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Development of environmental consequence index (ECI) using fuzzy composite programming

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ABSTRACT

Estimation of environmental consequences of hazardous substances in chemical industries is a very difficult task owing to (i) diversity in the types of hazards and their effects, (ii) location, and (ii) uncertainty in input information. Several indices have been developed over the years to estimate the environmental consequences. In this paper, a critical literature review was done on the existing environmental indices to identify their applications and limitations. The existing indices lack in consideration of all environmental consequence factors such as material hazard factors, dispersion factors, environmental effects, and their uncertainty. A new methodology is proposed for the development of environmental consequence index (ECI), which can overcome the stated limitations. Moreover, the recently developed fuzzy composite programming (FCP) is used to take care of the uncertainty in estimation. ECI is applied to benzene extraction unit (BEU) of a petrochemical industry situated in eastern part of India. The ECI for all the eight sections of BEU are estimated and ranked. The results are compared with well-established indices such as Dow fire and explosion index, safety weight hazard index (SWeHI), and environmental accident index (EAI). The proposed ECI may outperform other indices based on its detailed consideration of the factors and performed equally to Dow F&E index, and EAI in most of the cases for the present application.

1. Introduction

The ever increased world population coupled with their growing societal demands has been triggering rapid expansion of industrialization, resource extraction, and intensive production [1]. Unfortunately, such swift industrialization and urbanization have been accompanied by large negative environmental effects, resulting in damage to the ecosystem. Such a potential to cause harm to the environment is environmental hazard. Resource depletion, greenhouse effect, global warming, acidification, air pollution, water pollution, land pollution, and human health effects are the important consequences of environmental hazards [2]. Broadly these impacts may be categorized into two groups as (i) effects on sensitive environment and (ii) effects on human. In both cases, impact is routed through surface and ground waters, air routes, fire and explosion, or direct contact.

Industrial releases to the environment can clearly have these two types of effects. For example, in 1976 the accident at Seveso, released a cloud of chemicals containing tetrachloro dibenzo paradioxin (TCDD) which caused contamination of vegetation, death of about 80,000 animals, and exposure of chemical released to nearly 37,000 people in the surrounding area [3]. Other major incidents include the disaster at Bhopal in 1984, with methyl isocyanate released, which caused much damage to the environment as well as death of more than 3000 people by poisoning and injuring at least 100,000 people [3]. Similarly in 1986, a fire accident in the warehouse of pharmaceutical plant caused huge quantities of pesticides to be drained into the Rhine river, which killed half a million fish and rendered lifeless for 200 km of the river [4]. These past catastrophic accidents have made the public aware of current environmental issues. This awareness has brought worldwide concern for the environmental consequences of industrial releases and development of methods for its evaluation. Several methods have been developed for the assessment of environmental consequences. Among them, relative assessment and ranking techniques (Dow's fire and explosion index, Dow's chemical exposure index, and ICI Mond index) are well known. For environmental consequence assessment of chemical substances and processes, different concepts such as design for environment and Life Cycle Assessment (LCA) are employed to choose environmentally benign products and processes. Life Cycle Assessment tries to analyze all impacts to the humans and the environment caused by a system (product or process) during its whole life cycle from cradle (raw material or design) to grave (disposal or decommissioning) [2]. In the category of design for environment, inherent safety design and analysis was introduced as a different concept for risk analysis. A number of index meth-

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ods were developed to apply this concept to process design [5–8]. A comprehensive review of these methods will help in comparing the different methods for their applications and limitations and in identifying gray areas for betterment.

In this paper, a comprehensive review on the existing environmental consequence estimation methods has been done to identify pros and cons of the existing methods in assessing hazards due to environmental releases and emissions. A new method, namely environmental consequence index (ECI) is developed for relative ranking of industrial installations based on properties of hazardous substances used, produced or stored, inventory of the substances, and environmental conditions of the location. Different decision-making criteria are incorporated in the development of environmental consequence index by employing a hierarchy process and fuzzy composite programming.

2. Overview of existing methods of environmental consequence assessment

In order to assess environmental consequences of chemical processes, various methods have been developed by academicia (e.g. environmental hazard index (EHI) by Cave and Edwards [4]; atmospheric hazard index (AHI) by Gunasekera and Edwards [9]; inherent safety index by Gentile et al. [8]; life cycle index (LInX) by Khan et al. [2]; substance fire hazard index (SFHI), consequence index (CI) by Paralikas and Lygeros [5]) and industries (e.g. Dow's fire and explosion index by Dow Chemicals [10] and ICI Mond index [11]). Each method has its limitations, advantages and applicability for different scenarios. Broadly two separate sets of tools exist—methods for identification and quantification of abnormal situations, i.e. environmental hazards (e.g. Dow's fire and explosion index) and methods for quantification of planned releases or emissions (e.g. AHI by Gunasekera and Edwards [9]). Dow's fire and explosion index, Dow's Chemical exposure index [12] and ICI Mond index are the most known and widely used techniques for rapid hazard assessment of installations that use hazardous substances. In the quantification of planned releases, Cave and Edwards [4] and Gunasekera and Edwards [9] developed aquatic and terrestrial indices, and atmospheric indices, respectively, for impact assessment of chemical routes on environment. Further, Gunasekera and Edwards [13] derived an index called inherent environmental toxicity hazard (IETH) based on a combination of the work of Cave and Edwards [4] and Gunasekera and Edwards [9].

Recent development in this field involves in the development of indices for inherent environmental safety and chemical process route selection based on Boolean mathematics [4,14,15]. The use of fuzzy logic theory in the development of inherent safety index enhances the effectiveness of the results [6–8]. Substance fire hazard index (SFHI), consequence index (CI), and global environmental risk assessment index (GERA) were developed for direct estimation and ranking of hazards due to environment [5,16]. Environmental accident index (EAI) was developed for the quantification of planned releases and emissions to discharges to ground, water or ground water [17]. Golonka and Brennan [18] reviewed various methods available for forming environmental impact indices which are of two major types such as the indices based on the amount of waste produced and the indices based on the relative environmental effects of different key parameters such as pollutant emissions, land usage and energy consumption, as well as unquantifiable parameters like aesthetic value.

The shift from process or product specific impacts to long-term system-wide subsidiary impacts has created interest in the use of life cycle assessment (LCA). Thus, the focuses on LCA lead to the development of life cycle indices. Khan et al. [2,19] proposed life cycle index (LInX) and GreenPro to facilitate life cycle assessment and decision-making in product and process development. In the above methods, the environmental consequences include potential damage to both environment and humans. Khan et al. [6,20,21] calculated damage to the ecosystem and human health separately and developed relations for calculation of environmental damage.

The methods developed so far can be grouped for the following applications [22]:

- Inherent safety evaluation during conceptual process design.
- Hazards identification and ranking.
- Damage assessment.
- Automation of hazard evaluation.

2.1. Inherent safety evaluation during conceptual process design

At the early process design stage, the available technical details are very less to decide on the chemical process route selection and design. In the past, economics were the most important criterion in choosing the chemical process route. But consideration of safety and environmental criteria lead to the development of inherent safety indices with limited technical details. Edwards and Lawrence [14] introduced an inherent safety index for chemical process route selection.

Cave and Edwards [4] developed environmental hazard index (EHI) which assesses and ranks environmental hazard of chemical process routes. EHI is based on the predicted environmental impact as a total loss of containment. EHI is a function of environmental effects of the chemicals and the estimated chemical inventory thereof in a plant and is defined as below.

$$\mathrm{EHI} = \sum_{i=1}^{n} Q_i \times \mathrm{SEHI}_i \quad (1)$$

where SEHI_i is the specific environmental hazard index of chemical i, Q_i is the quantity of chemical i, in tonnes, and n is the number of chemicals.

The specific environmental hazard index (SEHI) comprises specific water hazard index and specific terrestrial hazard index (STHI). Therefore,

$$\mathrm{SEHI}_i = \mathrm{SWHI}_i + \mathrm{STHI}_i \quad (2)$$

SWHI and STHI are calculated with the following equations, respectively:

$$\mathrm{SWHI}_i = \frac{\mathrm{PEC_{wi}} \times 10^6}{\mathrm{LC}_{50_i}} \quad (3)$$

$$\mathrm{STHI}_i = \frac{d[(\mathrm{TDI}_{wx}\mathrm{PEC}_{w_i}) + (\mathrm{TDI}_{fx}\mathrm{PEC}_{s_i})]}{\mathrm{LD}_{50_{xi}}\mathrm{Wt}_x} \times 10^9 \quad (4)$$

Where

PEC_{w_i} is the predicted environmental concentration of chemical i in the water compartment per tonnes chemical released (m^{-3});
LC_{50_i} is the concentration of chemical i in water which kills 50% of a test population of the most sensitive species over a 96 h period (mg/dm^3);
TDI_{wx} is the daily food intake of species x (m^3/day);
TDI_{fx} is the daily fluid intake of species x (m^3/day);
PEC_{s_i} is the predicted specific environmental concentration of chemical i in the soil compartment per tonnes of chemical released (m^{-3});
$\mathrm{LD}_{50_{xi}}$ is the lethal dose of chemical i that kills 50% of the test population of species x (mg/kg);
Wt_x is the weight of species x (kg).

Gunasekera and Edwards [9] proposed an atmospheric hazard index (AHI) to estimate the atmospheric impact which was not considered in the EHI by Cave and Edwards [4] for the worst possible accident scenario. The atmospheric impact categories considered are toxicity, photochemical smog, acid deposition, global warming, and stratospheric ozone depletion. The adverse impacts due to each chemical are estimated and are then brought onto a common scale, and a combined impact for each chemical, called the chemical atmospheric hazard (CAH) is determined. The AHI value for a route is the sum of the CAH for the chemicals in the route.

$$\mathrm{AHI} = \sum_{i=1}^{m} \mathrm{CAH}_i \tag{5}$$

where CAH_i is the chemical atmospheric hazard for chemical i and m is the number of chemicals involved in the chemical process route.

The AHI is limited to atmospheric effects and it does not consider soil and water effects. Koller et al. [15] presented a flexible structure combing best available practices from risk analysis and environmental assessment. The method considers 11 impact categories of safety, health and environmental (SHE) aspects such as mobility, fire and explosion, reaction and decomposition, acute toxicity, irritation, chronic toxicity, air mediated effects, water mediated effects, solid waste, degradation, and accumulation. Different measures or properties can be used to calculate an index value for each of these categories based on available data and related information. However, the aggregation of these indices into a single index was not performed.

Gentile et al. [7,8] improved the measurement of inherent safety using fuzzy logic. The use of fuzzy logic reduced the uncertainty involved in the selection of hazard values. Shah et al. [23] developed a hierarchical approach with safety, health, and environment at different layers. Further, Paralikas and Lygeros [5] proposed a methodology based on both hierarchical approach [23] and fuzzy logic [7,8] for relative ranking of fire hazard of chemical substances and installations. The substance fire hazard index (SFHI) focuses on the major accident hazards of the substances and the consequences index (CI) assesses the consequence potential of an accident at the facility. Each index is calculated based on the following formula:

$$I_s = \sum_{j} W_j P_j^s \tag{6}$$

where W_j is the weight factor of the jth parameter and P_j^s is the performance measure, or penalty factor of the jth parameter for the sth substance.

Khan et al. [2] proposed a life cycle index (LInX) to facilitate life cycle assessment of processes and products. The LInX is comprised of four important sub-indices or attributes, namely environment, cost (capital cost, operation and maintenance cost, and cost due to health, safety, and environment damage), technical feasibility, and socio-political factors. Each attribute contains a number of basic parameters. An analytic hierarchy process is used to compute the weights for each basic parameter and sub-indices. The environment sub-index is represented by pollution, risk, and global warming. All the environmental parameters are quantified using the monographs developed. The cumulative value of the index is used to establish the penalty due to the potential threat of damaging ecological entities. However, the values selected from monographs are not accurate to produce better results. To overcome this, Khan et al. [6] presented an integrated inherent safety index (I2SI), which is a guideword based indexing approach to measure inherent safety using monographs developed for LInX. I2SI comprises sub-indices for hazard potential, inherent safety potential, and add-on control requirements.

$$\mathrm{I2SI} = \frac{\mathrm{ISPI}}{\mathrm{HI}} \tag{7}$$

where HI is hazard index and ISPI is inherent safety potential index.

HI is defined as the measure of damage potential of the process considering both hazards and available control measures. HI values range from 1 to 200. ISPI is defined as the measure of applicability of the inherent safety principles, and its values also range from 1 to 200.

2.2. Hazards identification and ranking

Over the years, several indices have been proposed for hazard identification and ranking of chemical plant and equipment. Well known among them are Dow's fire and explosion index, Dow's chemical exposure index, ICI Mond index, instantaneous fractional annual loss (IFAL) index, and mortality index [11]. Other indices developed in this line are safety weighted hazard index (SWeHI) [24], environmental accident index (EAI) [17], and global environmental risk assessment (GERA) [16]. While the former indices are very well known, the later were developed recently in the last 10 years or so. These recently developed indices are described below.

Khan et al. [24] developed SWeHI index which is a measure of the damage radius of an area under moderate hazard arising from a given chemical unit/plant considering the chemicals, operating conditions, and environmental setting involved at that instant.

$$\mathrm{SWeHI} = \frac{B}{A} \tag{8}$$

where B is the quantitative measure of the damage that may be caused by an unit/plant. 'A' represents the credits due to control measures and safety arrangements made to counter the undesirable situations.

Scott [17] developed a simple model, namely environmental accident index (EAI) that is limited to discharges to ground, water or ground water and is not applicable on fires, explosions or accidents with release of gases into the air. EAI consists of three parts: (i) the acute toxicity to water-living organisms (Tox), (ii) the stored or transported amount of the chemical (Am), and (iii) factors controlling the spreading of a chemical. The spreading part (consistency, solubility and properties of the surrounding environment) contains chemical–physical properties of the chemical, possibility of soil penetration and the depth and mobility of groundwater. EAI is calculated as follows:

$$\mathrm{EAI} = \mathrm{Tox} \times \mathrm{Am} \times (\mathrm{Con} + \mathrm{Sol} + \mathrm{Sur}) \tag{9}$$

where Tox is the acute toxicity to water-living organisms; Am is the stored or transported amount of the chemical; Con is the consistency or viscosity or physical state of the chemical; Sol is the water solubility of the chemical; Sur is the properties of surrounding environment.

Achour et al. [16] introduced a global environmental risk assessment (GERA) index for assessing environmental risk of new or existing industrial processes. The GERA index is calculated based on an overall component environmental risk balance (using the inlet and outlet streams of a process) and the individual environmental risk indices of the unit operations constituting the given process. The equation for GERA index is given below.

$$\mathrm{GERA} = \left(a \sum_{k=1}^{n_s} y_k \beta_k \right) + \left(b \sum_{m=1}^{n_u} \theta_m^{W_m} \right) \tag{10}$$

where a and b are the proportional factors (between 0 and 1) reflecting the relative contributions of the overall component risk balance and the unit operations' risk indices to the GERA index, respectively; n_s is the total number of inlet and outlet streams to the process directly interacting with the outside environment; y_k is the fraction of the flow rate of stream k compared to the total inlet flow rate; β_k is the stream risk index; n_u is the total number of unit operations constituting the process; θ_m is the unit operation risk index for unit m; and w_m is the weighting factor for unit operation m.

The cumulative risk effect of components existing in a process inlet or outlet stream is given by the following expression for the stream environmental risk index, β_k:

$$\beta_k = \sum_{i=1}^{n_c} x_{i,k}\alpha_i^{w_i} \tag{11}$$

where

n_c—the number of components in the process stream;
x_i—the mole/mass fraction of component i in the flow stream;
α_i—the environmental index for each component i;
w_i—the weighting factor for each component.

The environmental risk index for a given unit operation, θ_m, is determined as follows:

$$\theta_m = \left\{ y_k\beta_k + z_m\left(\frac{\sum_{j=1}^{M} I_j}{M}\right)\right\} \tag{12}$$

where

y_k—the fraction of the out let stream from the given unit;
β_k—the environmental risk index for the outlet stream from the given unit, not directly interacting with the outside environment;
z_m—the size factor for unit m, given values between 0 and 1;
M—the total number of indices characterizing the unit operation's environmental risk;
I_j—the risk value corresponding to the index j for the given unit operation.

There is high uncertainty in the selection of hazard values. This demerit degrades the results.

2.3. Damage assessment

The methods for environmental damage assessment are vague because the available information is imprecise. However, efforts have been made to assess the damage based on several assumptions.

Barlettani et al. [25,26] proposed an energy impact index which is a measure of the amount of energy lost per year, expressed in Joules. In this method, human life is equivalent to a certain amount of energy, about 800 billion Joules. The effect on the ecosystem and human is calculated as per the following formula:

$$\mathrm{GPP_{lost}} = \mathrm{EPP} + \mathrm{GPP}'T \tag{13}$$

where $\mathrm{GPP_{lost}}$ is the effect on the ecosystem and humans in Joules; EPP is the energy loss of the system; GPP′ is the amount of energy needed during period T for recovery of harmed organisms.

NORSOK [25,27] (the competitive standing of the Norwegian offshore sector) considered recovery time differently than Barlettani et al. [25,26]. Instead of considering energy needed to recovery, NORSOK proposed the probability of exceedance of the time needed by the ecosystem to recover from the damage as a measure for environmental risk based on the following formula:

$$1 - F_T(x) = P(T > x) = \int_x^{\infty} f_T(x)\,dx \tag{14}$$

where $F_T(x)$ is probability distribution function of the recovery time for the ecosystem; and $f_T(x)$ is probability density function of the recovery time for the ecosystem.

Khan and Haddara [28] used a different concept to estimate ecosystem damage using the following relations:

$$\text{Environmental loss} = \frac{\text{damage area} \times \text{importance factor}}{\text{unacceptable damage area}}.$$

Importance factor ranges from 0.1 to 1.0. This factor is quantified based on nearby sensitive ecosystem. If the damage radius is higher than the distance between the accident location and the location of the sensitive ecosystem, i.e. lake, forest, and bird sanctuary, a value of 1.0 is taken as importance factor.

In another paper, Khan and Haddara [20] suggested an improved and modified form of above method.

$$\begin{aligned}\text{Environmental loss} &= \text{damage area} \times \text{importance factor}\\ &\quad \times \text{environment media}\\ &\quad \times \text{dollar value of environmental damage}\end{aligned}$$

The following values are suggested for the environment media: 0.1 for air (coastal zone), 0.5 for water body, and 0.8 for soil. It is not simple to assign a dollar value for environmental damage. Assignment of importance factor is also another hindrance for the damage estimation. Khan and Amyotte [6] proposed a new approach for calculating environmental cleanup cost for soil, water and air environments without considering human safety aspects. The environmental cleanup cost for soil, water and air are calculated based on the mass or volume contaminated. The mass of contaminated soil is calculated by considering a general soil density of 2650 kg/m^3 and a depth of contamination of 0.5 m. The volume of contaminated water is calculated by considering the contaminated area multiplied by a 1 m depth of contamination; for contaminated air, the area is multiplied by a height of 10 m. Thus, the environmental cleanup cost is:

$$C_{\mathrm{ECC}} = C_{\mathrm{soil}} + C_{\mathrm{water}} + C_{\mathrm{air}} \tag{15}$$

$C_{\mathrm{soil}} = M_s \times$ cleanup cost ($/mass) × NH = DA × depth of contamination × density of soil × CC × NH;
$C_{\mathrm{water}} = V_w \times$ Cleanup cost ($/volume) × NH = DA × depth of contamination × density of water × CC × NH;
$C_{\mathrm{air}} = V_a \times$ dilution or cleanup cost ($/volume) × NH = DA × height of contamination × density of air × CC × NH;
M_s—mass of contaminated soil; V_w—volume of contaminated water; V_a—volume of contaminated air;
DA—damage area; CC–cleanup cost; NH—NFPA rank of the chemical as related to health hazards.

The assumptions made in this method, for example volume of the environmental compartments such as air, water, and soil, and individual cleanup cost value, introduce a high uncertainty in the environmental cleanup cost value.

2.4. Automation of hazard evaluation

The automation of hazard assessment by use of computer program can evaluate the hazards quickly and enhances decision-making. Sadiq et al. [29] developed GreenPro-I, a decision-making methodology for design problem formulation using LCA, and design problem solution using multi-objective optimization and multi-criteria decision-making (MCDM). But its application restricted to early stage design. Palaniappan et al. [30] developed a systematic methodology to integrate inherent safety and environmental impact assessment. The study provides a unified framework for

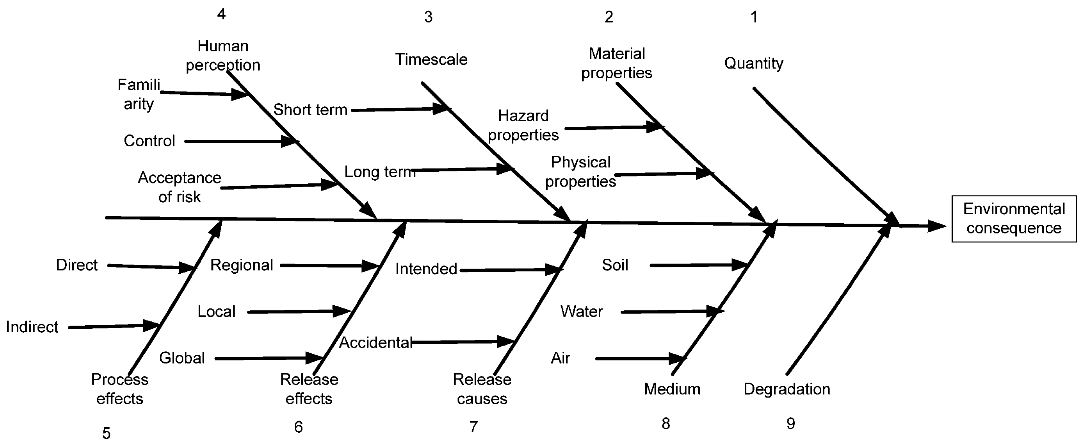

Fig. 1. Factors to be considered in the assessment of environmental consequences.

hazards and pollution analysis by focusing on process materials and their interactions with process units and conditions. A guide word-based alternative generation technique, which meshes Palaniappan et al.'s [30] study with inherent safety and waste minimization principles, was proposed. The automated tool called iBDT, was implemented as an expert system and successfully tested on an acrylic acid process.

2.5. Critical assessment of the literature

The review of research work identified (i) various methods and techniques used in environmental consequence assessment, (ii) the assumptions made in developing these methods and techniques, and (iii) their case study applications. The major hurdle to overcome while estimating the environmental consequence is the consideration of different hazard potentials with reasonable estimation of their effects, if undesired incidents occur. A central difficulty in measuring the overall environmental consequence is consideration of the different hazard potentials and their effects from accidents. The difficulty arises not only from the stochastic nature of such events, but also problems in quantifying the size of releases and the uncertainty of their effects [31]. The impact of a process that depends not only on amount of materials released intentionally, but also on its location, social acceptance, resource utilization, and risk of accident. As a result, even though substantial amount of research work has been conducted to assess environmental consequences, there still remain some vital points to be incorporated in the existing methodologies:

i. As diversity of factors with varying hazard potentials affect environmental consequences of accidental releases, the methodology should consider the important environmental compartments such as air, water and soil [e.g. Gunasekera and Edwards [9] considered only atmospheric environment; Cave and Edwards [4] considered aquatic and terrestrial environment; Scott [17] considered only the hazards due to discharges to ground, water or ground water].
ii. The spreading of chemical substances depends on physical properties of the chemical substances involved (e.g. vapor pressure and water solubility) and location factors of the environment (e.g. wind speed and distance from nearby water bodies). Therefore, the methodology should consider the location factors of environment and important dispersion factors of the chemical substances. For example, Gunasekera and Edwards [9] and Cave and Edwards [4] have not considered location effects in dispersion of chemicals.
iii. The methodology should be robust enough to reduce the uncertainty involved in the selection of values and decision-making.
iv. In case of preliminary design phase, generally there is less or no information about failures and its consequences. So, thorough analysis using data cannot be possible for assessing environmental consequences.

The existing environmental indices identified from the literature lack in consideration of the hazard properties, dispersion factors, and effects of chemical substances to the environment as well as the uncertainty in totality. The present study attempts to overcome these limitations in identifying all the factors of environmental consequence and developing a methodology for aggregation.

3. Factors to be considered in environmental consequence assessment

The inherent safety index of a plant or equipment generally considers fire, explosion, reactivity, and toxicity impacts in its derivation. But the environmental consequence is also affected by many other factors. The environmental impact categories usually consists of mobility, fire and explosion, reaction and decomposition, acute toxicity, irritation, chronic toxicity, air mediated effects, water mediated effects, solid waste, degradation, and accumulation. Other than these impacts, human perception, time scale, process effects, and release effects are also important factors to be considered for environmental consequence assessment. These environmental consequence factors are chiefly classified into nine categories, namely quantity of chemicals, material properties, time scale, human perception, process effects, release causes, release effects, spreading medium, and degradation, and are presented in Fig. 1 as a cause and effect diagram. How the nine factors relate to environmental consequences are explained below.

(i) Quantity of chemicals: It is assumed that the quantity of chemical released will be the quantity of chemicals present in the plant at the time of release. The damage due to a mixture of chemicals is assumed to be the sum of the impacts due to the individual chemicals involved in the process. According to Calamari and Vighi [32], this assumption is the simplest and that can be used for assessing the overall damage due to a mixture of chemicals. As mentioned by Koller et al. [22], quantity of chemicals has been used in two ways for deriving consequence indices: (a) some methods consider sum of the masses

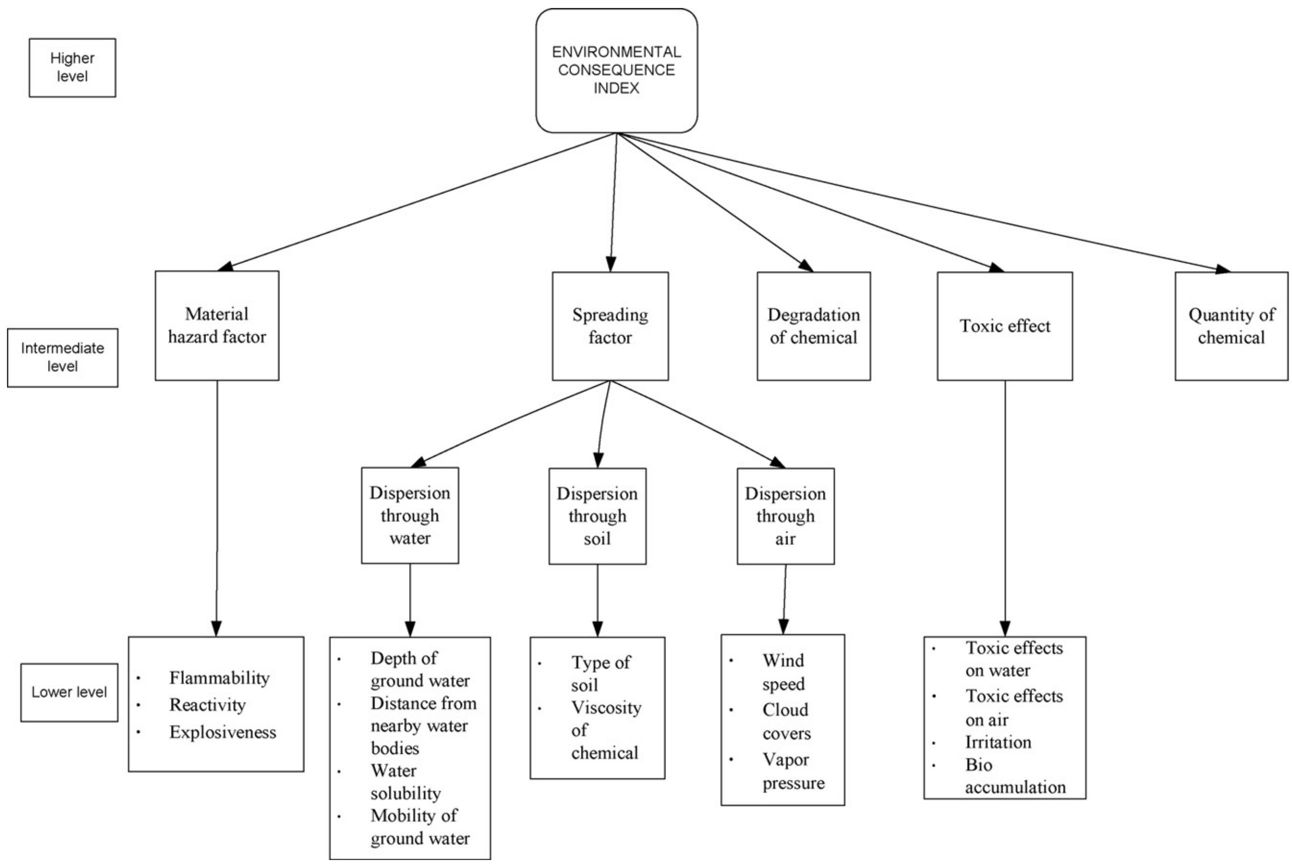

Fig. 2. Hierarchical structure of consequence parameters for proposed methodology.

and toxicity or use mass as a penalty (e.g. Dow's fire and explosion index). These methods are adopted in the case of materials which cause harm due to body contact or nearby exposure (e.g. carcinogenic material), and as such the amount of chemical is not an important factor. (b) Other methods use the product of mass and hazard potential for assessment (e.g. SWeHI, EAI). These methods are adopted for materials which are easily flammable, volatile, and toxic, where the amount of chemical directly influences the consequence index.

(ii) The material properties include hazard properties (e.g. flammability, toxicity, corrosivity, explosiveness, and reactivity) and physical properties (e.g. vapor pressure, solubility) of chemical substances.

(iii) The time scale includes both short-term (e.g. fire) and long-term effects (e.g. carcinogenic effects) [31].

(iv) The human perception plays an important role in risk quantification. Human perception factors include familiarity, control, and acceptance of risk.

(v) The process adds to direct (associated with the process itself) and indirect (associated with other parts of the life cycle of the product such as raw materials, waste management and end use) effects [31].

(vi) The effects of release comprise local (e.g. fire), regional (e.g. water contamination), and global (e.g. global warming, ozone depletion) effects [31].

(vii) The causes of release comprise intended or planned (e.g. effluent disposal) and accidental (e.g. spill) releases.

(viii) Traditionally, indices have been developed for one specific spreading medium such as air, water or land (e.g. EHI by Cave and Edwards [4]; AHI by Gunasekera and Edwards [9]). Recently, some tools have been developed to assess the environment as a whole (e.g. IETH by Gunasekera and Edwards [13]). The location factors are also important in estimating environmental consequences. Each medium has its own location factors. For example, for (a) air—wind speed, humidity, and cloud covers, (b) water—depth of ground water, distance from nearby water bodies, and (c) soil—thickness of soil layer, and type of soil are some of the location factors.

(ix) Finally, the degradation of chemical is the persistency of chemical (generally it is measured with half life period of the chemical) [15].

From above mentioned nine categories of environmental consequence factors, eight categories of consequence factors are considered for the development of proposed environmental consequence index except human perception factors. The evaluation of human perception is a difficult task and can be incorporated if the information is available. Further, in the case of plant or equipment failure, only the accidental releases can be taken into consideration from causes of release. The global effects such as global warming, acid rain, and ozone depletion effects are difficult to quantify for all the components. So, only local and regional release effects are taken into consideration in this study. In the case of process effects, only direct effects are considered, as the indirect effects are not significant. As per time scale, the effects are considered short-term, because the long-term effects estimation is not accurate in case of environmental consequence assessment. The selected categories of consequence factors are acquired for the development of a hierarchical structure to estimate environmental consequence index. The hierarchical structure of consequence factors as developed is shown in Fig. 2. This hierarchical structure is developed using the cause and effect diagram for factors affecting consequences (Fig. 1). The higher level of the hierarchical structure represents the environmental consequence index. The higher level is broken down into intermediate level contributory factors. The intermediate level consists of material hazard factor, spreading factor, degradation of chemical, environmental effect, and quantity of chemical. The intermediate level factors comprise sub-levels such that the spreading factor considers dispersion of hazardous substances through soil, water and air. The toxic effect has toxic effects on water and air, irritation, and bioaccumulation. Further, the intermediate sub-levels are partitioned into lower level contributory factors or the simplest possible entities. The material hazard factor includes hazard properties such as flammability, reactivity, and explosiveness. The dispersion through water includes depth of ground water, distance from nearby water bodies, water solubility, and mobility of ground water. The dispersion through soil includes type of soil and viscosity of chemical. The dispersion through air includes lower level contributory factors such as wind speed, relative humidity, and mobility in air. Finally, the developed hierarchical structure is used for the estimation of environmental consequence index. The hierarchical structure can be further enhanced by adding other environmental consequence factors to improve on the results desired.

4. Proposed methodology for environmental consequence assessment

In real life problem solving, the factors of environmental consequence are not assessed precisely due to unquantifiable, imperfect, and non-obtainable information and partial ignorance. These limitations lead to the use of fuzzy based approaches in environmental consequence assessment. The literature review shows the significant use of multi-criteria decision-making (MCDM) and fuzzy concepts in the environmental and life cycle assessment [5,7,8,28,33]. Gentile et al. [7] developed fuzzy logic based inherent safety index for evaluating the design alternatives. Paralikas and Lygeros [5] and Khan et al. [33] presented a combined approach of analytical hierarchy process (AHP) for incorporation of different factors and fuzzy logic for dealing with both linguistic variables and uncertainties. Recently fuzzy composite programming (FCP) approach is gaining popularity and many researchers have used FCP approach in environmental decision-making problems [28,34–36]. Sadiq et al. [36] used FCP for the management of drilling waste disposal in offshore to determine the best discharge scenario considering risk, cost and technical feasibility criteria. The FCP is a step-by-step procedure of regrouping of a set of various basic indicators to form a single indicator [30]. Generally, the FCP is advantageous to the decision-makers in solving problems of multiple attributes and conflicting objectives. In this study, FCP is therefore used in the development of environmental consequence index to capture the composite structure of environmental consequence factors.

Fig. 3 shows the proposed methodology for the development of environmental consequence index. The methodology involves in the following steps:

(i) Identification of relevant factors and development of hierarchical structure of these factors in groups and subgroups.
(ii) Assignment of weights to all parameters that belong to the groups and subgroups.
(iii) Fuzzification of environmental consequence factors.
(iv) Aggregation of environmental consequence factors.
(v) Development of environmental consequence index by combining environmental consequence factors using FCP.

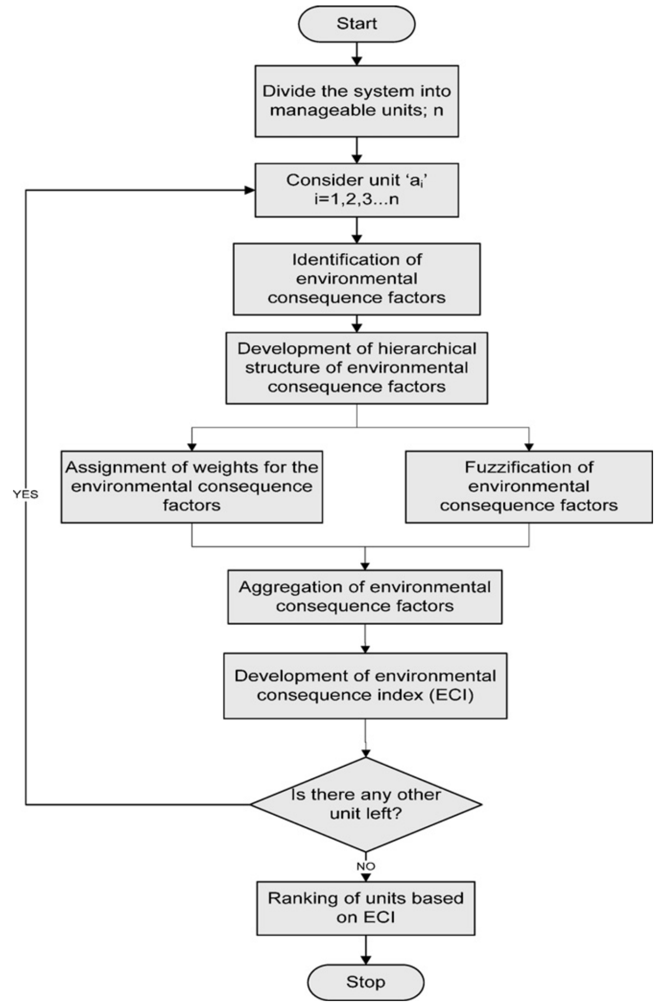

Fig. 3. Framework for estimating environmental consequence index (ECI).

4.1. Proposed environmental consequence index (ECI)

The first step in the development of the proposed ECI was the determination of the lower level factors (see Fig. 2) that would be taken into consideration in the development and calculation of the index. For the determination of those factors, data from the following sources were taken: Substance fire hazard index [5]; Dow's fire and explosion index hazard classification guide [12]; and Environmental accident index [17] and are presented in Appendix A. The second step involves the assignment of weights to the factors. The weights are assessed to reflect the relative importance of each of the factors, which can be normalized to a sum of 1. In case of n factors, a set of weights can be written as [2,29]

$$W = (w_1, w_2, w_3, \ldots, w_n), \quad \text{where} \sum_{i=1}^{n} w_i = 1 \tag{16}$$

To calculate the weights, Saaty [37] proposed analytical hierarchy process (AHP) to estimate the relative weight of each factor based on pair-wise comparisons. Further more, Chen and Lin [38] proposed the use of linguistic variables to assess the fuzzy importance of the factors as shown in Table 1. Sadiq et al. [29] adopted this method to convert linguistic terms into fuzzy numbers. Considering Chen and Lin [38] and Sadiq et al. [29], the weight w_i for each

Table 1
Triangular fuzzy number for intensity of importance [37]

Intensity of importance	Triangular fuzzy number, s_i
Very low	0, 0.05, 1
Low	0.1, 0.18, 0.25
Medium low	0.25, 0.33, 0.4
Medium	0.4, 0.5, 0.6
Medium high	0.6, 0.68, 0.75
High	0.75, 0.83, 0.9
Very high	0.9, 0.95, 1

factor in each category is calculated by:

$$w_i = \frac{s_i}{\sum_{i=1}^{k} s_i} \quad (17)$$

where s_i is the importance factor for ith factor, which can be selected from Table 2 for each factor. In this study, the fuzzy importance factors from Chen and Lin [38] are adopted for the estimation of weights of each environmental consequence factor because of its simplicity and inclusion of fuzziness.

In the third step of the methodology, the worst and best values for each of the environmental consequence factors are assessed and they are summarized in Table 2. The worst and best value for quantity of chemical is considered as the maximum and minimum amount of chemical substance present in the process, respectively. These classes can be represented as triangular or trapezoidal fuzzy numbers. For simplicity, triangular fuzzy numbers are used in the present study.

Then membership degree (m_{ij}) of the input value to each of a factor (i) for any chemical substance (j) (if the plant or equipment involves more than one chemical substances) is estimated by a normalization process using the best and worst values for that factor. This has been done for all factors. Bardossy and Duckstein [39] noted that the maximum and minimum values might be crisp or fuzzy. In this study, the best and worst values are assumed to be crisp. The normalization is performed using the Eqs. (18) and (19) [34,35] described below.

Let $Z(x, y)$ be the fuzzy number. The membership function, $m(Z(x, y))$, of the fuzzy number $Z(x, y)$ can be approximately calculated from the piecewise linear function (Fig. 4):

If Zmax_{ij} is the best value, then

$$m_{ij} = \begin{Bmatrix} 1, & \text{when } Z_{ij} \le \mathrm{Zmin}_{ij} \\ \left(1 - \dfrac{Z_{ij} - \mathrm{Zmin}_{ij}}{\mathrm{Zmax}_{ij} - \mathrm{Zmin}_{ij}}\right), & \text{when } \mathrm{Zmin}_{ij} < Z_{ij} < \mathrm{Zmax}_{ij} \\ 0, & \text{when } Z_{ij} \ge \mathrm{Zmax}_{ij} \end{Bmatrix} \quad (18)$$

and if Zmin_{ij} is the best value, then

$$m_{ij} = \begin{Bmatrix} 1, & \text{when } Z_{ij} \le \mathrm{Zmax}_{ij} \\ \left(\dfrac{Z_{ij} - \mathrm{Zmin}_{ij}}{\mathrm{Zmax}_{ij} - \mathrm{Zmin}_{ij}}\right), & \text{when } \mathrm{Zmin}_{ij} < Z_{ij} < \mathrm{Zmax}_{ij} \\ 0, & \text{when } Z_{ij} \ge \mathrm{Zmin}_{ij} \end{Bmatrix} \quad (19)$$

where
$i = 1, 2, 3, \ldots, n$, $j = 1, 2, 3, \ldots, k$;
n is the number of factors;
k is the number of substances;
Z_{ij} = value of the ith factor of jth substance;
Zmax_{ij} = maximum of best and worst possible value = $\max(\underset{\forall i,j}{\text{best}}\|Z_{ij}\|, \underset{\forall i,j}{\text{worst}}\|Z_{ij}\|)$;
Zmin_{ij} = minimum of best and worst possible value = $\min(\underset{\forall i,j}{\text{best}}\|Z_{ij}\|, \underset{\forall i,j}{\text{worst}}\|Z_{ij}\|)$;
m_{ij} = membership degree; $m \in (0, 1)$.

Table 2
Best and worst values of environmental consequence factors

Environmental consequence factors	Worst	Best	Units
Material hazard factor			
Flammability[a]	4	0	NFPA value
Reactivity[a]	4	0	NFPA value
Explosiveness[b]	100	1	Upper explosive level – lower explosive level
Spreading factor			
Dispersion through water[c]			
Depth of ground water	1	1,000	m
Distance from nearby waterbodies	0	2,000	m
Water solubility	100	0	%
Mobility of ground water	5	0	Qualitative
Dispersion through soil[c]			
Type of soil	0	9	Substance
Viscosity of chemical	5	1	cP
Dispersion through air[d]			
Wind speed	21	<1	m/s
Relative humidity	100	0	%
Mobility in air	200	0	Boiling point (°C)
Environmental effects			
Bioaccumulation[e]	100	0	Bioconcentration factor
Irritation[f]	1	0	Substance
Toxic effects on soil and water[f]	<1	>1,000	LC_{50} acute
Toxic effects on air[f]	10	10,000	EPRG3 value (ppm)
Degradation of chemical[f]	100	1	Persistency (days)

[a] Dow's Fire and Explosion Index Hazard Classification Guide [10].
[b] Edwards and Lawrence [14].
[c] Scott [17].
[d] ALOHA manual [42].
[e] Allen and Shonnard [40].
[f] Koller et al. [15].

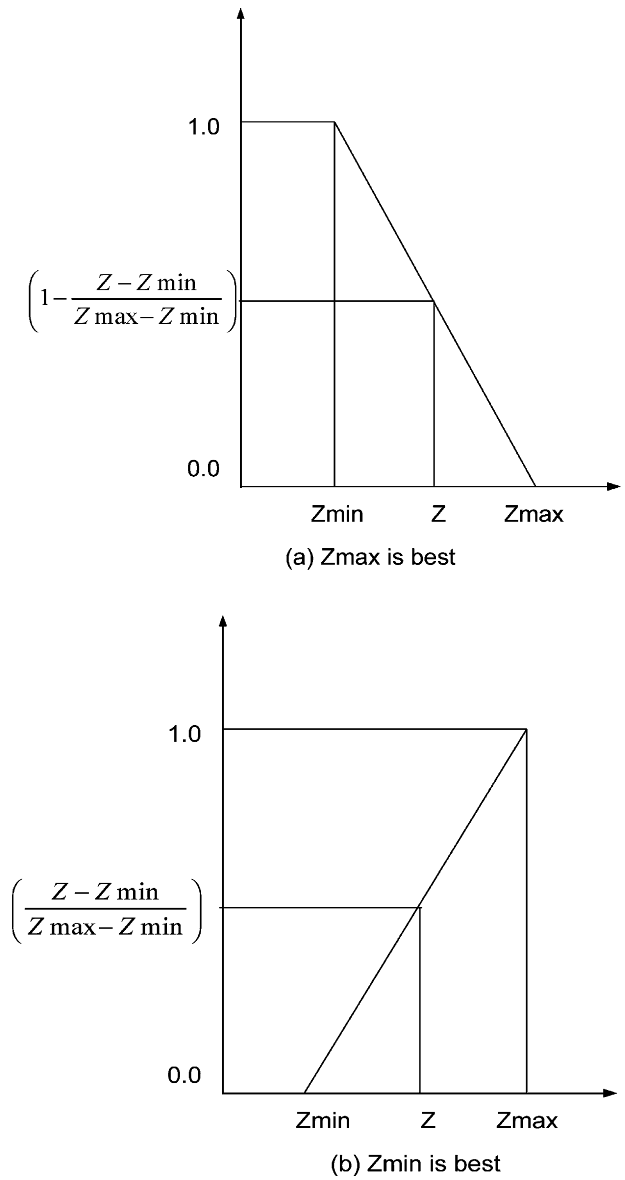

Fig. 4. Fuzzy membership function of parameter *Z*.

The membership function (m_{ij}) can be expressed as $n \times k$ matrix shown below:

$$m_{ij} = \begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1k} \\ m_{21} & m_{22} & \cdots & m_{2k} \\ \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & m_{ik} \\ m_{n1} & m_{12} & \cdots & m_{nk} \end{bmatrix}$$

After the normalization process, the membership values are fuzzified and the uncertainty in the normalized scale is expressed by ±50% [29]. In the fourth step, weighted environmental consequence factor for each *j*th substance (ECF_j) is obtained by summation of product of the weights (w_{ij}) and membership values (m_{ij}) for all factors using the following relation:

$$ECF_j = \sum_{i=1}^{n} w_{ij} m_{ij} \quad (20)$$

where

w_{ij}—weights for property of substance;
m_{ij}—membership value of property of substance.

The level cut concept is used to define the interval of each of the factor at various levels of confidence. The confidence level can be determined by expert opinion. In this study, the base values of the factors are assumed for the best and worst values.

The final step includes the defuzzification of ECFs for each *j*th substance which is performed to estimate the crisp values of ECFs using any defuzzification method. The averaging method is used in this study for defuzzification of ECF. Then, the overall environmental consequence index is calculated as the fuzzy sum of the environmental consequence factors of all the chemical substances, and is shown below.

$$ECI = \sum_{j} DECF_j \quad (21)$$

where DECF—defuzzified environmental consequence factor.

4.2. Application of the methodology

The proposed environmental consequence index is calculated for a benzene extraction unit (BEU) located in the eastern part of India. The BEU plant essentially comprises of a pre-distillation and an extractive distillation unit based on the Lurgi Distapex process. The benzene extraction unit is designed to produce 77,050 tonnes per annum (TPA) of benzene. The overall process flow sheet of the BEU plant is shown in Fig. 5. The benzene extraction unit includes rerun column, extractive distillation column, raffinate column, benzene column, solvent regenerator, storage and slop drums, vacuum system, and process condensate system. In the BEU unit, there are in total 74 equipment including 17 vessels, 32 pumps, 22 heat exchangers, and 4 distillation columns. The process produces benzene and *n*-methyl pyrrolidone (NMP).

4.2.1. Determination of weights

As a first step of the methodology, the triangular fuzzy numbers for all the linguistic measures of importance are selected from Table 1 for all the factors considered in the hierarchical structure (see Fig. 2). Then the weights are calculated from the triangular fuzzy numbers for each of the factors using Eq. (17) as shown in Table 3.

4.2.2. Normalization and fuzzification of environmental consequence factors

Based on the degree of severity of consequence, each of the environmental consequence factors is assigned a numerical score. The numerical scores of severity for consequence factors are obtained through literature. The severity categorization with the numerical scoring is given in Appendix A. For example, the degree of severity for the factor flammability of benzene is 'significant' and the corresponding numerical score is 2 (see Appendix A.1).

The procedure discussed in the third step of the proposed methodology (see Section 4.1) was used to estimate the fuzzy membership values for all the environmental consequence factors for all the sections of BEU. The input data are normalized to bring all the parameters in the same scale. The worst and best values for environmental consequence factors are considered for normalization. The normalized environmental consequence factors are fuzzified by a factor of ±50%. The maximum (Zmax) and minimum (Zmin) of the worst and best values are taken from Table 2. If Zmax is the best value, then the factor values are fuzzified using Eq. (18). If Zmin is the best value, then the factor values are fuzzified using Eq. (19). The normalized fuzzy values of environmental consequence fac-

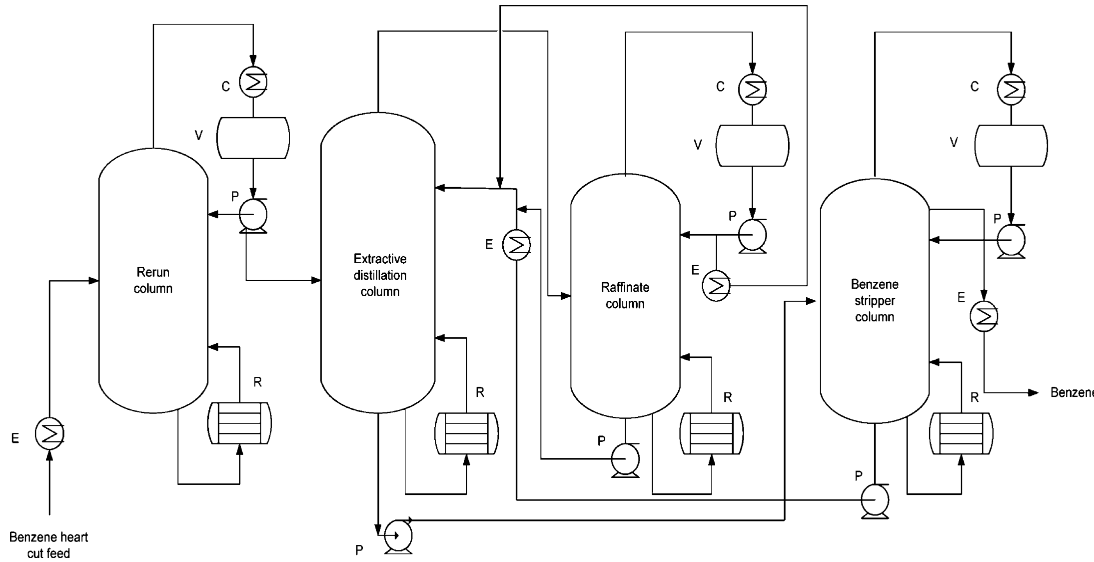

Fig. 5. Overall process flow sheet of BEU (C—Condenser; E—Exchanger; P—Pump; R—Reboiler; V—Vessel).

tors are shown in Table 4. As the quantity of chemical varies from equipment to equipment, considering the large number of equipment (74), the estimated normalized fuzzy values for amount of chemical are not shown in Table 4.

4.2.3. Aggregation of environmental consequence factors and defuzzification of environmental consequence index

The weighted environmental consequence factors (ECF) are calculated from the fuzzified membership degrees of the factors (Table 4) and fuzzy weights (Table 3) using Eq. (20) for benzene and NMP and are shown in Table 5. The estimated ECF for all equipment present in each section of the BEU are defuzzified into crisp values using the averaging method. The defuzzified ECF values are summed up to yield ECI for each section in the BEU using Eq. (21).

Table 3
Fuzzy weights for environmental consequence factors

Environmental consequence factors	Weights		
	Minimum	Most likely	Maximum
Material hazard factor	0.1231	0.1355	0.1500
Flammability	0.0577	0.0611	0.0659
Reactivity	0.0462	0.0501	0.0549
Explosiveness	0.0192	0.0243	0.0293
Spreading factors	0.1846	0.1843	0.1875
Dispersion through water	0.0633	0.0536	0.0625
Depth of ground water	0.0158	0.0134	0.0156
Distance from nearby waterbodies	0.0158	0.0134	0.0156
Water solubility	0.0158	0.0134	0.0156
Mobility of ground water	0.0158	0.0134	0.0156
Dispersion through soil	0.0791	0.0654	0.0750
Type of soil	0.0396	0.0327	0.0375
Viscosity of chemical	0.0396	0.0327	0.0375
Dispersion through air	0.0710	0.0654	0.0703
Wind speed	0.0237	0.0218	0.0234
Relative humidity	0.0237	0.0218	0.0234
Mobility in air	0.0237	0.0218	0.0234
Environmental effects	0.2308	0.2249	0.2250
Bioaccumulation	0.0369	0.0396	0.0429
Irritation	0.0554	0.0539	0.0536
Toxic effects on water	0.0692	0.0657	0.0643
Toxic effects on air	0.0692	0.0657	0.0643
Degradation of chemical	0.1846	0.1843	0.1875
Amount of chemical	0.2769	0.2710	0.2500

The estimated defuzzified and normalized ECI values for all sections in BEU are shown in the last column of Table 6. Columns 2–4 of Table 6 shown the computed normalized values of 'hazard potential of SWeHI', Dow F&E index, and EAI for the sections of BEU which are used for comparison in Section 6.

5. Results and discussions

Some of the important issues that should be considered while developing a method or a methodology are (i) goal or purpose of this development, (ii) input factors, (iii) application potential, and (v) accuracy of the results obtained. The ECI developed in this study has to satisfy all these criteria. The following sections describe these issues for the developed ECI.

The first and foremost important issue is goal or purpose for which the assessment is established. Generally, hazard is the potential of a substance or a situation to cause harm or to create adverse impacts on persons or the environment. However, the magnitude of the hazard reflects the potential adverse consequences [41]. So, environmental hazard with vulnerability is taken as the consequence potential in the assessment of ECI. ECI is particularly developed for the detailed assessment of environmental consequence easily and quickly, so that the user can proceed to utilize these results for a part or for overall assessment.

The second important issue in the development of ECI is the consideration of environmental factors that influence the ECI. Based on literature, almost all the factors were identified and a cause–effect diagram was constructed. Moreover, in the development of ECI except human perception, all other factors were considered. For example, the proposed ECI considers spreading factors, material hazard properties of chemical substances, and their effects on environment. The material factors include flammability, reactivity, and explosiveness. The spreading factors consider dispersion of hazardous substances through land, water and air which includes depth of ground water, distance from nearby water bodies, water solubility, and mobility of ground water, type of soil and viscosity of chemical, wind speed, relative humidity, and mobility in air. The toxic effects comprise irritation, emission toxicity, and bioaccumulation. In this context, one of the most important influencing factors is the way of inclusion of amount of chemical value in the index. In the development of ECI, the quantity of chemical is considered as first level factor in the hierarchy. The normalized value of quan-

Table 4
Fuzzifed values of environmental consequence factors for benzene and NMP in BEU

Environmental consequence factors[a]	Benzene			NMP		
	Minimum	Most likely	Maximum	Minimum	Most likely	Maximum
Material hazard factor						
Flammability	0.2500	0.5000	0.7500	0.2500	0.5000	0.7500
Reactivity	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Explosiveness	0.0232	0.0465	0.0697	0.0364	0.0727	0.1091
Spreading factor						
Dispersion through water						
Depth of ground water	0.1695	0.3390	0.5085	0.1695	0.3390	0.5085
Distance from nearby waterbodies	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Water solubility	0.0009	0.0018	0.0027	0.0125	0.0250	0.0375
Mobility of ground water	0.1000	0.2000	0.3000	0.1000	0.2000	0.3000
Dispersion through soil						
Type of soil	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Viscosity of chemical	0.4996	0.9992	1.4988	0.4981	0.9962	1.4943
Dispersion through air						
Wind speed	0.1000	0.2000	0.3000	0.1000	0.2000	0.3000
Cloud covers	0.1500	0.3000	0.4500	0.1500	0.3000	0.4500
Mobility in air	0.1200	0.2400	0.3600	0.4300	0.8600	1.2900
Environmental effects						
Bioaccumulation	0.0044	0.0087	0.0131	0.0016	0.0032	0.0047
Irritation	0.2500	0.5000	0.7500	0.2500	0.5000	0.7500
Toxic effects on water	0.4782	0.9564	1.4346	0.0000	0.0000	0.0000
Toxic effects on air	0.4950	0.9901	1.4851	0.4925	0.9851	1.4776
Degradation of chemical	0.0305	0.0610	0.0915	0.1131	0.2263	0.3394

[a] The normalized fuzzy values for *quantity of chemical* factor were not shown in table because a large number of equipment (74) is present in the BEU plant. The values vary from equipment to equipment. However, the normalized fuzzy values for quantity of chemical for each of the 74 equipment were calculated.

tity of chemical is adopted as a membership value, not as a penalty value.

The third important issue is the application potential (applicability) of the developed ECI. The developed ECI aims to assess the contribution of different sections as well as different consequence factors to the overall ECI for any plant in a transparent and scientific manner. The analysis in this methodology is broader because of its consideration of eight significant environmental consequence categories (see Section 3). The analysis is deeper because the developed ECI is represented by ratio scale as suggested by Koller et al. [22] which is the highest level of measurement. Unlike ordinal scale which is used in AHP and NFPA ranking methods, the ratio

Table 5
Weighted environmental consequence values of the factors for benzene and NMP in BEU

Environmental consequence factors[a]	Benzene			NMP		
	Minimum	Most likely	Maximum	Minimum	Most likely	Maximum
Material hazard factor						
Flammability	0.0144	0.0306	0.0494	0.0144	0.0306	0.0494
Reactivity	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Explosiveness	0.0004	0.0011	0.0020	0.0007	0.0018	0.0032
Spreading factor						
Dispersion through water						
Depth of ground water	0.0027	0.0045	0.0079	0.0027	0.0045	0.0079
Distance from nearby waterbodies	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Water solubility	0.0000	0.0000	0.0000	0.0002	0.0003	0.0006
Mobility of ground water	0.0016	0.0027	0.0047	0.0016	0.0027	0.0047
Dispersion through soil						
Type of soil	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Viscosity of chemical	0.0198	0.0327	0.0562	0.0197	0.0326	0.0560
Dispersion through air						
Wind speed	0.0024	0.0044	0.0070	0.0024	0.0044	0.0070
Cloud covers	0.0036	0.0065	0.0105	0.0036	0.0065	0.0105
Mobility in air	0.0028	0.0052	0.0084	0.0102	0.0187	0.0302
Environmental effects						
Bioaccumulation	0.0002	0.0003	0.0006	0.0001	0.0001	0.0002
Irritation	0.0138	0.0269	0.0402	0.0138	0.0269	0.0402
Toxic effects on water	0.0331	0.0629	0.0922	0.0000	0.0000	0.0000
Toxic effects on air	0.0343	0.0651	0.0955	0.0341	0.0648	0.0950
Degradation of chemical	0.0056	0.0112	0.0172	0.0209	0.0417	0.0636

[a] The weighted values for *quantity of chemical* factor were not shown in the table because a large number of equipment (74) is in the BEU plant. The values vary from equipment to equipment. However, the weighted quantity of chemical for each of the 74 equipment was calculated.

Table 6
Normalized values of hazard potential of SWeHI, Dow F&E index, EAI, and ECI for the sections of BEU

Sections of BEU	Hazard potential of SWeHI index	Dow F&E index	EAI	ECI
Rerun column section	0.1717	0.2933	0.2604	0.2278
Extractive distillation column section	0.0506	0.1551	0.1098	0.1342
Raffinate column section	0.1217	0.2045	0.2059	0.1552
Benzene stripper section	0.1107	0.1703	0.1693	0.1603
Solvent regeneration section	0.0584	0.0202	0.0215	0.0625
Storage and slop drums	0.3919	0.0538	0.1334	0.1254
Vacuum system	0.0731	0.0880	0.0854	0.1065
Process condensate system	0.0220	0.0147	0.0143	0.0283

between two values of ECI corresponds to a defined physical value in addition to its ability in ranking different sections of a plant or different factors effecting the environment. As a part of this effort, the developed ECI was applied to a BEU, comprising eight sections. The ECI for each section was computed and the results were analyzed. The ECI ranks (i) rerun column section, raffinate distillation column section, and benzene stripper section as highly hazardous, (ii) extractive column section, vacuum system, and storage and slop drums as medium hazardous, and (iii) process condensate system and solvent regeneration system as low hazardous. Rerun column is

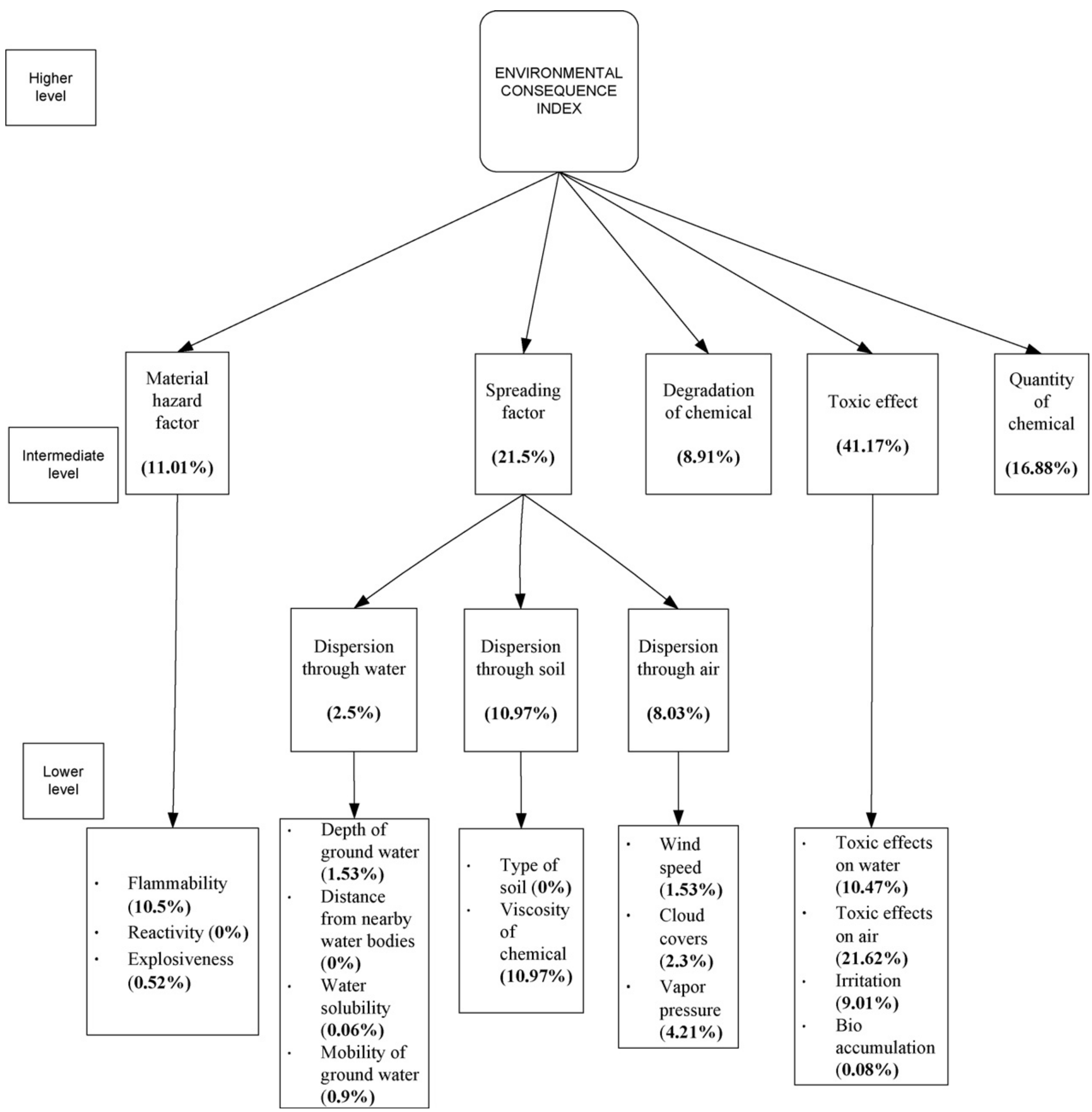

Fig. 6. Relative percentage contribution of each of the environmental consequence factors to ECI for the BEU plant.

Table 7
Ranking of sections of BEU using Hazard potential of SWeHI, Dow F&E index, EAI, and ECI

Sections of BEU	Hazard potential of SWeHI index	Dow F&E index	EAI	ECI
Rerun column section	2	1	1	1
Extractive distillation column section	7	4	5	6
Raffinate column section	3	2	2	2
Benzene stripper section	4	3	3	3
Solvent regeneration section	6	7	7	7
Storage and slop drums	1	6	4	5
Vacuum system	5	5	6	4
Process condensate system	8	8	8	8

environmentally highly hazardous amongst all the sections of BEU because it contains a large number of equipment which handle high amount of benzene. The process condensate system and solvent regeneration system are less hazardous because of high involvement with steam and water which are environmentally harmless. The extractive distillation column section, benzene stripper column section, and vacuum system are having less equipment and handle fewer amounts of chemicals in comparison to highly hazardous sections.

In addition to ranking the different sections of the BEU, the relative percentage contribution of each of the environmental consequence factors to ECI for the BEU plant were computed which is shown in Fig. 6. For the BEU studied, toxic effect contribute the most (41.17%) followed by spreading factor (21.50%) and quantity of chemical (16.88%). The relative contribution can be used to prioritize the environmental consequence factors to propose resource allocation for improvement.

Finally, the accuracy of the ECI was tested through comparison with some other well-established methods like Dow's fire and explosion index, safety weighted hazard index (SWeHI) index, and environmental accident index. The comparison method was adopted here because there is no absolute value for overall consequence, known so far. This issue is dealt separately in Section 6. Environmental standards can be developed with acceptance probability as a function of the ECI provided it is applied in a large number of similar plants. The acceptable level of environmental consequence can be chosen by transforming the acceptance probability into ECI for different consequences.

6. Comparison with Dow's Fire and explosion index, hazard potential of SWeHI, and EAI ranking

The normalized values of environmental consequence indices for all sections of BEU are compared with hazard potential of SWeHI, Dow's fire and explosion index, and environmental accident index. Dow's fire and explosion index is the most widely used hazard index. SWeHI is developed by Khan et al. [24]. The control measures value A of SWeHI is not considered, only B value is adopted in this comparison. EAI is developed by Scott [17]. The normalized index values are listed in Table 6. The ECI index is compared with Dow's fire and explosion index, environmental accident index, and hazard potential of SWeHI index by ranking the sections of BEU. The comparative ranking of sections of BEU is shown in Table 7.

Table 7 shows that for five sections (out of eight in total) of the BEU, ECI ranks exactly as done by Dow's fire and explosion index and EAI. They are rerun column section (rank 1), raffinate column section (rank 2), benzene stripper section (rank 3), solvent regeneration section (rank 7), process condensate system (rank 8).

Although, the rerun column section is ranked as the most hazardous by Dow's fire and explosion index, EAI, and ECI, but SWeHI ranks it as second. The significant variation lies in the ranking of storage and slop drum section. The storage and slop drum section is ranked as the most hazardous by SWeHI. This is because SWeHI considers the release of energy from steam and hot water, but EAI and ECI did not consider that potential energy release because it does not effect the environment. So, EAI and ECI ranks storage and slop drums as fourth and fifth hazardous section, respectively. In Dow's fire and explosion index, although the energy release from steam and hot water is considered, the amount of chemical involved is taken as a penalty. So, Dow's fire and explosion index ranks storage and slop drums section as sixth hazardous section. This variation is mainly due to the way of inclusion of quantity of chemical. The process condensate system is ranked as the less hazardous section by all indices.

7. Conclusions

In this study, the review of various existing hazard indices available in literature was conducted. As a result, the methods were identified and classified based on their applications and capabilities. The important limitations of the existing methods were highlighted. For example, the importance of dispersion factors and effects in soil, water and air were recognized and incorporated with proposed methodology. Further the proposed methodology developed the ECI using fuzzy composite programming (FCP). The developed ECI was applied to benzene extraction unit (BEU) to estimate the environmental consequence of the sections of BEU. The estimated results of ECI for sections of benzene extraction units were discussed. Finally, ECI ranking was compared with Dow's fire and explosion index, safety weighted hazard index (SWeHI), and environmental accident index (EAI) ranking. The proposed ECI may outperform other indices based on its detailed consideration of the factors and performed equally to Dow's fire and explosion index, and EAI in most of the cases for the present application.

Acknowledgements

The authors gratefully acknowledge the support from the management of the case study plant for providing necessary data and suggestions. The valuable comments from the reviewers are highly appreciated.

Appendix A. Degree of severity of consequence factors

A.1. Flammability [10]

Nature of flammability	Numerical score
Stable	0
Mild	1
Significant	2
Vigorous	3
Explosive	4

A.2. Reactivity [10]

Nature of reaction	Numerical score
Stable	0
Mild	1
Significant	2
Vigorous	3
Explosive	4

A.3. Explosiveness [14]

Explosiveness (S) = (upper explosive level – lower explosive level)	Numerical score
$0 < S < 10$	1
$10 < S < 20$	2
$20 < S < 30$	3
$30 < S < 40$	4
$40 < S < 50$	5
$50 < S < 60$	6
$60 < S < 70$	7
$70 < S < 80$	8
$80 < S < 90$	9
$90 < S < 100$	10

A.4. Viscosity of chemical [17]

Viscosity (cP)	Numerical score
<0.5	5
0.5–4.4	4
4.4–47	3
47–300	2
>300	1

A.5. Water solubility [17]

Water solubility (wt.%)	Numerical score
>90%	5
25–90	4
5–25	3
1–5	2
<1	1

A.6. Distance to nearest well, lake or watercourse [17]

Distance (m)	0–10	10–20	20–35	35–50	50–75	75–150	150–300	300–1000	1000–2000	>2000
Numerical score	9	8	7	6	5	4	3	2	1	0

A.7. Depth to groundwater surface [17]

Depth (m)	0–0.2	0.2–1	1–3	3–5	5–7	7–12	12–20	20–30	30–60	>60
Numerical score	9	8	7	6	5	4	3	2	1	0

A.8. Mobility of ground water [17]

Mobility of ground water	The groundwater surface is leaning towards a well, lake or watercourse	The groundwater surface is horizontal	No well, lake or watercourse is laying within 1 km of the direction of the groundwater flow
Numerical score	5	1	0

A.9. Permeability of the soil [17]

Type of soil	Numerical score
Gravel	9
Sand	7–9
Moraine	6–8
Silt	4–8
Clay	0–6

A.10. Wind speed [42]

Wind speed	Numerical score
Calm	<1
Light air	1–2
Light breeze	2–3
Gentle breeze	3–5
Moderate	5–8
Fresh	8–11
Strong	11–14
Near gale	14–17
Gale	17–21

A.11. Relative humidity [42]

Relative humidity (%)	Numerical score
Low	0
Medium	50
High	100

A.12. Mobility in air [15]

Difference between boiling point and process temperature (°C)	Numerical score
0–50	0–0.25
50–100	0.25–0.5
100–150	0.5–0.75
150–200	0.75–1

A.13. Bioaccumulation [40]

Accumulation level	Numerical score
Low	<250
Moderate	250–1000
High	>1000

A.14. Irritation (eye, skin) [15]

Corrosiveness	Numerical score
No corrosive group	0
Weak acids, alkalines	0.5
Strong acids, alkalines	1

A.15. Toxic effects on water [15]

LC_{50} acute (mg/l)	Numerical score
0.1–10	1–0.5
10–1000	0.5–0

A.16. Toxic effects on air [15]

ERPG3 (emergency response planning guidelines)	Numerical score
10–1000	1–0.5
1000–100,000	0.5–0

A.17. Degradation [15]

Persistence time (days)	Numerical score
1–3.2	0–0.25
3.2–10	0.25–0.5
10–32	0.5–0.75
32–100	0.75–1

References

[1] K. Jegasothy, Population and rural–urban environmental interactions in developing countries, Int. J. Soc. Econ. 26 (7/8/9) (1999) 1027–1055.
[2] F.I. Khan, R. Sadiq, B. Veitch, Life cycle index (LInX): a new indexing procedure for process and product design and decision-making, J. Cleaner Prod. 12 (1) (2004) 59–76.
[3] M. Sam Mannan, Harry H. West, Kiran Krishna, Abdulrehman A. Aldeeb, Nir Keren, Sanjeev R. Saraf, Michela Gentile, The legacy of Bhopal: the impact over the last 20 years and future direction, J. Loss Prevent. Process Ind. 18 (4–6) (2005) 218–224.
[4] S.R. Cave, D.W. Edwards, Chemical process route selection based on assessment of inherent environmental hazard, Comput. Chem. Eng. 21 (1997) S965–S970.
[5] A.N. Paralikas, A.I. Lygeros, A multi-criteria and fuzzy logic based methodology for the relative ranking of the fire hazard of chemical substances and installations, Trans. IChemE Process Saf. Environ. Prot. 83 (B) (2005) 122–134.
[6] F.I. Khan, P.R. Amyotte, I2SI: a comprehensive quantitative tool for inherent safety and cost evaluation, J. Loss Prevent. Process Ind. 18 (4–6) (2005) 310–326.
[7] M. Gentile, W.J. Rogers, M.S. Mannan, Development of an inherent safety index based on fuzzy logic, AIChE J. 49 (4) (2003) 959–968.
[8] M. Gentile, W.J. Rogers, M.S. Mannan, Development of a fuzzy logic-based inherent safety index, Trans. IChemE Process Saf. Environ. Prot. 81 (B) (2003) 444–456.
[9] M.Y. Gunasekera, D.W. Edwards, Estimating the environmental impact of catastrophic chemical releases to the atmosphere an index method for ranking alternative chemical process routes, Trans. IChemE Process Saf. Environ. Prot. 81 (B) (2003) 463–474.
[10] Dow's Fire and Explosion Index Hazard Classification Guide, 7th ed., American Institute of Chemical Engineers, 1994.
[11] F.I. Khan, S.A. Abbasi, Techniques and methodologies of risk analysis in chemical process industries, J. Loss Prevent. Process Ind. 11 (1998) 261–277.
[12] Dow's Chemical Exposure Index Guide, 1st ed., American Institute of Chemical Engineers, 1994.
[13] M.Y. Gunasekera, D.W. Edwards, Chemical process route selection based upon the potential toxic impact on the aquatic, terrestrial and atmospheric environments, J. Loss Prevent. Process Ind. 19 (2006) 60–69.
[14] D.W. Edwards, D. Lawrence, Assessing the inherent safety of chemical process routes: Is there a relation between plant costs and inherent safety? Trans. IChemE Process Saf. Environ. Prot. 71 (B) (1993) 252–258.
[15] G. Koller, U. Fischer, K. Hungerbuhler, Assessing safety, health, and environmental impact early during process development, Ind. Eng. Chem. Res. 39 (2000) 960–972.
[16] M.H. Achour, A.E. Haroun, C.J. Schlt, K.A.M. Gasem, A new method to assess the environmental risk of a chemical process, Chem. Eng. Process. 44 (2005) 901–909.
[17] Asa Scott, Environment accident index: validation of a model, J. Hazard. Mater. 61 (1998) 305–312.
[18] K. Golonka, D.J. Brennan, Application of life cycle assessment to process selection for pollutant treatment: a case study sulphur dioxide emissions from Australian metallurgical smelters, Trans. IChemE Process Saf. Environ. Prot. 74 (B) (1996) 105–119.
[19] F.I. Khan, B.R. Natrajan, P. Revathi, GreenPro: a new methodology for cleaner and greener process design, J. Loss Prevent. Process Ind. 14 (4) (2001) 307–328.
[20] F.I. Khan, M. Haddara, Risk-based maintenance (RBM): a new approach for process plant inspection and maintenance, Process Saf. Prog. 23 (4) (2004) 252–265.
[21] F.I. Khan, M. Haddara, Risk-based maintenance of ethylene oxide production facilities, J. Hazard. Mater. A108 (2004) 147–159.
[22] G. Koller, U. Fischer, K. Hungerbuhler, Comparison of methods suitable for assessing the hazard potential of chemical processes during early design phases, Trans. IChemE Process Saf. Environ. Prot. 79 (B) (2001) 157–166.
[23] S. Shah, U. Fischer, K. Hungerbuhler, A hierarchical approach for the evaluation of chemical process aspects from the perspective of inherent safety, Trans. IChemE Process Saf. Environ. Prot. 81 (B) (2003) 430–443.
[24] F.I. Khan, T. Husain, S.A. Abbasi, Safety Weighted Hazard Index (SWeHI) A new user-friendly tool for swift yet comprehensive hazard identification and safety evaluation in chemical process industries, Trans. IChemE Process Saf. Environ. Prot. 79 (B) (2001) 65–80.
[25] S.N. Jonkman, P.H.A.J.M. van Gelder, J.K. Vrijling, An overview of quantitative risk measures for loss of life and economic damage, J. Hazard. Mater. 99 (1) (2003) 1–30.
[26] M. Barlettani, G. Fruttuoso, P. Lombardi, An ecological approach for risk and impact ranking, in: B.M. Drottz Sjoberg (Ed.), Proceedings New Risk Frontiers, Society of Risk Analysis, Stockholm, 1997.
[27] NORSOK, Risk and emergency preparedness, Annexure C: Methodology for establishment and use of environmental risk acceptance criteria, 1998.
[28] F.I. Khan, M. Haddara, Risk-based maintenance (RBM): a quantitative approach for maintenance/inspection scheduling and planning, J. Loss Prevent. Process Ind. 16 (6) (2003) 561–573.
[29] R. Sadiq, F.I. Khan, B. Veitch, Evaluating offshore technologies for produced water management using GreenPro-I—a risk based life cycle analysis for green and clean process selection design, Comput. Chem. Eng. 29 (2005) 1023–1039.
[30] C. Palaniappan, R. Srinivasan, I. Halim, A material-centric methodology for developing inherently safer environmentally benign processes, Comput. Chem. Eng. 26 (2002) 757–774.
[31] P. Sharratt, Environmental criteria in design, Comput. Chem. Eng. 23 (10) (1999) 1469–1475.
[32] D. Calamari, M. Vighi, Scientific basis for the assessment of several chemical substances in combination at low level, EEC, Luxemborg.
[33] F.I. Khan, R. Sadiq, M. Haddara, Risk-based inspection and maintenance (RBIM) Multi-attribute decision making with aggregate risk analysis, Trans. IChemE Process Saf. Environ. Prot. 82 (B6) (2004) 398–411.
[34] Y.W. Lee, I. Bogardi, J. Stansbury, Fuzzy decision making in dredged-material management, J. Environ. Eng. 117 (5) (1991) 614–630.
[35] D. Jones, E.M. Barnes, Fuzzy composite programming to combine remote sensing and crop models for decision support in precision crop management, Agric. Syst. 65 (2000) 137–158.
[36] R. Sadiq, T. Husain, B. Veitch, N. Bose, Risk based decision making for drilling waste discharges using a fuzzy synthetic evaluation technique, Ocean Eng. 31 (2004) 1929–1953.
[37] T.L. Saaty, Multi-criteria Decision Making: The Analytic Hierarchy Process, University of Pittsburgh, 1988.
[38] C. Cheng, Y. Lin, Evaluating the best battle main battle tank using fuzzy decision theory with linguistic criteria evaluation, Eur. J. Oper. Res. 142 (2002) 174–186.
[39] A. Bardossy, L. Duckstein, Analysis of a karstic aquifer management problem by fuzzy composite programming, Water Resour. Bull. 28 (1) (1992) 63–73.
[40] D.T. Allen, D.R. Shonnard, Green Engineering: Environmentally Conscious Design of Chemical Processes, Prenticehall PTR, 2002.
[41] E.G. Hertwich, W.S. Pease, C.P. Koshland, Evaluating the environmental impact of products and production processes: a comparison of six methods, Sci. Total Environ. 196 (1997) 13–29.
[42] ALOHA user's manual, U.S. Environmental Protection Agency, Washington, 2007. http://www.epa.gov/swercepp/cameo/pubs/ALOHAManual.pdf.