routes are presented in Table 5. It is evident that ammonia and VOC in air, urea, heavy metals and acids in water and soil are of major concern.

It is noted that the ammonia reactor, reforming and hydro-desulfurization units are of utmost importance and improvement in the operational performance of these units would significantly improve the environmental quality of the overall production process.

3.3   Application of RBMCDM

Selecting a management alternative which requires minimum cost, causes minimum environmental damage and is technically sound is a challenging task due to conflicting nature of the objectives. These conflicting objectives are achieved by employing FCP and AHP, where the best alternatives will be the one, which has the highest value of system improvement index (*SI*).

The attributes considered in this study are a long list of basic indicators, which include technical feasibility and cost other than environmental parameters discussed before. These basic indicators are expressed in non-commensurate units. Some basic indicators are expressed qualitatively. The technical feasibility and cost saving indicators are defined based on a scale given in Figure 3. The values obtained from this scale are unitless. To convert other basic indicators into unitless terms, normalisation is required as explained earlier in this paper. Basic indicators are normalized based on their reported *BES* and *WOR* values (as explained in Figure 5)

Table 6 presents all basic indicators into their normalized form. The normalized values of the environmental basic indicators show that higher the value more will be the environmental protection. The advantage of converting all basic indicators into their normalized forms is that they are commensurate with each other and can be aggregated to form a general group.

The next step is to decide the weights of attributes based on their relative importance. Table 7 presents the relative importance matrix used in this study. The human health, ecological and safety risk indices are grouped to develop a risk reduction index (*RI*). The higher value of risk reduction index shows lower risk. It is now consistent with all other environmental basic

indicators whose higher values depict improvement in the system. The grouping is performed at four levels. At first level all basic indicators are grouped. The weights are estimated based on their relative importance. The eigen value method is used to estimate the w for each attribute.

Triangular fuzzy numbers are used to define basic indicators therefore the estimated indices (at higher levels) will also be fuzzy numbers. The risk reduction index is developed from human health, ecological damage and safety risks due to fire, spills and accidents is shown in Figure 7. The alternative 2 is the best management alternative in comparison to other options for risk reduction index. MLV of option is nearest to 1.0 representing lower risk, and the base of the alternative 2 fuzzy number is the smallest showing lower uncertainty. Alternative 2 is followed by options 1, 3 and 4. Similar plots can be developed for indices at various hierarchical levels.

The final system improvement indices are shown in Figure 8. The system improvement index shows that alternative 2 is the best management option, which is followed 1, 3 and 4. The alternative 1 is close to alternative 2. The alternative 4 is the least desirable design alternative (coal as feed stock based process). The uncertainty in estimates of alternatives 1, 2 and 3 are approximately same which can be observed from base of fuzzy numbers.

To make a trade-off among conflicting objectives environmental improvement and cost saving, 2-D fuzzy numbers are shown in Figure 9. The x-axis represents the cost saving index (CI) whereas the y-axis represents the environmental improvement index (EI). The base of the fuzzy numbers are plotted in 2-D, where a line of rectangle parallel to x-axis represents the cost saving index range and line parallel to y-axis represents the environmental improvement index range. The most likely values are plotted as points. It can be noticed that alternative 2 rectangle is smaller in size and close to the ideal conditions (1.0, 1.0). Therefore, from cost saving and environmental improvement viewpoints, alternative 2 promises better results than the other options. Table 8 summarises the utility index values, and ranking orders of alternatives. The Chen (1985) ranking method is used here. From utility values, it can be concluded that alternative 1 and 2 are very close to each other.

The last step of FCP is to conduct a sensitivity analysis. The assignment of relative importance and balancing factors (p) depends on human judgement. To avoid the human bias, different weighting schemes are used for this purpose and analysis is repeated. Table 9 shows the alternate weighting schemes to re-evaluate the system improvement indices. In trial 1 the environment was given higher priority. The trial 2 represents the case when cost saving is given more importance than environmental improvement. The trial 3 represents the case when environment and cost saving are given equal importance. The final utility values for all three trials are plotted in Figure 10. The result shown in Figure 10 proves that alternative 2 is the best management alternative, which is followed by alternatives 1, 3 and 4.

4.   Summary and Conclusions

The *GreenPro-I* is a systematic approach to estimate environmental risks/impacts associated with life cycle of products, processes and services. It evaluates environmental burdens by quantifying energy and materials used and waste released into the environment. It identifies and

evaluates opportunities, which affect environmental improvements. The assessment may include the extraction/excavation and processing of raw materials, manufacturing, transportation and distribution, use, recycle, and final disposal. The *GreenPro-I* is proposed as a comprehensive decision-making tool for designers, regulatory agencies, business organizations and other stakeholders.

The *GreenPro-I* overcomes many of the problems faced in the conventional approaches and establishes a link between the environmental risks/impacts, cost, and technical feasibility of processes. It offers an extended environmental perspective, considering risks/impacts from resource extraction to the end product use and disposal. The *GreenPro-I* relates these effects to the mass and energy flows into, out of, and within the process. The present work has focused on the development of process selection and design methodology considering assessment and minimization of risks/impacts by embedding the conventional LCA principles in decision-making framework. It has implications to process synthesis as it includes environmental objectives with technical feasibility and economics at the design stage to determine cost effective solutions. Authors believe that employing the *GreenPro-I* for process design and decision-making would yield a best management alternative among options available.

5.   Acknowledgements

6.   References

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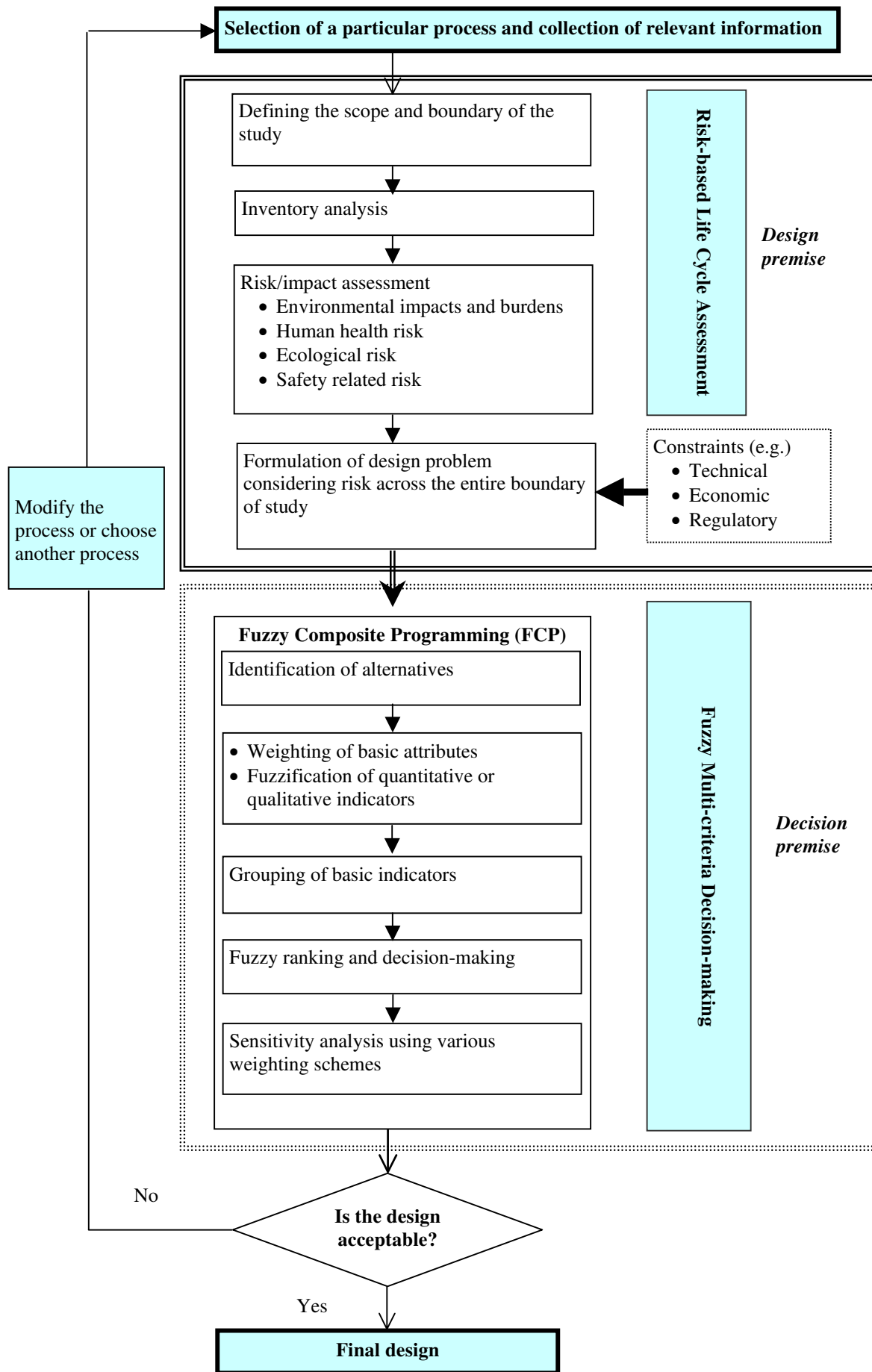
Figure 1. Basic framework for *GreenPro*-I (after Khan *et al*., 2002)

Defining the objective

- Design of process or product

Process Design and Development

Regulatory constraints
- Local regulatory requirement
- State regulatory requirement
- Federal regulatory requirement

Technical constraints
- Technical requirement
- Operational requirement
- Maintenance requirement
- Quality requirement

Conceptual design (Block diagram) stage
Process selection

Flow sheet stage
Identification of technology and equipments

Safety constraints
- On-site safety requirement
- Offsite safety requirement

Environmental constraints
- Offsite requirement
- Onsite requirement
- Working requirement

Detailed design stage
Detailed engineering design of all equipment, instrument, and accessories

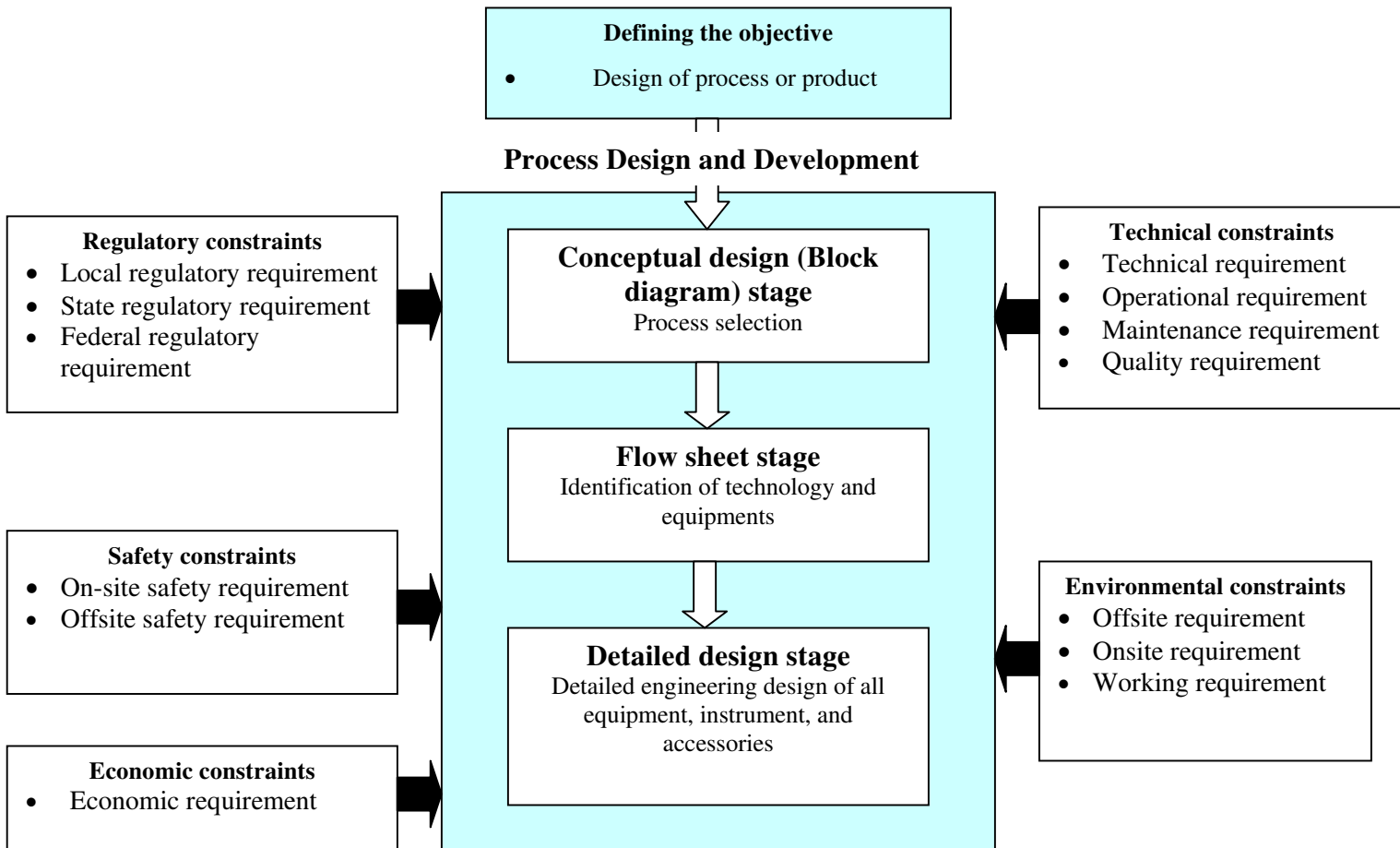**Economic constraints**
- Economic requirement

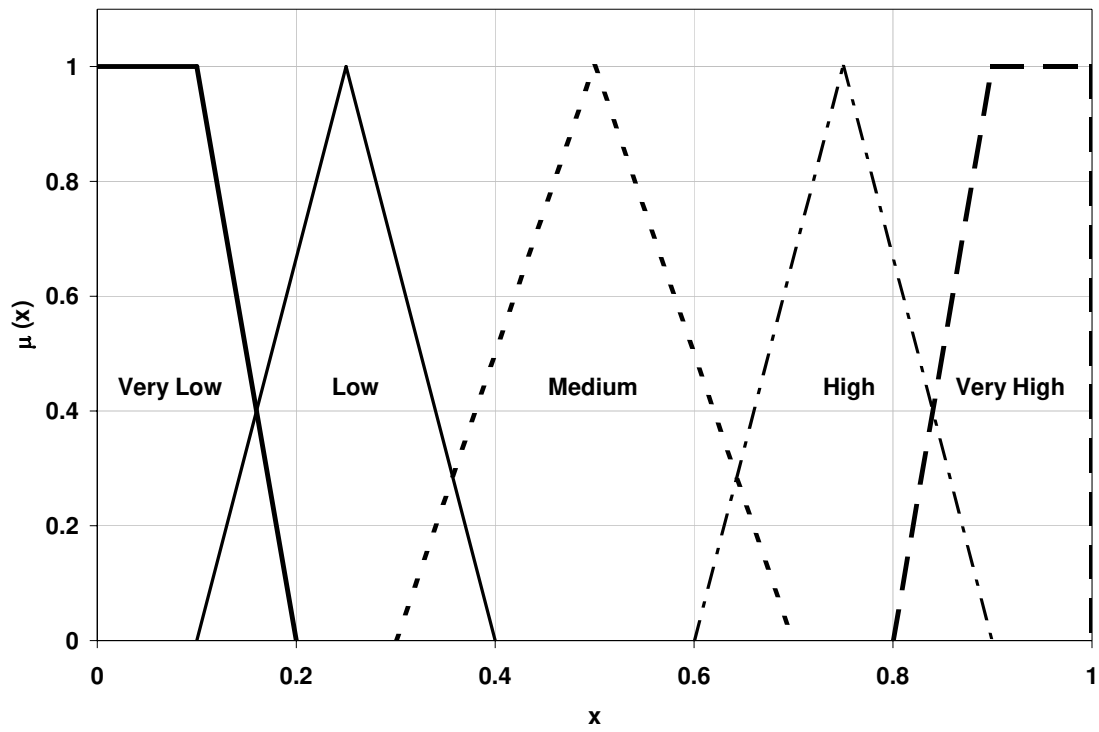Figure 2. Constraints involved at various stages of process plant design and life cycle

Figure 3. Conversion of linguistic terms into numerical
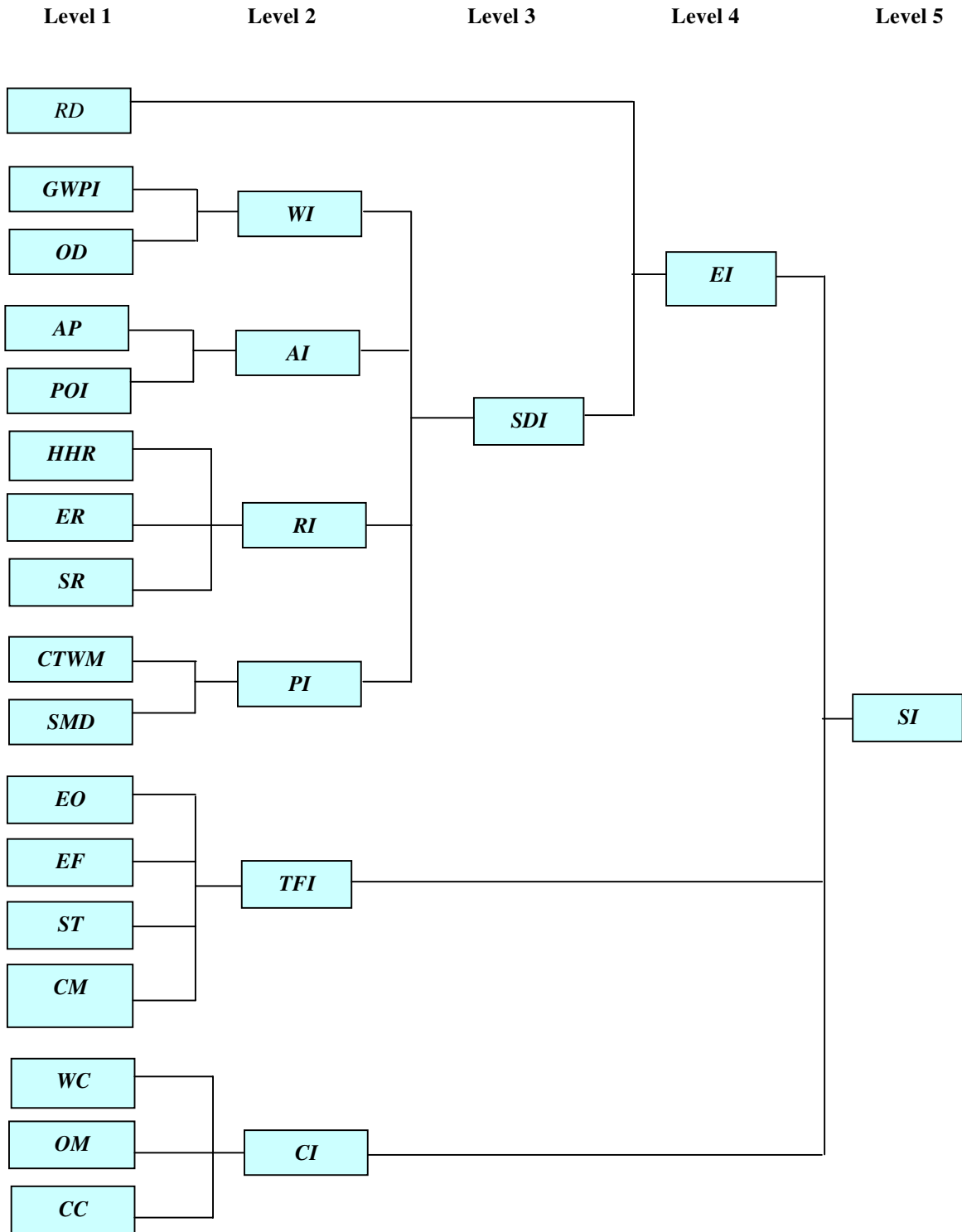
Figure 4. The framework for fuzzy composite programming (FCP)
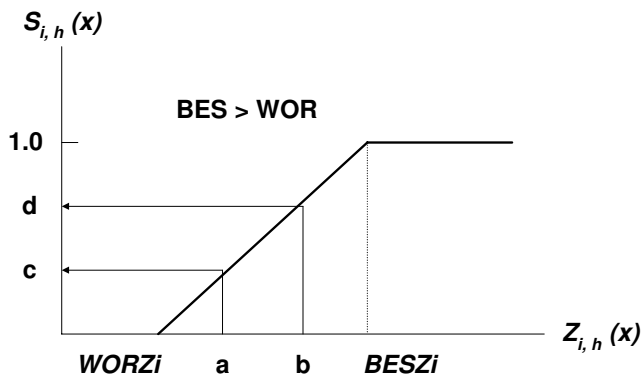
$$S_{i,h}(x) = \begin{bmatrix} 1 \\ \dfrac{Z_{i,h}(x) - WORZi}{BESZi - WORZi} \\ 0 \end{bmatrix}$$

$Z_{i,h(x)} \geq BESZi$

$WORZi < Z_{i,h}(x) < BESZi$

$Z_{i,h}(x) \geq WORZi$

$$S_{i,h}(x) = \begin{bmatrix} 1 \\ \dfrac{Z_{i,h}(x) - WORZi}{BESZi - WORZi} \\ 0 \end{bmatrix}$$

$Z_{i,h(x)} \leq BESZi$

$BESZi < Z_{i,h}(x) < WORZi$

$Z_{i,h}(x) \geq WORZi$

Figure 5. Transforming actual value $Z_{i,h}(x)$ into normalized index value $S_{i,h}(x)$

Resources

Resource implies fossil fuel, minerals, metals, lime, and water
Waste implied air, water and solid emission coming out from the industry

Natural gas production system

Natural gas transportation system

Waste

Waste

Air

CO₂

Energy generation system

Ammonia production system

Urea production system

Waste

Waste

Waste

Ores mining and purification system

Chemical production and transportation system

Waste

Waste

Figure 6. Simplified life cycle diagram for urea production
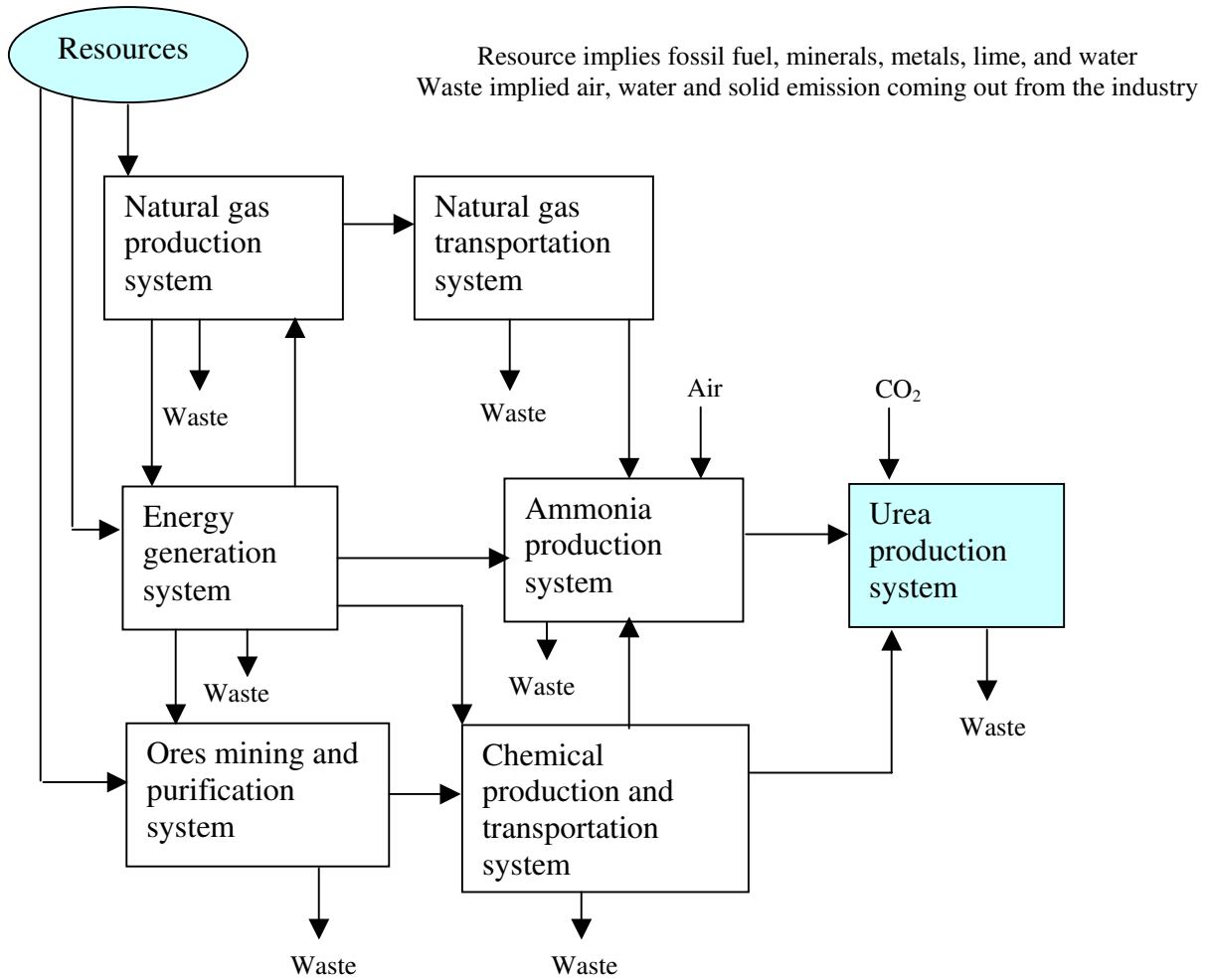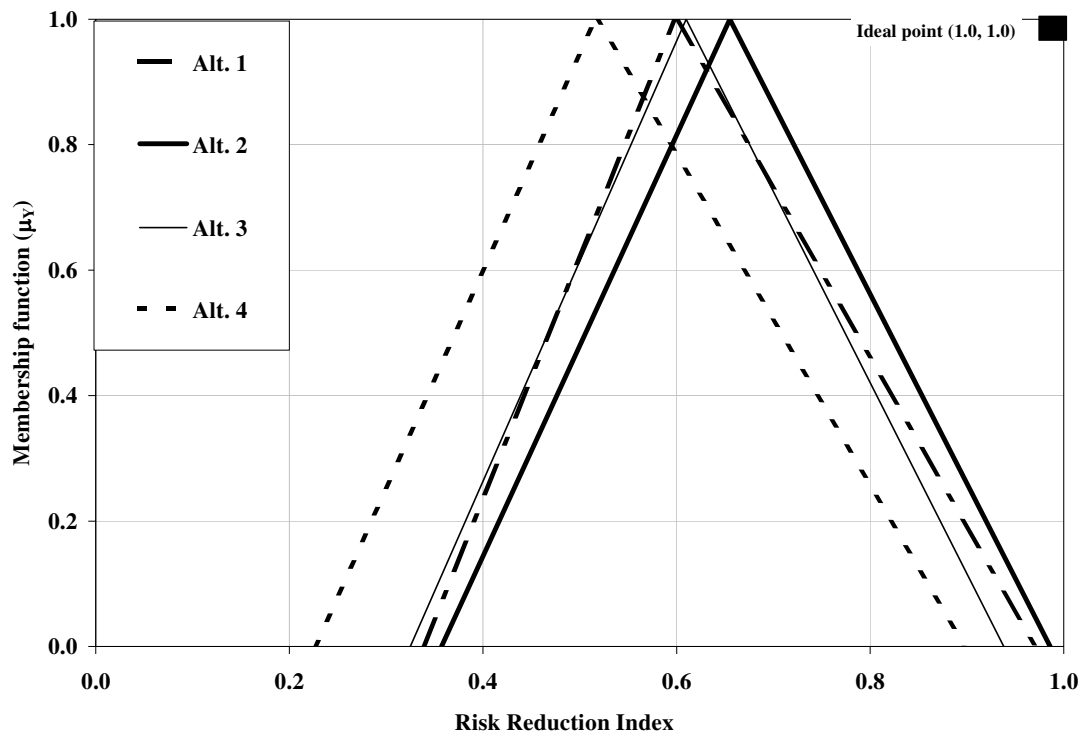
Figure 7. Comparison of *RI* for various alternatives
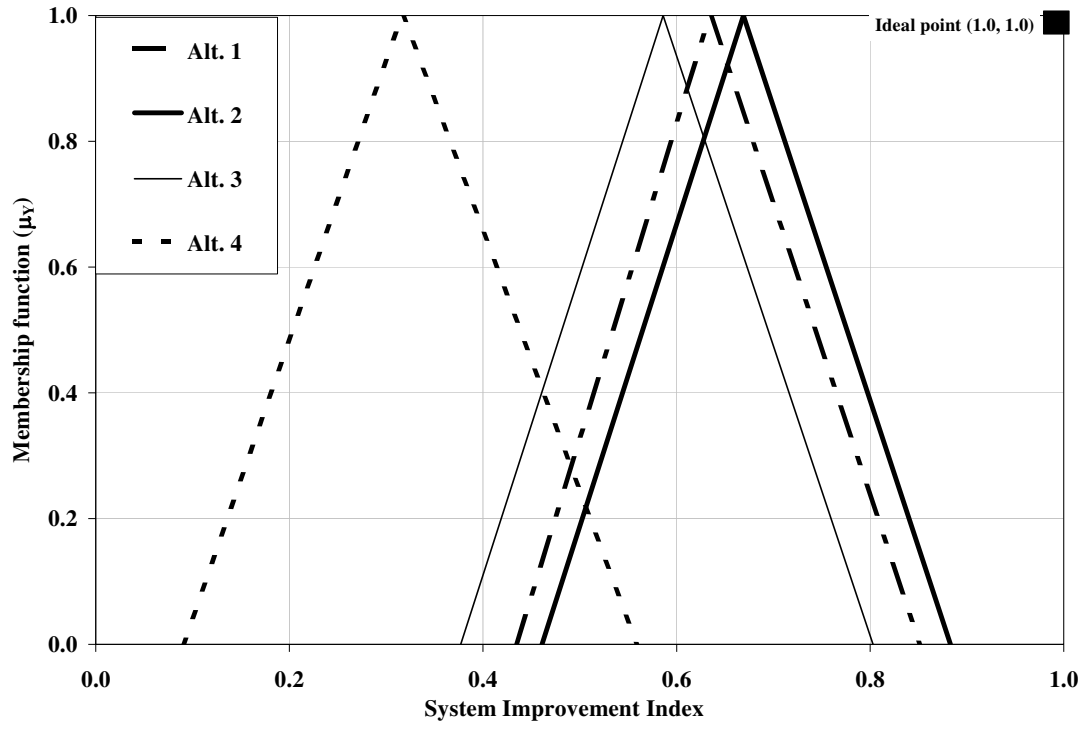
Figure 8. Comparison of *SI* for various alternatives
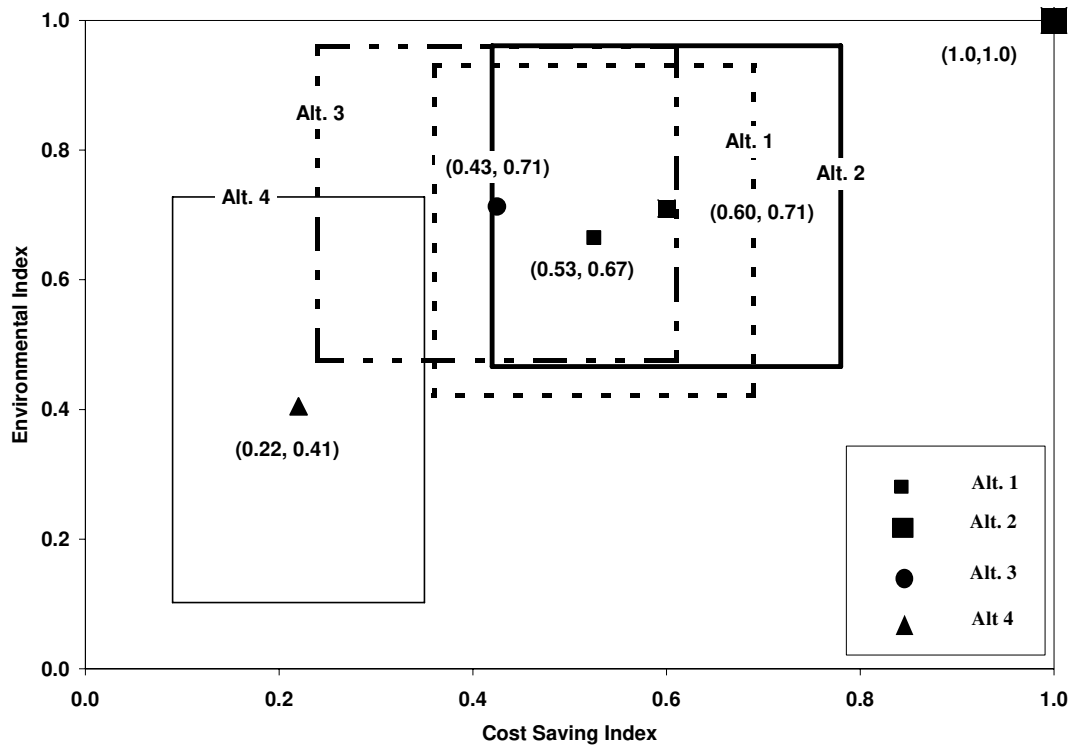
Figure 9. A 2-D comparison of *CI* and *EI* indices
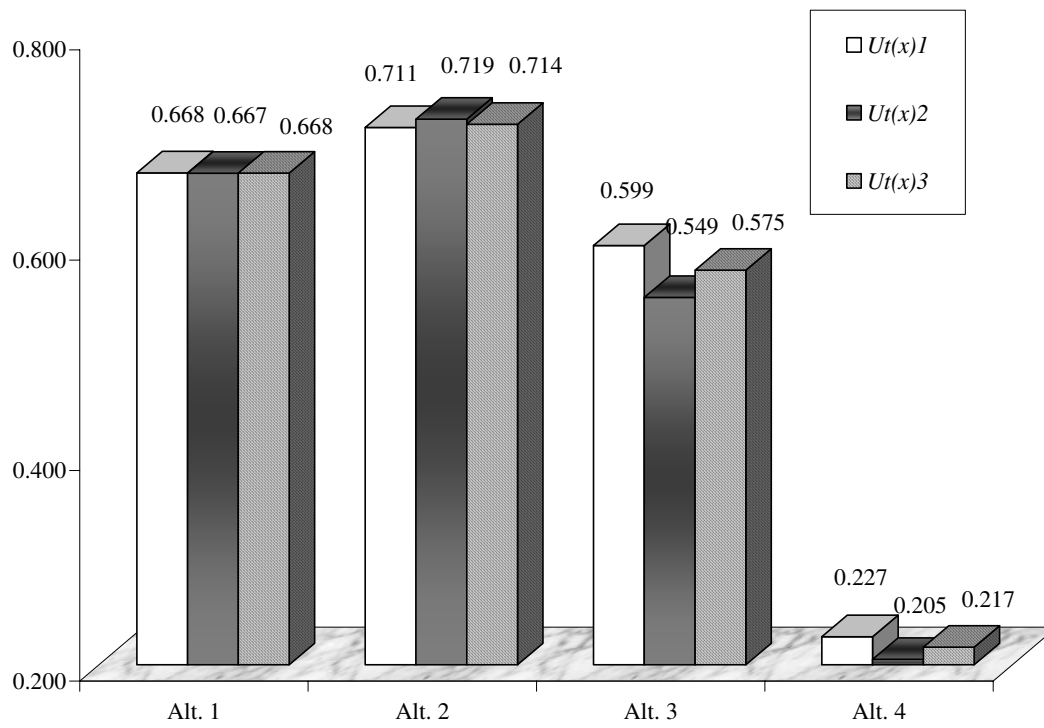
Figure 10. Sensitivity analysis for estimating robust ranking orders

Table 1. Fundamental scale used in AHP (Saaty, 1988)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak	-
3	Moderate importance	Experience and judgement slightly favour one activity over other
4	Moderate plus	-
5	Strong importance	Experience and judgement strongly favour one activity over other
6	Strong plus	-
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
8	Very, very strong	-
9	Extreme importance	The evidence favouring one activity over another is of highest possible order of affirmation

Table 2. Percent ccontribution to environmental impacts by urea production life cycle

Items	Ammonia production	Urea production	Energy production	Natural gas production & trasnport	Mining of ores	Refining of ores, chemical production & transport
RD			35	55	10	
GWPI	25	10	30	10	15	10
OD	15	5	45	25	5	5
AP	20	10	20	30	15	5
SMD	15	15	20	30	20	10
CTWM	10	20	20	25	15	10
POI	20	10	30	25	10	5
HHR	25	15	20	20	10	10
SR	30	10	20	25	10	15
ER	15	25	10	20	20	10

Table 3. Percent ccontribution to environmental burden by urea and ammonia plant

Items	Hydro-desulfurizing unit	Reforming unit	CO converter	NH_3 reactor	Compressor	Urea reactor	Decomposer	NH_3 and CO_2 absorber
GWPI	15	35	5	15	10	5	10	5
OD	10	25	10	5	25	10	5	10
AP	25	10	10	15	5	10	10	15
SMD		10	30	20		30		10
CTWM		10	20	25		20	10	15
POI	5	25	5	20	5	10	10	20
HHR	20	10	15	25	5	10		15
SR	10	20	5	30	10	15	5	5
ER	10	5	20	30	5	5	5	20

Table 4. Percent contribution to safety risk (*SR*) during ammonia and urea production

Items	Hydro-desulfurizing unit	Reforming unit	CO converter	NH$_3$ reactor	Compressor	Urea reactor	Decomposer	NH$_3$ & CO$_2$ absorber
Total safety risk	15	15	5	30	10	15	5	5
Fire risk	60	40	50	30	30	30	30	20
Explosion risk	20	40	30	30	40	20	30	20
Toxic risk	20	20	20	40	30	50	40	60

Table 5. *HHR* through various exposure routes caused by different chemicals

Chemicals	Natural gas process			Naptha process			Fuel oil process			Coal process		
	Air	Water	Soil	Air	Water	Soil	Air	Water	Soil	Air	Water	Soil
NH3	35	5		30	5		30	5		25	5	
SOx	5	5	5	20	5	5	25	5	5	25	10	5
NOx	5	5		20	5		15	5		20	10	
Urea dust	10	30	20	10	25	25	10	25	20	5	20	15
VOCs	20	5		5			5			10		
Heavy metal	10	20	40	5	30	45	5	30	50	5	30	40
PM$_{10}$	10	5	5	5	5	5	5	10	5	5	5	10
Acids	5	25	30	5	25	20	5	20	20	5	20	30

Table 6. The normalised values of the basic indicators for various management alternatives

Normalised values of basic indicators	Alternative 1			Alternative 2			Alternative 3			Alternative 4		
	Min.	MLV	Max.	Min.	MLV	Max.	Min.	MLV	Max.	Min.	MLV	Max.
Resource depletion (RD)	0.265	0.642	1.000	0.224	0.606	0.982	0.158	0.552	0.946	0.000	0.427	0.851
Global warming potential (GWPI)	0.490	0.686	0.882	0.294	0.529	0.765	0.686	0.843	1.000	0.000	0.294	0.588
Ozone depletion (OD)	0.698	0.849	1.000	0.698	0.849	1.000	0.698	0.849	1.000	0.000	0.291	0.581
Acidification potential (AP)	0.705	0.853	1.000	0.556	0.734	0.911	0.556	0.734	0.911	0.000	0.290	0.577
Photochemical oxidation (POI)	0.000	0.286	0.571	0.714	0.857	1.000	0.714	0.857	1.000	0.429	0.571	0.714
Human health risk (HHR)	0.500	0.750	1.000	0.500	0.750	1.000	0.333	0.583	0.833	0.000	0.417	0.833
Ecological risk (ER)	0.364	0.682	1.000	0.364	0.682	1.000	0.364	0.682	1.000	0.000	0.409	0.818
Safety risk (SR)	0.000	0.357	0.929	0.179	0.500	0.964	0.286	0.571	0.964	0.357	0.643	1.000
Solid mass disposal (SMD)	0.820	0.910	1.000	0.820	0.910	1.000	0.613	0.747	0.879	0.000	0.256	0.511
Controlled toxic water mass (CTWM)	0.556	0.778	1.000	0.556	0.778	1.000	0.556	0.778	1.000	0.000	0.334	0.666
Ease of operation (EO)	0.600	0.750	0.900	0.300	0.500	0.700	0.100	0.250	0.400	0.100	0.250	0.400
Efficiency (Eff.)	0.600	0.750	0.900	0.600	0.750	0.900	0.300	0.500	0.700	0.000	0.100	0.200
Status of technology (ST)	0.600	0.750	0.900	0.600	0.750	0.900	0.300	0.500	0.700	0.000	0.100	0.200
Control measures (CM)	0.300	0.500	0.700	0.300	0.500	0.700	0.100	0.250	0.400	0.000	0.100	0.200
Working capital (WC)	0.100	0.250	0.400	0.300	0.500	0.700	0.300	0.500	0.700	0.300	0.500	0.700
Operation and maintenance (OM)	0.300	0.500	0.700	0.300	0.500	0.700	0.100	0.250	0.400	0.000	0.100	0.200
Capital investment (CI)	0.300	0.500	0.700	0.100	0.250	0.400	0.300	0.500	0.700	0.100	0.250	0.400

Table 7. Weighting schemes for fuzzy composite programming (FCP)

Basic Indicators	Level	Relative importance	w	p	Groups
GWPI	1	1	0.5	1	Warming - improvement index (WI)
OD	1	1	0.5		
AP	1	1	0.3	1	Acidification - improvement index (AI)
POI	1	2	0.7		
HHR	1	1	0.3	2	Risk reduction index (RI)
ER	1	4/3	0.4		
SR	1	1	0.3		
SMD	1	1	0.5	1	Pollution reduction index (PI)
CTWM	1	1	0.5		
EO	1	1	0.2	2	Technical feasibility index (TFI)
Eff.	1	2	0.4		
ST	1	1	0.2		
CM	1	1	0.2		
WC	1	1	0.3	1	Cost saving index (CI)
OM	1	1	0.3		
CI	1	4/3	0.4		
WI	2	3/2	0.3	1	Sink depletion - improvement index (SDI)
AI	2	1	0.2		
RI	2	3/2	0.3		
PI	2	1	0.2		
SDI	3	1	0.8	1	Environmental - improvement index (EI)
RDI	3	1/4	0.2		
EI	4	1	0.5	2	System - improvement index (SI)
TFI	4	2/5	0.2		
CI	4	3/5	0.3		

Table 8. Ranking of alternatives for trial 1

Alternatives	Source	Ut(x)1	Rank
1	Natural gas	0.668	2
2	Naptha	0.711	1
3	Fuel oil	0.599	3
4	Coal	0.227	4

Table 9. Weighting scheme for sensitivity analysis

Trials	Groups	Relative importance	w
Ut(x)1 (pro-environment)	EI	1	0.5
	CI	3/5	0.3
	TFI	2/5	0.2
Ut(x)2 (pro-cost saving)	EI	3/5	0.3
	CI	1	0.5
	TFI	2/5	0.2
Ut(x)3 (equal importance to cost saving and environment)	EI	1	0.4
	CI	1	0.4
	TFI	1/2	0.2