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A methodology for overall consequence modeling in chemical industry

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ABSTRACT

Risk assessment in chemical process industry is a very important issue for safeguarding human and the ecosystem from damages caused to them. Consequence assessment is an integral part of risk assessment. However, the commonly used consequence estimation methods involve time-consuming complex mathematical models and simple assimilation of losses without considering all the consequence factors. This lead to the deterioration of quality of estimated risk value. So, the consequence modeling has to be performed in detail considering all major losses with optimal time to improve the decisive value of risk. The losses can be broadly categorized into production loss, assets loss, human health and safety loss, and environment loss. In this paper, a conceptual framework is developed to assess the overall consequence considering all the important components of major losses. Secondly, a methodology is developed for the calculation of all the major losses, which are normalized to yield the overall consequence. Finally, as an illustration, the proposed methodology is applied to a case study plant involving benzene extraction. The case study result using the proposed consequence assessment scheme is compared with that from the existing methodologies.

1. Introduction

In the last decades, world has seen a wide range of major accidents with a number of fatalities, economic losses, and damage to the environment [1]. Attempts have been undertaken to prevent these accidents and to reduce risk to a level as low as reasonably practicable (ALARP) without resorting to costly protective systems [2]. This has been done through the identification and assessment of major risk contributors, which can be accomplished using quantitative risk assessment (QRA) techniques, and implementation of risk control measures. QRA involves four main steps: hazard identification, consequence assessment, probability calculation, and risk quantification. Consequence assessment, which is crucial to determination of risk in QRA, involves quantification of the likely loss or damage due to anticipated eventualities. It attempts to identify and quantify the full range of adverse consequences arising from the identified patterns and sequences of hazards. Of the high-risk industries, chemical industry is one of the most hazardous sectors. Among the various possible chemical hazards, the major hazards are fire, explosion, and toxic release. Of these three hazards, fire is the most frequent but explosion is more important in terms of damage potential, often leading to fatalities and property loss [1].

The consequence analysis aims to quantify the negative impacts when a hazardous event takes place. The consequences are generally quantified in terms of production loss, human health loss, assets loss, and environmental loss [3]. The assessment of consequences can be done using a wide variety of mathematical and empirical models. First, source models are used to predict the rate of release of hazardous material, the degree of flashing, and the rate of evaporation [3,4]. These models are used to find the initial sizes of fires and explosions. Secondly, the impact intensity models are used to estimate the damage area due to fires and explosion load [4]. Finally, the toxic gas models are used to estimate human response to different levels of exposures to toxic chemicals [3,4]. These consequence assessment models involve assessment of likely consequences which are quantified in terms of damage radii (the radius of area in which damage would readily occur). The calculated damage radii can be used to assess the effect on assets, human, and environment [3].

Commercially, there are many software packages available for consequence and risk assessment in chemical industries [4–10]. Khan and Abbasi [6,7] developed some tools such as MOSEC, HAZDIG, and DOMIFFECT to conduct consequence analysis. MOSEC (*m*odeling *s*imulation of fire and *e*xplosion in *c*hemical process industries) has been developed specifically to estimate the impacts of accidents involving explosion and fire [6]. HAZDIG is developed to estimate consequences due to release of toxic materials [7]. DOMIFFECT is a computer-automated methodology, developed to know possibilities and impacts of domino effects [6]. Apart from these consequence analysis tools, several software tools developed to support the implementation of the Seveso II Directive. RISKIT, PHAST, SAFETI, BREEZE HAZ, SEVEX, WHAZAN, SAVE are some of

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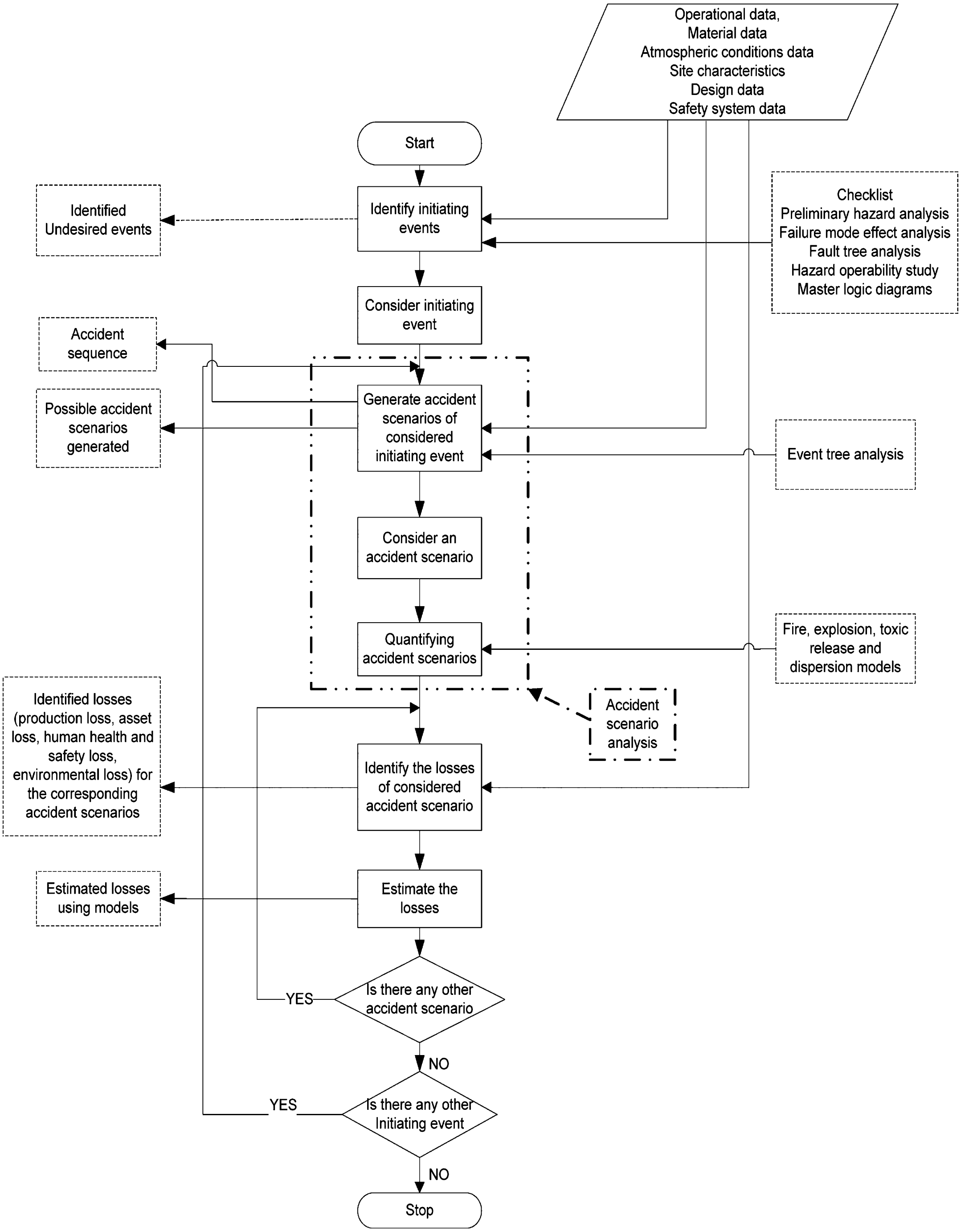

Fig. 1. Process of accident scenario analysis in consequence estimation.

the widely used software packages for risk assessment [8]. Khan and Abbasi [8–10] also developed some risk assessment software tools such as MAXCRED and TORAP for rapid risk assessment. These software use empirical, semi-empirical, and phenomenological models for analyzing the characteristics and hazard potential of accidents [2]. The available complex methodologies lacks in estimating the losses due to consequences. These limitations led to the development of new methodologies without much complexity. The use of such simple methodology should ensure less computational time and less expertise user. Thus, it aids the risk analysts to carry out numerous "what if" runs, to test the effect of maintenance decisions and process or product design modifications. It also helps in conducting a detailed QRA study in short span of time [2].

The consequence assessment schemes for chemical process industries are mainly based upon the models of fire, explosion and toxic release and dispersion. Based on these models, the consequences are quantified in terms of damage radii and toxic effects. In empirical models, the consequences are quantified using hazard index in terms of damage radii [11]. The use of hazard indices for consequence estimation based on damage radii is reliable for risk assessment and it can be done without much complexity in calculation. Further, the use of hazard index instead of mathematical models to calculate damage radius reduces efforts and time in consequence assessment.

The most important aspect of consequence assessment is the identification, quantification, and integration of all significant

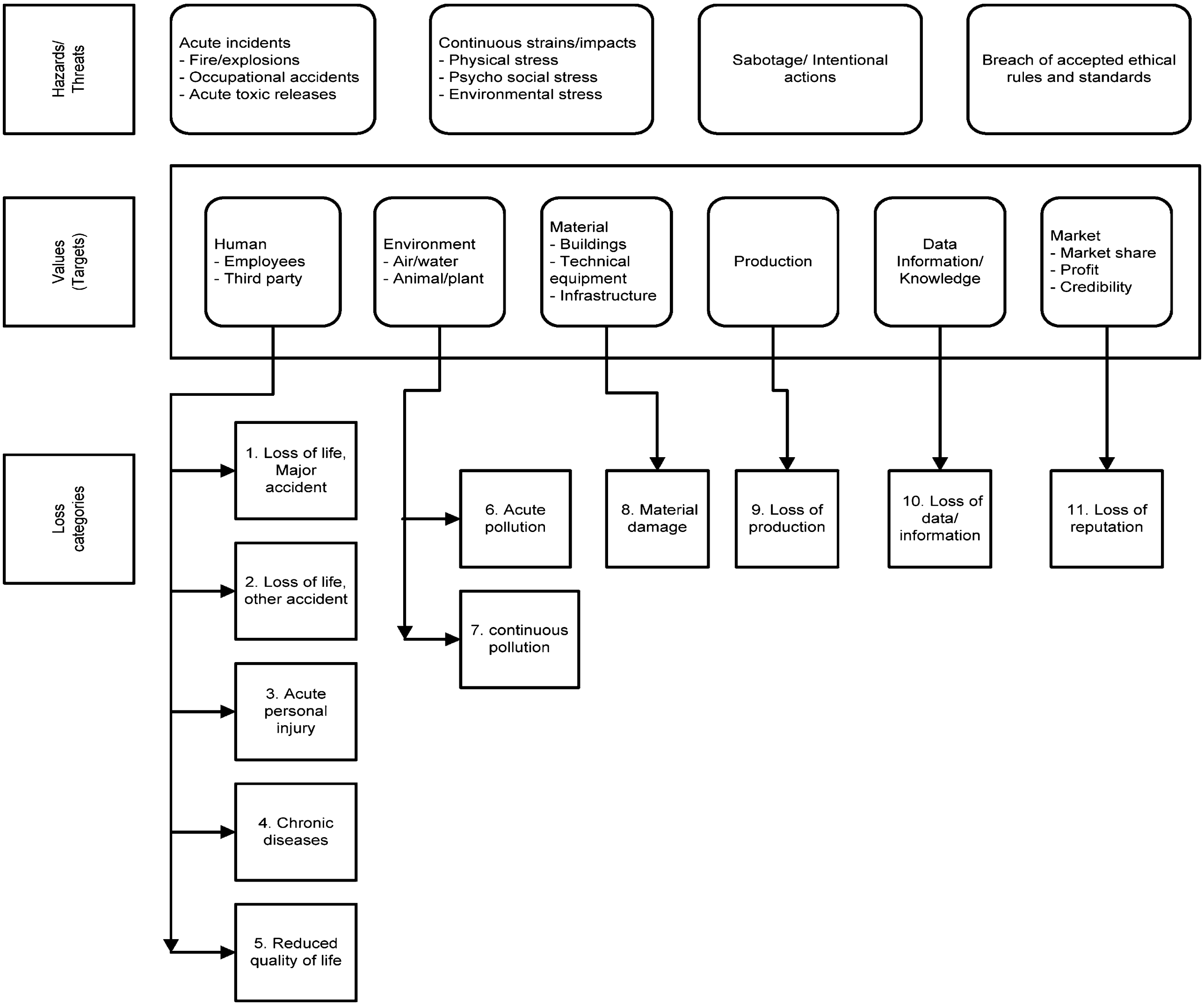

Fig. 2. Illustration of threats, values and 'loss categories' in risk- and vulnerability management (adopted from [14]).

losses (e.g. production loss, assets loss, human health and safety loss, environmental loss) due to hazards while estimating the overall consequence. Even though some of the studies conducted by Khan and Haddara [3,11,12] addressed this issue, still there remain a few lacunas as follows:

(i) While quantifying production loss, only maintenance and downtime cost were considered. Other relevant production loss components such as recycling cost and material wastage cost may be considered.
(ii) While calculating assets loss, previous studies considered only the cost of assets. But present value and reinstallation cost of these assets are important and required to be considered.
(iii) In case of human health and safety loss, noteworthy injury category should be considered in addition to fatality.
(iv) Quantification of environmental loss in terms of cost (e.g. environmental cleanup cost [11]) is a difficult as well as controversial task. The difficulty in measuring environmental loss arises due to consideration of different hazard potentials. So, there is a need for an appropriate environmental consequence index to develop which should estimate the environmental loss based on various environmental consequence factors and their uncertainty.
(v) In the estimation of overall consequence, the stochastic nature of the losses should also be taken into consideration.

In this paper an index-based consequence assessment methodology is adopted, estimating and integrating all possible loss categories and rectifying the lacunas as addressed above. The developed methodology is also applied to benzene extraction unit of a petrochemical industry located in eastern India.

2. Consequence estimation

The consequence estimation scheme involves three steps: (i) accident scenario analysis, (ii) identification and classification of losses, and (iii) estimation of losses. The following sections describe them in details.

2.1. Accident scenario analysis

The accident scenario is the typical situation created by a failure event. The accident scenario may be single or more. From the past literature, it is identified that most of the studies considered only single worst accident scenario. The worst-case scenario is the situation at which the worst possible accident occurs to keep people and environment under risk. Environmental Protection Agency

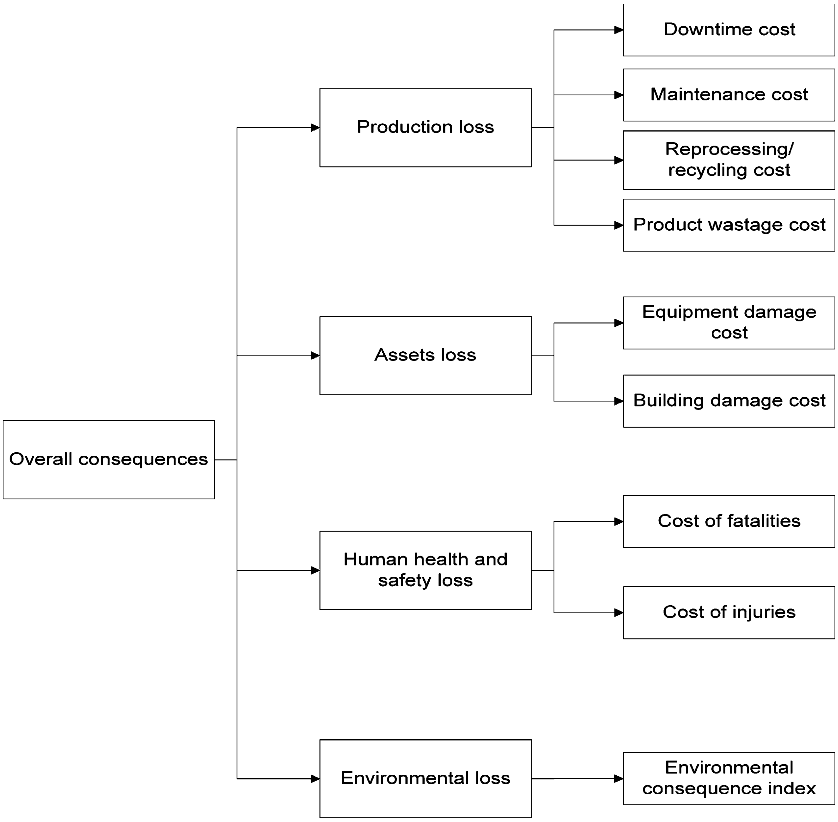

Fig. 3. Consequence categories with their loss indicators (considered).

(EPA) and Clean Air Act Amendments (CAAA) of 1990 recommend worst-case scenarios to include in emergency planning and risk management plan. But in proposed worst-case method by EPA, only release and dispersion of toxic substances are considered because of their exposure to people and environment covering the maximum area to cause a huge damage [10]. However, other than toxic effects of chemical, flammable and explosive nature of chemical are also important contributing factors to the accidents.

In any accident involving dangerous substances, the accident scenarios may be fire, explosion, and toxic release and dispersion or combination of these events based on numerous conditions and situations at the plant [8]. The process of accident scenario analysis is shown in Fig. 1. The process involves in the following steps:

(i) Identification of initiating events.
(ii) Generation of accident scenarios for each initiating events.
(iii) Quantification of accident scenarios.

The accident initiators or initiating events are any disruptions in normal plant operation. The identification of initiating events is an important process because these events progress to accident which results in onsite and offsite consequences. Some of initiating events identification approaches are as follows: checklists, preliminary hazard analysis, failure modes and effects analysis, fault tree analysis, hazard operability study, and master logic diagrams [4].

Once an initiating event is identified, the sequence of events leading to accident scenarios has to be identified. The transformation of an initiating event into accident is done using event tree analysis. The event tree is developed based on the relationship with conditions and mitigation systems which respond to that event. The accident scenarios are generally developed based on operational data (e.g. temperature, pressure, and flow rate), material data (e.g. physical and chemical properties, hazardous properties, and quantity), atmospheric conditions, site characteristics, design data (e.g. geometries and material strength of the equipment), and safety system data (e.g. reliability of safety arrangements and degree of containment) [2,4].

After the generation of accident scenarios, the modeling of accident scenarios is done using a wide variety of mathematical models. In this study, ALOHA (*a*real *l*ocations of *h*azardous *a*tmospheres) is used to model the accident scenarios. ALOHA is an emergency response model intended primarily for rapid deployment by responders, as well as for use in emergency preplanning. It incorporates source strength, as well as Gaussian and heavy gas dispersion models and an extensive chemical property library [13]. ALOHA models three hazard categories: toxic gas dispersion, fires, and explosions. It computes time-dependent source strength for evaporating puddles (boiling or non-boiling), pressurized or non-pressurized gas, or liquid release from a storage vessel, and pressurized gas from a pipeline and models Gaussian puff and plume, and heavy gas dispersion.

2.2. Identification and classification of losses

In order to get a thorough understanding of classification of losses, consequence assessment schemes suggested by many authors applicable to chemical industries were reviewed and the types of losses are identified. There are different consequence measures reported in the literature. They range from purely qualitative to highly quantitative evaluation. Hokstad and Steiro [14] suggested six categories of consequence values under four hazard/threat categories as shown in Fig. 2.

Hokstad and Steiro [14] recommended a total of 11 loss categories. These are loss of life in major accidents, loss of life in other accidents, acute personal injury, chronic disease, reduced functionality, acute pollution on external environment, continuous

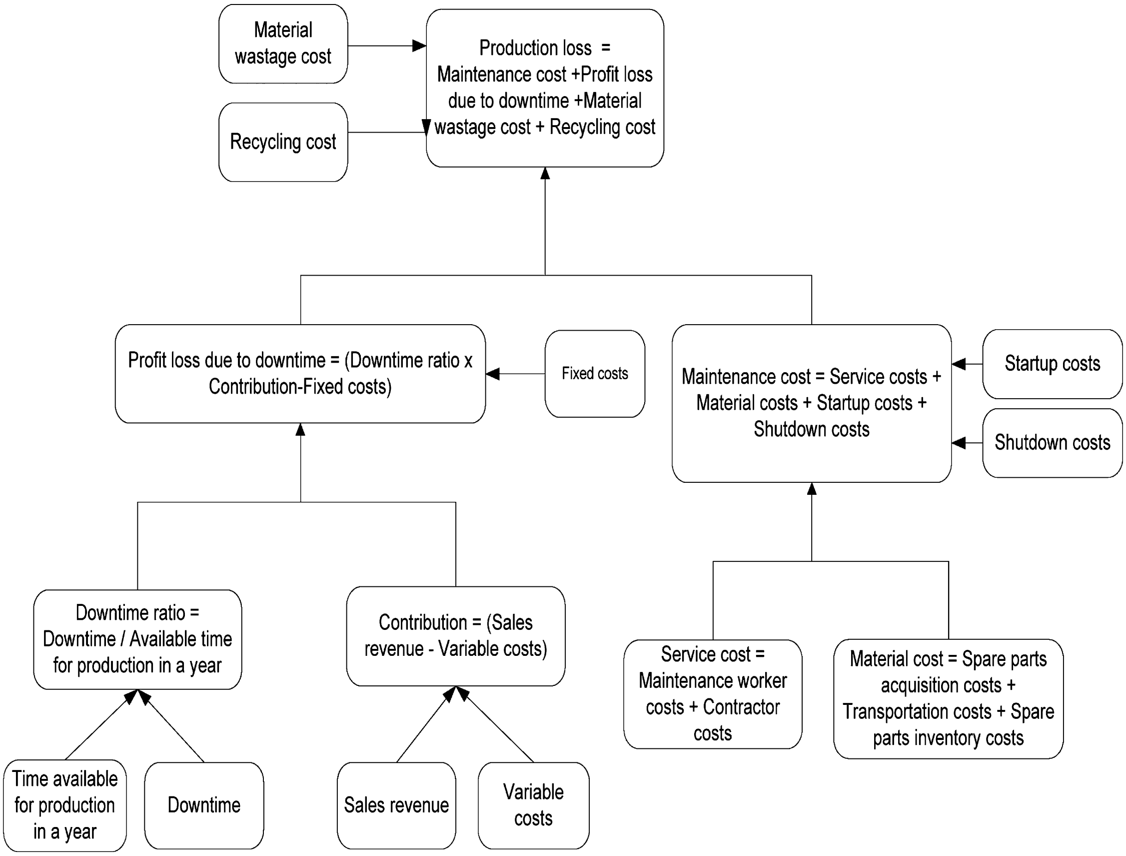

Fig. 4. Framework for production loss calculation (after [18–20]).

pollution on external environment, material damage, loss of production (could include deferred and damaged production), loss of data/information/knowledge, and loss of reputation. Out of the 11 loss categories, the first 9 categories relate to four targets namely, human, environment, material, and production and are contributing the major share of potential losses as reported in literature [3,11–13,15]. The remaining losses such as loss of data information and loss of reputation are difficult to quantify and not available in most of the cases. So, the overall losses can be categorized into production loss, assets loss, human health and safety loss, and environmental loss. The consequence categories with their cost indicators are shown in Fig. 3. The production loss can be measured using downtime cost, maintenance cost, reprocessing cost, and product wastage cost. The assets loss can be measured using equipment damage cost and building damage cost. The human health and safety loss indicators considered are cost of fatalities and cost of injuries. Costs of illnesses are not considered here owing to two facts (i) partly there is overlap with environmental damage cost, and (ii) lack of data. The environmental loss can be measured using environmental damage cost and waste accumulation cost. These losses are discussed next in detail.

2.3. Estimation of losses

This section mainly focuses on methods available from the literature to quantify production loss, human health and safety loss, assets loss, and environmental loss. The methods are reviewed and the modifications are suggested to achieve the effective estimate of the loss values.

2.3.1. Production loss

The production loss is the loss due to downtime due to breakdown and maintenance [16,17]. The downtime is the total amount of time the assets would normally be out of service owing to its failure from the moment it fails until the moment it is fully operational again. The maintenance cost includes the cost of labor, spare parts, and downtime associated with its repair. From the literature, it has been found that the production loss calculation involves high subjectivity [12]. Furthermore, a structured method to estimate production loss in terms of downtime cost and maintenance cost is still missing in consequence estimation [17]. A proposed framework for production loss calculation is shown in Fig. 4.

From Fig. 4, it is revealed that the production loss includes maintenance cost (C_m), profit loss due to downtime (C_d), material wastage cost (C_{pw}), and material recycling cost (C_{rc}) [18–20]. There are two different situations for estimating the profit loss from downtime (C_d). They are:

(i) If component failure or service does not affect plant production then the profit loss from downtime is zero.
(ii) When component unavailability results in production loss, the profit loss due to downtime (C_d) can be estimated as a product between downtime ratio and difference of contribution to fixed costs ($CC - C_f$). The downtime ratio (DR) is the ratio between downtime due to breakdown (t_d) and time available for production in a year (t_p). The downtime (t_d) is the time that maintenance measures (e.g. repairs) and failure contribute to lost production. The contribution (CC) can be estimated as a difference between sales revenue (C_{sr}) and variable costs (C_v) based on marginal cost model. The maintenance cost is calculated from service costs (C_{a1}), material costs (C_{a2}), startup costs (C_s), and shutdown costs (C_{sd}). The service cost includes maintenance worker costs (C_w) and contractor costs (C_{pc}). The material cost includes spare parts acquisition costs (C_p), transportation costs (C_t), and spare parts inventory costs (C_i).

Thus, the production loss (PL) can be estimated using the following relations:

$$\mathrm{PL} = C_d + C_m + C_{pw} + C_{rc} \tag{1}$$

where

$$\text{Profit loss from downtime} = C_d = \mathrm{DR} \times (\mathrm{CC} - C_f) \tag{2}$$

$$\text{Downtime ratio} = \mathrm{DR} = \frac{t_d}{t_p} \tag{3}$$

$$\text{Contribution} = \mathrm{CC} = C_{sr} - C_v \tag{4}$$

$$\text{Maintenance cost} = C_m = C_{a1} + C_{a2} + C_s + C_{sd} \tag{5}$$

$$\text{Service cost} = C_{a1} = C_w + C_{pc} \tag{6}$$

$$\text{Material cost} = C_{a2} = C_p + C_t + C_i \tag{7}$$

2.3.2. Assets loss

In chemical industries, fire and explosion may cause loss of physical assets, such as loss of equipment and loss of buildings. Assets loss is the economic loss related to replacing and removing the damaged equipment and buildings. It is based on several measures of loss. Alexander [21] suggested three measures of assets loss:

- *Normal maximum loss (NML)*: The maximum loss that would occur if all protective equipment functions correctly.
- *Estimated maximum loss (EML)*: The maximum loss that would occur if one critical item of protective equipment does not function correctly.
- *Maximum credible loss (MCL)*: The maximum loss that would occur if a number of critical items of protective equipment do not function or where a credible catastrophic event occurs.

The method of assets valuation is also important though it is limited to the information available at the site under investigation. The assets values will generally be estimated in one of two formats:

- Overall valuation for a selected section of the plant, and
- individual valuation of the equipment or building assets.

The preferred format is for valuation of individual equipment, as this will provide a more accurate result. If this is not possible, overall valuation for specific plant section can be used. In later case, it is assumed that the value is distributed evenly across the plot area of the plant section; however, the overall value of a plant may be concentrated in a particular subsection due to the presence of high-value equipment. This can be accounted for by assigning a proportionately higher value for this subsection. Khan and Amyotte [11] computed assets loss (AL) using the following relation:

$$\mathrm{AL} = \text{Damage area} \times \text{Assets density (\$/area)} \tag{8}$$

where the assets density is the value of equipment and other properties present in the damage area. The cost of equipment and other properties are to be collected to assess the cost of total property accumulated within the damage area.

The assets loss evaluation method proposed by Khan and Haddara [11,13] is simple and recommended by many of the recent studies and is adopted for consequence estimation in this study. According to this method, the assets loss is considered as a maximum credible loss and is valuated by individual equipment or building assets valuation method. However, present value of the assets and their installation cost were not considered by Khan and Haddara [11,13]. This study overcomes this shortcoming by estimating the present value of the assets and through inclusion of the installation cost using Lang factor. Lang factor is a ratio of the total cost of installing a process in a plant to the cost of its major technical components. The factor was introduced by Lang in Chemical Engineering magazine in 1947 as a method for estimating the total installation cost for plants and equipment [19].

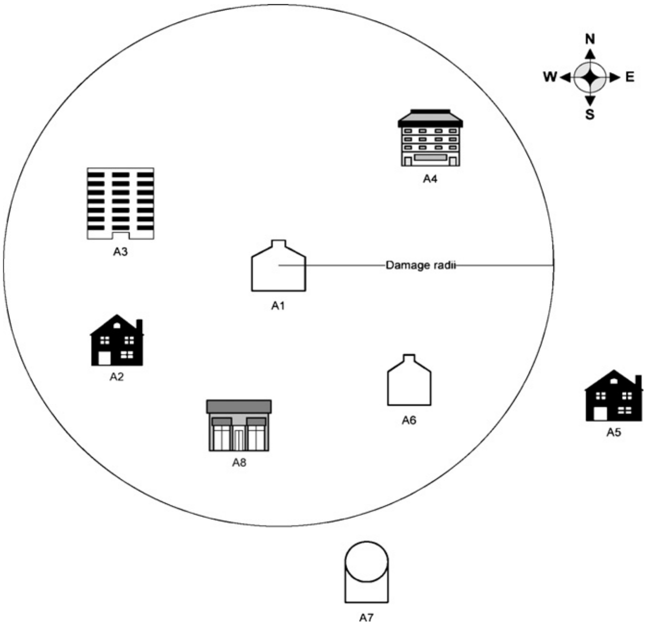

Fig. 5. Assets loss estimation.

The assets loss evaluation scheme is depicted in Fig. 5. To evaluate the asset loss due to the failure of a subsystem such as A1 (as shown in Fig. 5), the following steps are required to be performed:

(i) Estimation of the maximum damage area produced by failure of A1.
(ii) Identification of equipment (A1, A6) and buildings (A2, A3, A4, A8) present within the damage area.
(iii) Estimation of cost of the equipment and buildings.
(iv) Estimation of present value of the assets.
(v) Estimation of total replacement cost of the equipment and buildings using Lang factor.
(vi) Estimation of assets loss.

For Fig. 5, the assets loss will be:

$$\mathrm{AL} = \sum_i C_i(1+d_i)^{-t_i} + \sum_i C_i(1+r_i)^{t_i} \cdot L \tag{9}$$

where C_i is the cost of asset A_i, $i = 1, 2, 3, 4, 6,$ and 8; d the depreciation rate; r the interest rate; t the number of years; and L is the Lang factor.

2.3.3. Human health and safety loss

Human health and safety loss is the loss due to the occurrence of fatalities and/or injuries resulted from a failure of a system or subsystem. Human life resulting from an accident can be counted in terms of the number of people injured or killed when accidents occur. The reference to 'people injured' by an accident is justifiable since, many times, it is not only the product users but also people who were near the scene are injured when an accident occurred. Injuries suffered may vary from light scratches to fatalities.

Khan et al. [11,13] suggested a method for calculation of human health loss using damage radii and population density. Along with the number of people injured by an accident, the severity of the injuries is required to be considered. The severity is related to the intensity of the incident, varying from injuries with an easy and rapid recuperation to ones that are irrevocable [22].

Human health and safety loss can be calculated in terms of the number of fatalities and/or injuries times the costs associated with a fatality and/or an injury. However, there can be high degrees of subjectiveness and discomfort associated with assigning the dollar value to a fatality and/or an injury. Though the value of human life is immeasurable, attempts have been made to apportionate it by adopting worker compensation costs, insurance costs, and rehabilitation costs [11]. The rehabilitation costs for injuries vary according to the severity of injury. Pandey and Nathwani [23] and Jonkman et al. [24] proposed the use of life quality index (LQI) as a measure of value of human life. The life quality index is a social indicator derived to reflect the expected length of life in good health and the quality of life enhanced by wealth. Life quality index can be calculated using the following relation:

$$\mathrm{LQI} = g^q e \qquad (10)$$

where g is the gross domestic product (GDP) (US$/year), e the expectancy of life (years), $q - w/(1 - w)$, w is the part of human life used for economic activities.

Furthermore, Paralikas and Lygeros [25] suggested three undesired outcome categories for human health:

(i) *Possible death effects*: number of people inside the damage radius to whom deaths could be induced. This radius corresponds to the ERPG-3 (Emergency Response Planning Guidelines) concentrations for toxic release.
(ii) *Possible injuries*: number of people inside the damage radius to whom injuries could be induced. This radius corresponds to the ERPG-2 concentration for toxic release.
(iii) *Possible annoyance*: number of people inside the damage radius that slight injuries, annoyance or other slight reversible effect could be induced. This corresponds to the ERPG-1 concentration for toxic release.

Paralikas and Lygeros [25] suggested the use of ALOHA and ARCHIE (*a*utomated *r*esource for *c*hemical *h*azard *i*ncident *e*valuation) software for estimation of ERPG thresholds. The ERPG thresholds are published by AIHA (American Industrial Hygiene Association).

The human health and safety loss (HHSL) due to accident scenarios such as toxic release, explosion, and fire are estimated using the following relation respectively as proposed in this study:

$$\begin{aligned}\mathrm{HHSL_{Toxic}} = {} & \{(\mathrm{N1} \in \mathrm{DA1} \times \mathrm{VSL}) + (\text{Cost of injury 2 of } \mathrm{N2} \in \mathrm{DA2}) \\ & + (\text{Cost of injury 3 of } \mathrm{N3} \in \mathrm{DA3})\} \qquad (11)\end{aligned}$$

$$\begin{aligned}\mathrm{HHSL_{Explosion}} = {} & \{(\mathrm{N1} \in \mathrm{DAE1} \times \mathrm{VSL}) \\ & + (\text{Cost of injury 2 of } \mathrm{N2} \in \mathrm{DAE2}) \\ & + (\text{Cost of injury 3 of } \mathrm{N3} \in \mathrm{DAE3})\} \qquad (12)\end{aligned}$$

$$\begin{aligned}\mathrm{HHSL_{Fire}} = {} & \{(\mathrm{N1} \in \mathrm{DAF1} \times \mathrm{VSL}) + (\text{Cost of injury 2 of } \mathrm{N2} \in \mathrm{DAF2}) \\ & + (\text{Cost of injury 3 of } \mathrm{N3} \in \mathrm{DAF3})\} \qquad (13)\end{aligned}$$

where DA1, DA2, DA3 are the damage areas of ERPG-1, ERPG-2, and ERPG-3 concentration; DAE1, DAE2, DAE3 the damage areas of 8.0, 3.5, 1.0 psi overpressure from explosion; DAF1, DAF2, DAF3 the flammable damage areas of 1000, 150, and 50 ppm vapor cloud; N1, N2, N3 the number of persons present within damage area DA1, DA2, and DA3; NE1, NE2, NE3 the number of persons present within damage area DAE1, DAE2, and DAE3; NF1, NF2, NF3 the number of persons present within damage area DAF1, DAF2, and DAF3; VSL the value of statistical life in India; Cost of injury 2 the estimated cost of moderate injury; and Cost of injury 3 is the estimated cost of slight injury.

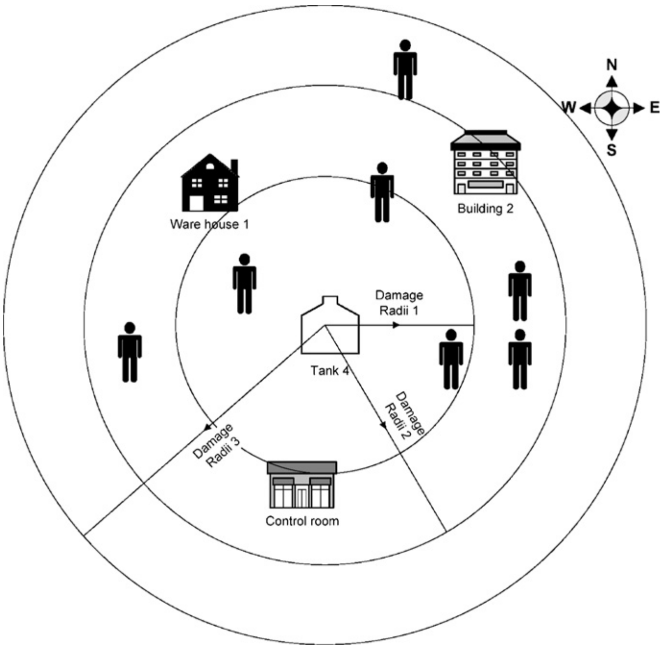

Fig. 6. Estimation of human health and safety loss.

In the proposed method, Paralikas and Lygeros method [25] is suitably integrated with Khan et al. [11,13] and a new method is developed. The Paralikas–Lygeros method is adopted for the estimation of possible number of people getting death effects and injuries using fire, explosion and toxic release damage radii as shown in Fig. 6. While calculating the damage radii for fatalities, moderate injuries and slight injuries, the maximum values of (DA1, DAE1, DAF1), (DA2, DAE2, DAF2) and (DA3, DAE3, DAF3) are considered, respectively.

2.3.4. *Environmental loss*

Environmental 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. While estimating the environmental consequence, the consideration of different hazard potentials is the important issue. The environment 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. In real life problem solving, the factors of environmental consequence are not assessed precisely due to unquantifiable, deficient, lack of knowledge, and non-obtainable information and partial ignorance. These limitations lead to the use of fuzzy-based approaches in environmental consequence assessment. In this study, fuzzy composite programming (FCP) is therefore used in the development of environmental consequence index (ECI) to capture the composite structure of environmental consequence factors, which is developed by Arunraj and Maiti [26]. The methodology involves five stages as mentioned below:

(i) The first step involves the identification of the factors contributing towards the magnitude of overall environmental consequence and their measurement. The factors considered are chiefly classified into nine categories, namely quantity of chemicals, material properties, time scale, human percep-

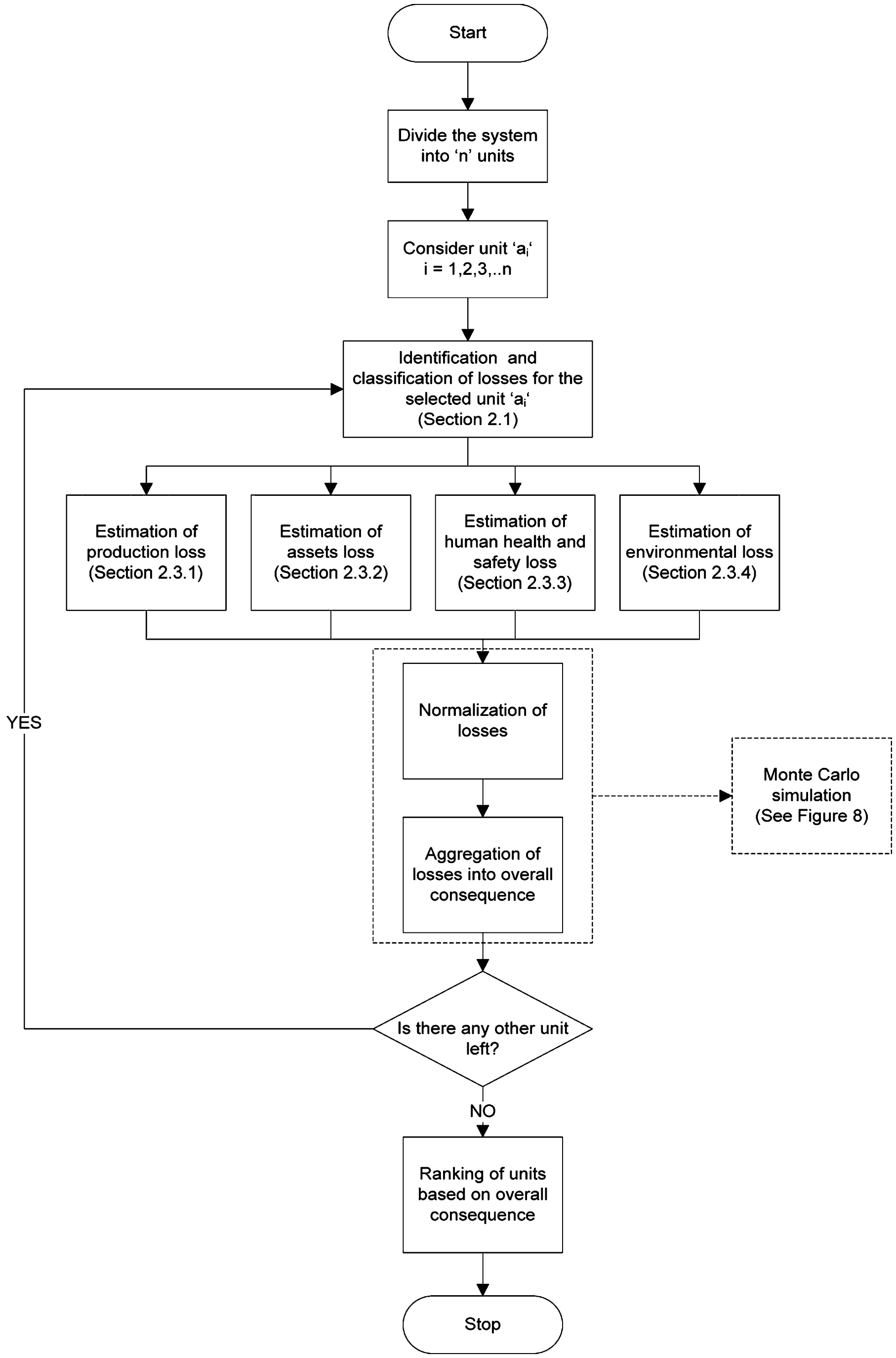

Fig. 7. Framework for overall consequence assessment.

tion, process effects, release causes, release effects, spreading medium, and degradation. For the determination of those factors, data from the following sources were taken: substance fire hazard index [25], Dow's fire and explosion index hazard classification guide [27], ALOHA manual [13], and environmental accident index [28].

(ii) The second step involves the assignment of weights (w_i) to the factors. The fuzzy importance factors as mentioned by Cheng and Lin [29] are adopted for the estimation of weights of each criterion because of its simplicity and inclusion of fuzzy sets.

(iii) The third step of the methodology considers the worst and best values for each of the environmental consequence factors. Then the membership degree (m_i) for the input value of each of the factor (i) is estimated by a normalization process using the best and worst values for that factor. After the normalization process, the membership values are fuzzified.

(iv) In the fourth step, overall environmental consequence factor for each jth 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:

$$\mathrm{ECF}_j = \sum_{i=1}^{n} w_{ij} m_{ij} \qquad (14)$$

where w_{ij} is the weights for property of substance, and m_{ij} is the membership value of property of substance.

(v) Finally, defuzzification of ECFs (DECF) for each jth substance can be 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 as shown below:

$$\mathrm{ECI} = \sum_{j} \mathrm{DECF}_j \qquad (15)$$

2.4. Overall consequence estimation

In general, the overall consequence can simply be estimated by normalizing and adding all four losses. Fig. 7 shows the proposed methodology for the estimation of the overall consequence. The methodology involves in the following steps:

(i) Identification and classification of losses as shown in Section 2.1, and as such four loss categories are identified namely production loss, assets loss, human health and safety loss, and environmental loss.
(ii) Estimation of all the four losses as mentioned in Section 2.2.
(iii) Normalization of losses.
(iv) Aggregation of losses into overall consequence.

After identification and estimation of all losses, the losses are normalized and integrated using Monte Carlo simulation, based on the assumption that the losses follow triangular distribution. The normalization of losses is required in order to combine the losses measured in different scales. The normalization of the losses is done using the following equation:

$$\delta_i = \frac{l_i}{\sum l_i} \qquad (16)$$

where δ_i is the normalized value of loss, l_i is the individual loss value, and i represents the loss category namely; production loss, assets loss, human health and safety loss, and environmental loss.

The normalized random numbers of all four losses are added to estimate the overall consequence. Likewise, repeating 5000 runs, the parameters of the overall consequence distribution are obtained. The development suggested by Chang et al. [30] in Monte Carlo method was adopted for analysis of uncertainty propagation in the estimation of overall consequence. A flow chart for this scheme is presented in Fig. 8. Confidence bounds (minimum and maximum) are obtained for the parameters of the overall consequence distribution. The distance between the bounds are divided into segments and the number of overall consequence values in each segment is counted. Finally, the cumulative distribution function is developed and plotted.

3. Application of the developed methodology

The developed methodology for overall consequence assessment is applied to the benzene extraction unit (BEU) of a petrochemical industry 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 using benzene heart cut feedstock from pyrolysis gasoline hydrogenation unit (PGHU). The process produces benzene using n-methyl pyrrolidone (NMP) as catalyst. The overall process flow sheet of the BEU plant is shown in Fig. 9. 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.

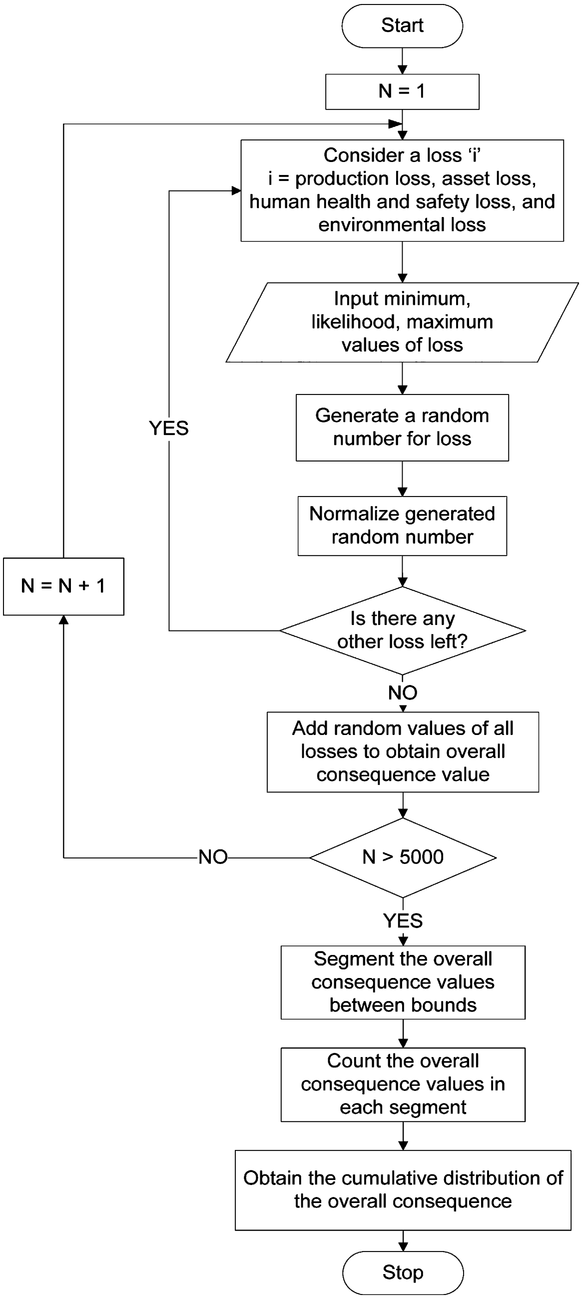

Fig. 8. Flow chart for estimation of overall consequence using Monte Carlo method.

3.1. Accident scenario analysis

The initiating events of the accident scenarios are the failure of sections of BEU plant. From the initiating events, the accident scenarios are generated on the failure of safety systems such as leakage detector, toxic vapor warning alarm, and fire extinguishing system present in the sections of the BEU plant. The failure probabilities of the safety equipment, probability of vapor formation, and probability of ignition responsible for accident scenario generation are taken from the plant data, databank, and other past

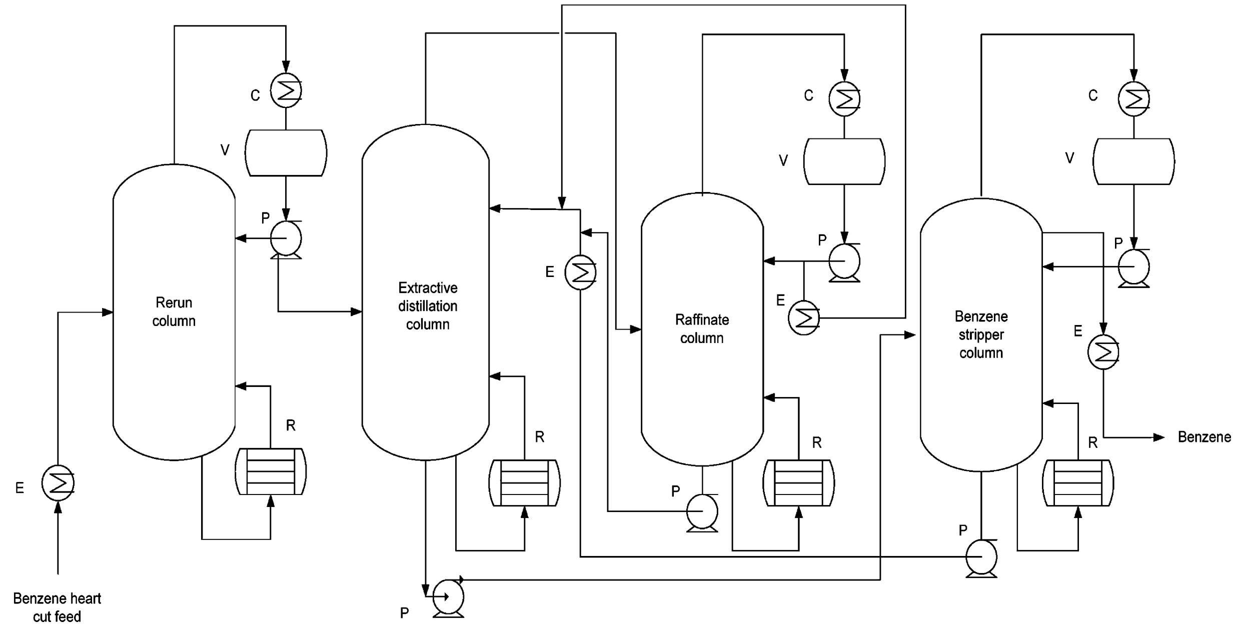

Fig. 9. Overall process flow sheet of BEU (C: condenser; E: exchanger; P: pump; R: reboiler; V: vessel).

Table 1
Input data for ALOHA.

Factors	Inputs
Atmospheric conditions	Cloud covers: clear Wind speed: 11 m/s Ground roughness: urban Relative humidity: 50% Air temperature: 98 °F
Material properties (chemical name: benzene)	Molecular weight: 78.11 g/mol ERPG-1: 50 ppm; ERPG-2: 150 ppm ERPG-3: 1000 ppm IDLH: 500 ppm LEL: 12,000 ppm; UEL: 80,000 ppm Normal boiling point: 176.2 °F Freezing point: 42.0 °F

studies [31–33]. The accident scenarios are generated for failure of each of the sections of BEU plant using event tree analysis. The event tree for the rerun column section of the BEU is shown in Fig. 10. Similar event trees were developed for other sections too.

After the generation of accident scenarios, the software ALOHA is used for consequence modeling. In ALOHA, the source strength and heavy gas models are adopted for the consequence modeling. Based on the results of the consequence modeling, the damage radii was computed and used to quantify the various losses. The input data for ALOHA are given Table 1. The consequence losses from each accident scenarios of failure of BEU sections are identified and quantified in the sections below to estimate the overall consequence.

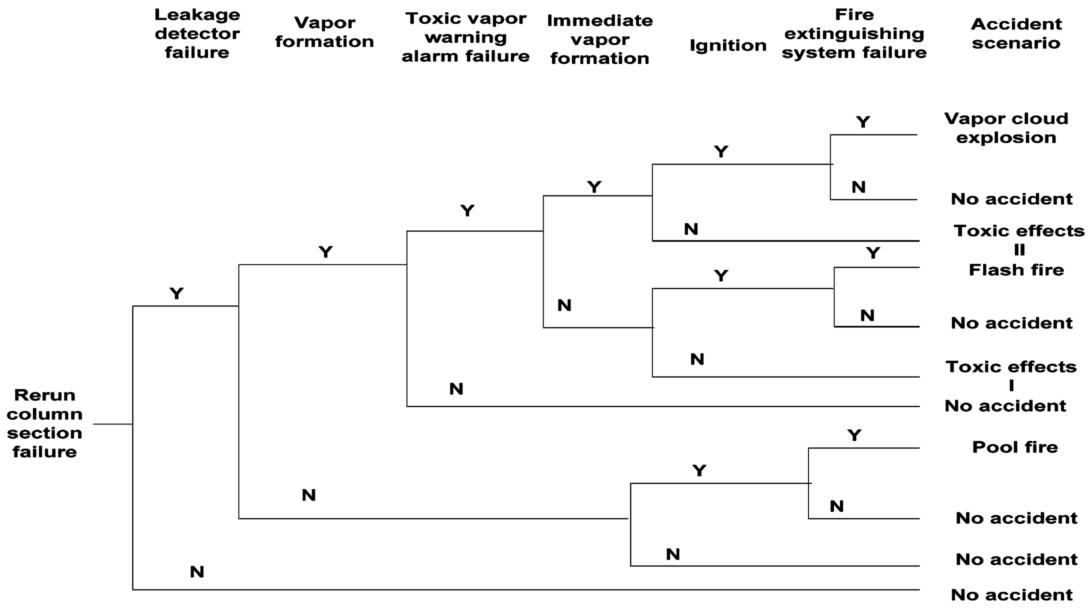

Fig. 10. Event tree of rerun column section failure.

Table 2
Maintenance cost calculation.

Sections of BEU	Spare parts cost, C_p (US$)	Delivery cost, C_d (US$)	Inventory cost, C_i (US$)	Material cost, C_{a2} (US$)	Private contractor cost, C_{pc} (US$)	Maintenance workers cost, C_w (US$)	Service cost, C_{a1} (US$)	Startup cost, C_s (US$)	Shutdown cost, C_{sd} (US$)	Maintenance cost, C_m (US$)
Rerun column section	14608.1	3652.0	6086.7	9130.1	5478.0	3652.0	18260.2	12173.4	15216.8	60867.2
Extractive distillation column section	2021.8	505.5	842.4	1263.6	758.2	505.5	2527.3	1684.8	2106.0	8424.2
Raffinate column section	1266.0	316.5	527.5	791.3	474.8	316.5	1582.5	1055.0	1318.8	5275.0
Benzene stripper section	963.3	240.8	401.4	602.1	361.2	240.8	1204.2	802.8	1003.5	4013.9
Solvent regeneration section	190.3	47.6	79.3	118.9	71.4	47.6	237.9	158.6	198.2	792.9
Storage and slop drums	20.8	5.2	8.7	13.0	7.8	5.2	26.0	17.3	21.7	86.7
Vacuum system	30.9	7.7	12.9	19.3	11.6	7.7	38.7	25.8	32.2	128.8
Process condensate system	32.1	8.0	13.4	20.1	12.0	8.0	40.1	26.8	33.4	133.8

Table 3
Downtime cost calculation.

Sections of BEU	Downtime (h)	Sales revenue (US$)	Variable costs (US$)	Fixed costs (US$)	Available time for production	Downtime ratio	Contribution (US$)	Contribution – fixed costs (US$)	Loss of profit due to downtime (US$)
Rerun column section	61.1	101571484.8	67764789.0	16941197.3	8760.0	0.0070	33806695.8	16865498.5	117673.4
Extractive distillation column section	70.2	82319318.0	54943791.6	13735947.9	8760.0	0.0080	27375526.4	13639578.5	109350.2
Raffinate column section	45.6	87140211.6	58361413.9	14590353.5	8760.0	0.0052	28778797.6	14188444.1	73890.0
Benzene stripper section	52.9	113567159.3	76137018.8	19034254.7	8760.0	0.0060	37430140.5	18395885.8	111047.3
Solvent regeneration section	21.7	43274133.3	29164859.1	7291214.8	8760.0	0.0025	14109274.2	6818059.4	16889.5
Storage and slop drums	20.0	52923667.9	35870031.8	8967508.0	8760.0	0.0023	17053636.1	8086128.2	18443.0
Vacuum system	22.3	54215001.5	36306565.5	9076641.4	8760.0	0.0025	17908436.0	8831794.7	22482.8
Process condensate system	30.9	73102766.0	49197659.1	12299414.8	8760.0	0.0035	23905107.0	11605692.2	40898.1

Table 4
Material wastage and recycling cost.

Sections of BEU	Material wastage cost (US$)	Material recycling cost (US$)
Rerun column section	1313.08	437.69
Extractive distillation column section	1035.53	345.18
Raffinate column section	928.31	309.44
Benzene stripper section	880.86	293.62
Solvent regeneration section	670.95	223.65
Storage and slop drums	563.94	187.98
Vacuum system	458.72	152.91
Process condensate system	441.62	147.21

3.2. Production loss

As explained in Section 2.3.1, the PL is estimated using the following relation:

$$PL = C_d + C_m + C_{pw} + C_{rc}$$

The production loss value for each section of BEU plant is calculated using the loss of profit due to downtime, maintenance cost, and material wastage and recycling cost data from Tables 2–4. Table 5 shows that the rerun column section, benzene stripper section, extractive column section, and raffinate distillation column section are main contributors of production loss in comparison with other sections and collectively contribute over 83% of the total production loss for the BEU. As per contribution to the total production loss, the eight sections are grouped into four categories. The rerun column section is most hazardous (category I), followed by extractive distillation column, and benzene stripper section (category II), raffinate column section (category III), and other four sections as category IV.

3.3. Assets loss

The assets loss (AL) is calculated by using the six-step assets loss evaluation scheme as developed in Section 2.3.2. The damage areas produced by the fire and explosion are estimated using ALOHA. In this calculation, Lang factor and its variability were considered from Peters et al. [19]. For example, Cran [34] did a statistical analysis of original data used by Lang and found that standard deviation of Lang factor is 0.47. Although the mean value of the Lang factor varies from plant to plant, however, based on studies by Lang [35] and Peters et al. [19], the mean value of the Lang factor is considered as 3.7. The range for asset loss was calculated using standard deviation range for the Lang factor taken and found as −30% and +29% of the most likely value of asset loss. The above-mentioned text is included in the manuscript. Estimation of the cost of the equipment and buildings present within damage areas are done using Eq. (9)

Table 5
Production losses for all sections of the BEU plant.

Sections of BEU	Production loss (US$)	% of total	Loss category
Rerun column section	180291.40	30.2	I
Extractive distillation column section	119155.07	19.9	II
Raffinate column section	80402.82	13.4	III
Benzene stripper section	116235.67	19.4	II
Solvent regeneration section	18576.95	3.00	IV
Storage and slop drums	19281.65	3.1	IV
Vacuum system	23223.23	3.8	IV
Process condensate system	41620.76	6.9	IV

Table 6
Damage radii due to accident scenarios for all sections of BEU sections.

Sections of BEU	Vapor cloud explosion			Flash fire			Pool fire			Toxic release		
	Damage radius (m)	Damage radius (m)	Damage radius (m)	Damage radius (m)	Damage radius (m)	Damage radius (m)	Damage radius (m)	Damage radius (m)	Damage radius (m)	Damage radius (m)	Damage radius (m)	Damage radius (m)
Rerun column section	527.34	288.22	60.80	210.94	115.29	24.32	97.88	57.64	12.16	603.30	1263.00	3000.00
Extractive distillation column section	278.94	142.31	32.90	111.58	56.92	13.16	55.79	28.46	6.58	502.75	1052.50	2500.00
Raffinate column section	367.82	80.10	21.70	147.13	32.04	8.68	63.21	16.02	4.34	522.86	1094.60	2600.00
Benzene stripper section	306.21	92.30	36.00	122.48	36.92	14.40	61.24	18.46	7.20	542.97	1136.70	2700.00
Solvent regeneration section	36.83	16.20	6.10	14.73	6.48	2.44	7.37	3.24	1.22	361.98	757.80	1800.00
Storage and slop drums	96.80	15.60	14.20	38.72	6.24	5.68	19.36	3.12	2.84	402.20	842.00	2000.00
Vacuum system	158.30	20.50	7.80	63.32	8.20	3.12	31.66	4.10	1.56	502.75	1052.50	2500.00
Process condensate system	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.21	2.53	3.00

Table 7
Assets losses for all sections of the BEU plant.

BEU sections	Assets loss ($\times 10^6$ US$)	% of total	Loss category
Rerun column section	40.81	30.67	I
Extractive distillation column section	32.54	24.45	II
Raffinate column section	29.31	22.02	II
Benzene stripper section	17.57	13.20	III
Solvent regeneration section	0.60	0.45	V
Storage and slop drums	10.95	8.23	IV
Vacuum system	0.60	0.45	V
Process condensate system	0.70	0.53	V

as follows:

$$\mathrm{AL} = \sum_i C_i(1+d_i)^{-t_i} + \sum_i C_i(1+r_i)^{t_i} \cdot L$$

where the interest rate (r) is taken as 8%.

The damage radii due to accident scenarios for all sections of BEU sections are shown in Table 6. Table 7 shows that the rerun column section is having high-hazard potential to BEU assets as well as neighboring assets contributing over 30.7% of the total assets loss followed by extractive column section (24.45%), raffinate distillation column section (22.02%), benzene stripper section (13.2%). These four sections collectively contribute over 90.3% of the total assets loss. Similar to production loss categories, the eight sections of the BEU unit are grouped into five loss categories (I–V).

3.4. Human health and safety loss

The human health and safety loss (HSL) is estimated using Eqs. (11)–(13) as follows:

$$\begin{aligned}\mathrm{HHSL}_{\mathrm{Toxic}} = {} & \{(\mathrm{N1} \in \mathrm{DA1} \times \mathrm{VSL}) + (\text{Cost of injury 2 of } \mathrm{N2} \in \mathrm{DA2}) \\ & + (\text{Cost of injury 3 of } \mathrm{N3} \in \mathrm{DA3})\}\end{aligned}$$

$$\begin{aligned}\mathrm{HHSL}_{\mathrm{Explosion}} = {} & \{(\mathrm{N1} \in \mathrm{DAE1} \times \mathrm{VSL}) \\ & + (\text{Cost of injury 2 of } \mathrm{N2} \in \mathrm{DAE2}) \\ & + (\text{Cost of injury 3 of } \mathrm{N3} \in \mathrm{DAE3})\}\end{aligned}$$

$$\begin{aligned}\mathrm{HHSL}_{\mathrm{Fire}} = {} & \{(\mathrm{N1} \in \mathrm{DAF1} \times \mathrm{VSL}) + (\text{Cost of injury 2 of } \mathrm{N2} \in \mathrm{DAF2}) \\ & + (\text{Cost of injury 3 of } \mathrm{N3} \in \mathrm{DAF3})\}\end{aligned}$$

Shanmugam [36] made an attempt to estimate the value of statistical life using the data from Indian labor market for manufacturing industries and the estimated value of statistical life (VSL) ranges from US$0.76–US$1.026 million. The same methodology was used to estimate the average value of statistical life of US$75,113.33 in case of Indian chemical industries, which is considered as the cost of a single fatality. Shanmugam [36] method can be used to estimate the cost of injury but was not considered as he did not consider the degree of severity of injuries. The cost of a moderate and a slight injury were calculated based on the studies by Alexander [37] and Peter Barss et al. [38]. Alexander [37] indicated that if death results in a loss of an average value of $2.2 million, the equivalent for moderate and slight injuries are $5000 and $200, respectively for USA. Comparing the ratio of GDP per capita of US and India with the ratio of cost of fatality of US and India, Peter Barss et al. [38] suggested that the ratio can be used deriving the cost of fatality and injuries in India. Based on these studies, the ratio between cost of fatality versus moderate and slight injuries in USA was used for the estimation of the cost of moderate and slight injuries in India. The cost for moderate and slight injury was estimated as US$170.7 and US$6.8, respectively. Quah and Boon [39] adopted a similar approach to estimate the cost of illness due to particulate air pollution in Singapore. They derived the VSL of mortality effects and morbidity effects for Singapore using the VSL in United Kingdom.

Table 8
Human health and safety loss for all sections of the BEU plant.

Sections of BEU	Human health and safety loss ($\times 10^6$ US$)	% of total	Loss category
Rerun column section	83.14	18.60	I
Extractive distillation column section	68.02	15.22	II
Raffinate column section	69.07	15.45	II
Benzene stripper section	69.08	15.46	II
Solvent regeneration section	40.91	9.15	III
Storage and slop drums	50.24	11.24	III
Vacuum system	66.45	14.87	II
Process condensate system	0.00	0.00	IV

The human health and safety losses for all sections of the BEU plant are shown in Table 8. The number of people working within the damage area of all sections of BEU plant for different accident scenarios was collected from the plant. In case of consequence due to fire and explosion, the loss was estimated considering the number of people working within the damage area. But in case of consequence due to toxic release, the damage area is too large compared to the damage areas of fire and explosion and goes beyond plant area. The local population figure was considered for the calculation. The population density around the plant is 613 persons/km^2.

Table 8 shows that the rerun column section is again the most hazardous section (category I) contributing over 18.6% of the total human health and safety loss. The benzene stripper section, raffinate distillation column section, extractive column section, and vacuum system are the next most hazardous sections (category II) contributing over 61% of the total human health and safety loss. The process condensate system is having negligible contribution (less than 0.0001%) (category IV) because it is handling only water and steam, not any toxic materials such as benzene and NMP.

3.5. Environmental loss

The normalized values of environmental consequence indices for all sections of BEU are obtained and shown in Table 9.

Table 9 shows the environmental loss for all sections of the BEU plant in terms of environmental consequence index. The rerun column section and raffinate distillation column section contribute around 40% of the total environmental loss and are grouped as category I. The benzene stripper section, vacuum system, storage and slop drums, and extractive column section contribute over 50.1% of the total loss, and are grouped as category II.

The categorization of loss types across different sections of the BEU was done by qualitative comparison of the loss values. The categorization reflects the relative importance of different sections of the BEU considered in the overall loss calculation. To make the categorization quantitative, statistical-based methods such as pair-wise comparison can be used with suitable distributional assumption. If

Table 9
Normalized values of ECI for all sections of BEU plant.

Sections of BEU	ECI	Loss category
Rerun column section	0.2278	I
Extractive distillation column section	0.1342	II
Raffinate column section	0.1552	II
Benzene stripper section	0.1603	II
Solvent regeneration section	0.0625	III
Storage and slop drums	0.1254	II
Vacuum system	0.1065	II
Process condensate system	0.0283	III

normal distribution is assumed, the estimated loss values for different sections can be considered as their mean values of loss and then pair-wise comparison can be made between the mean loss values. The one-way analysis of variance (ANOVA) can be used to evaluate whether there is any evidence that the means values of loss for different sections differ. If the one-way ANOVA leads to a conclusion that there is evidence that the group means differ, Tukey's multiple comparison test can be further used to determine which means amongst a set of means differ from the rest. Alternative multiple comparison tests include Sheffeâ's test and Dunnett's test [40].

3.6. Overall consequence

The overall consequence is estimated for all sections of BEU plant as per the scheme developed in Section 2.4. The normalized values for the overall consequences are shown in Table 10.

The overall consequence ranks (i) rerun column section as highly hazardous (category I), (ii) extractive distillation column section, raffinate column section, and benzene stripper section as medium hazardous (category II), and (iii) vacuum system, storage and slop drums, solvent regeneration system, and process condensate system as low hazardous (category III). Rerun column section is highly hazardous amongst all the sections of BEU. It contributes over 24.2% of the total overall consequence. As the rerun column section contains a huge number of equipment which handle high amount of benzene, it develops a large damage area to produce an aggregated heavy loss. The category II loss sections namely, raffinate column section, extractive distillation column section, and benzene stripper section contributed for 52%, i.e. nearly half of the total overall consequence of BEU plant. The category III loss categories contributed for over 23.8% of the total loss. They are less hazardous because of less severe operating conditions.

Table 10
Normalized values of overall consequence for all sections of BEU plant.

Sections of BEU	Normalized overall consequence	Category
Rerun column section	0.242	I
Extractive distillation column section	0.179	II
Raffinate column section	0.179	II
Benzene stripper section	0.162	II
Solvent regeneration section	0.048	III
Storage and slop drums	0.088	III
Vacuum system	0.076	III
Process condensate system	0.028	III

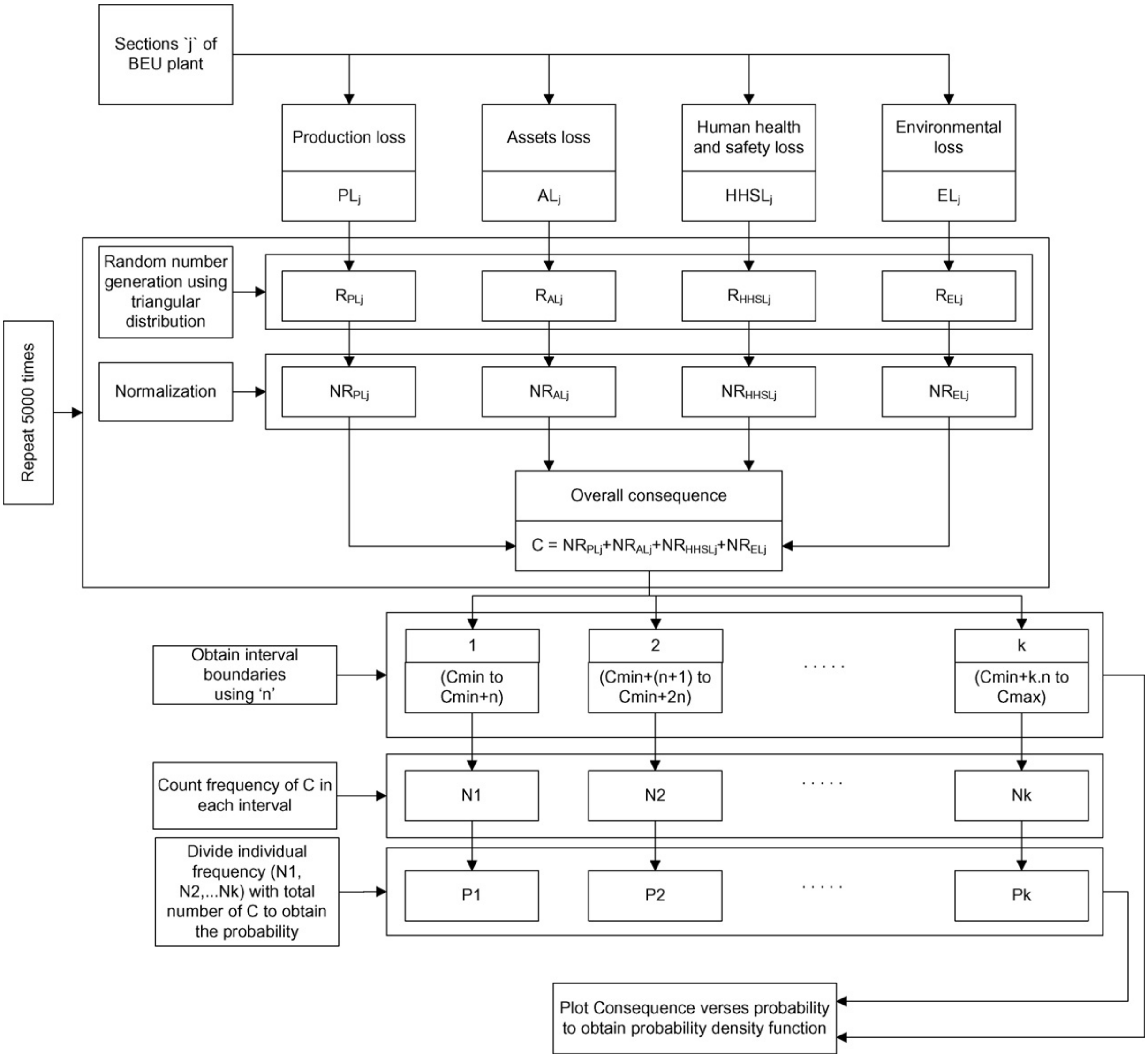

Fig. 11. Estimation of overall consequence using Monte Carlo simulation.

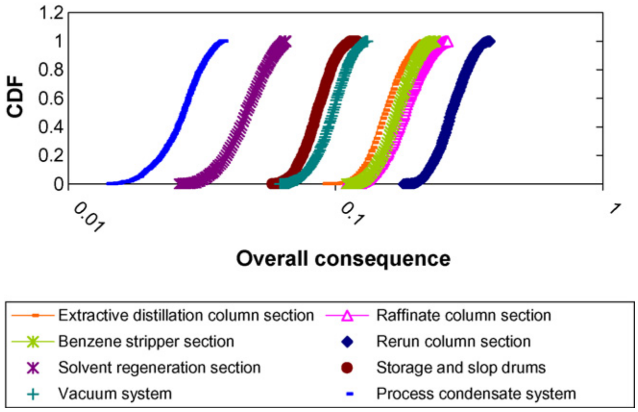

Fig. 12. Cumulative distribution functions of overall consequence for sections of BEU plant.

3.6.1. *Uncertainty in overall consequence*

In a point estimate approach, a single numerical value is chosen to specify the overall consequence. But the point estimate value will not represent the spread in the estimate of overall consequence. This can be solved by using probabilistic method that considers the probability distribution of the estimate, rather than the single value only. In a probabilistic method, distributions used as inputs to the consequence assessment can characterize the inter-individual variability inherent in each of the losses. The uncertainty considered in this study of overall consequence modeling is stochastic uncertainty. The aleatory uncertainty which arises due to lack of knowledge and measurement error is not taken into consideration. By characterizing variability with one or more input distributions, the output from the Monte Carlo simulation is a distribution of overall consequence that could occur in that population. The use of Monte Carlo simulation is shown in Fig. 11. In addition to providing a better understanding of where consequences occur in the distribution, a probabilistic method can also provide an estimate of the probability of occurrence associated with a particular level of concern. A probabilistic method that quantifies variability can be used to address the question, "What is the likelihood (i.e. probability) that consequence to an exposed individual will exceed acceptable level?" Based on the best available information regarding overall consequence, a decision-maker might conclude that the estimated distribution for variability in consequence across the target population indicates that percentage of the individuals exposed under these circumstances have a consequence exceeding acceptable level.

The cumulative distribution functions of overall consequence for each section of BEU plant are presented in Fig. 12. Each of these distributions represents the variability in overall consequence. These distributions provide a quantitative indication of the uncertainty in overall consequence. The low end, central tendency, high-end consequence values of sections of BEU plant are listed in Table 11. Standards can be developed with acceptance probability as a function of the consequence provided it is applied in a large number of similar plants. The acceptable level of consequence can be chosen by transforming the acceptance probability into overall consequence for different consequences. Furthermore, they can also be used to determine to what degree of confidence each section of BEU plant has overall consequence value. For example, suppose that in rerun column section an overall consequence value of 0.34 is of regulatory interest for safety reasons. This overall consequence value corresponds to the 93rd percentile of the probability distribution for uncertainty in overall consequence. Thus the simulation results indicate that there is 93% probability that the rerun column section would have the overall consequence less than this value. The 50th percentile of the probability distribution in overall consequence is less than 93rd percentile, so it is acceptable. But the 95th percentile of the probability distribution in overall consequence is greater than the regulatory value of 93rd percentile, so it is unacceptable. Further, remedial measures have to be taken by decision-makers to reduce the 95th percentile to the 93rd percentile or less value of overall consequence.

Table 11
Low-end, central tendency, high-end consequence distribution values of sections of BEU plant.

Sections of BEU	5%	50%	95%
Rerun column section	0.227	0.253	0.274
Extractive distillation column section	0.172	0.186	0.204
Raffinate column section	0.167	0.192	0.214
Benzene stripper section	0.160	0.177	0.194
Solvent regeneration section	0.045	0.053	0.059
Storage and slop drums	0.085	0.099	0.111
Vacuum system	0.075	0.083	0.091
Process condensate system	0.027	0.032	0.036

4. Comparison of proposed overall consequence methodology with existing methodologies

Comparison of the proposed methodology with the existing methodologies is done based on model development and case study application. The existing methodologies that are used in comparison are Khan and Amyotte [11], Khan and Haddara [3], Bernatik and Libisova [41], and IAEA-TECDOC-727 [42]. The strength of the overall consequence estimation is likely to vary due to the losses considered, type of estimation (qualitative, semi-quantitative or quantitative), potential to exploit the information to estimate the losses, and consideration of uncertainty in the estimation of overall consequence. In this study, the major losses such as production loss, asset loss, human health and safety loss, and environmental loss were identified and classified for overall consequence modeling. Furthermore, a quantitative methodology for the estimation of losses was developed, which extensively utilizes the information that were not used in the existing consequence methodologies and the additional innovative aspect of the proposed methodology is the development of a probabilistic consequence model to estimate and aggregate the major losses.

As per as model development is considered, for computation of production loss both Khan and Haddara [3] and Khan and Amyotte [11] calculated production loss as the product of production hours lost and cost of production per hour. Whereas in the proposed methodology, in addition to downtime loss, maintenance cost, material wastage and recycling cost are considered. Khan and Amyotte [11] used hazard potential value of SWeHI index to estimate damage radii. However, hazard potential value of SWeHI index is strongly influenced by the inventory values of chemicals. This result in the domination of quantity factor over other factors and rank a high-inventory unit as a highly hazardous unit. The damage to property and life were calculated as asset loss and human health loss respectively from damage area using SWeHI index. In the study made by Khan and Haddara [3], the damage to assets and human life were estimated using damage area which was derived from Dow fire and explosion index and were mentioned as financial loss and human health loss, respectively. However, in the proposed methodology, the software ALOHA is used for consequence modeling. In ALOHA, the source strength and heavy gas models are adopted for the consequence modeling. After the generation of accident scenarios (pool fire, flash fire, vapor cloud explosion, and BLEVE), the damage area was computed for fire, explosion, and toxic release using ALOHA and used to quantify asset and human health and safety loss. Khan and Amyotte [11] and Khan and Had-

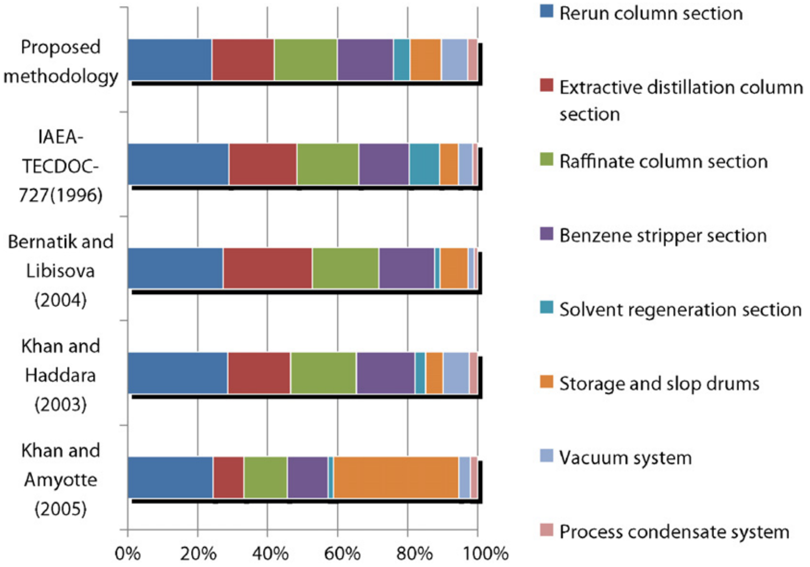

Fig. 13. Comparison of proposed overall consequence methodology with existing methodologies (Khan and Amyotte [11], Khan and Haddara [3], Bernatik and Libisova [41], and IAEA-TECDOC-727 [42]).

dara [3] considered only fatality in the calculation of damage to human health and life. Bernatik and Libisova [41] considered only fatality due to toxic effect as consequence. They determined the toxic damage area using ALOHA [13]. IAEA-TECDOC-727 [42] published by International Atomic Energy Agency, considered fatality due to flammability, explosiveness, and toxicity using qualitative scales. But the proposed methodology considered both fatality and injuries in the assessment of human health and safety loss. For environmental loss calculation, Khan and Amyotte [11] calculated environmental loss as environmental cleanup cost, in which the assumption on depth of the contamination may definitely mislead to wrong results. Khan and Haddara [3] assessed environmental damage as a monetary value which may be imprecise. The fuzzy-based ECI, used in this study is therefore considered to be better.

For a case study application, the normalized values of overall consequence for all sections of BEU as estimated by the proposed methodology are compared with existing consequence assessment methodologies. The normalized values of the overall consequence for the BEU plant sections are plotted in Fig. 13. All the sections were ranked separately using five different methodologies including the proposed methodology and the result is presented in Table 12. Table 12 and Fig. 13 show that rerun column section is ranked as having the maximum hazard potential in all the methodologies except Khan and Amyotte [11]. However, more than 20% of overall consequence is contributed by rerun column section in case of all consequence methodologies. Although the extractive distillation column section was ranked as the second highest hazardous section by Bernatik and Libisova [41], IAEA-TECDOC-727 [42], and the proposed methodology, the percentage contribution towards overall consequence by this section in these three methodologies varies as 25%, 19%, and 17%, respectively. Khan and Amyotte [11] ranks storage and slop drums as the most hazardous, i.e. nearly 36% of overall consequence is contributed by storage and slop drums as shown in Fig. 13, which was entirely different from the proposed methodology. This is because of the influence of quantity or inventory of chemicals over other factors in the calculation of hazard potential of SWeHI index. The process condensate system section was ranked as eight by all methodologies except Khan and Amyotte [11]. This is because of the influence of penalty factor due to the release of energy from steam and hot water over the toxic effects in the calculation of hazard potential of SWeHI index.

In Table 12, even though the ranking of BEU sections using proposed methodology exactly matches with Bernatik and Libisova [41], the consideration of losses in their calculation varies. In Bernatik and Libisova [41], only the fatality due to toxic effects was considered using ALOHA, which is nothing but a tip of iceberg in the estimation of overall consequence or even in the estimation of human health and safety loss itself. In the proposed methodology, all the major losses such as production loss, asset loss, human health and safety loss, and environment loss were considered. In particular, when compared to Bernatik and Libisova [41], the proposed methodology considered both fatality and injuries due to flammability, explosiveness, and toxicity using ALOHA. The monetary value of human health and safety loss was estimated using human fatality and injuries and the cost of human life and injuries. As shown in Fig. 13, the percentage contributions towards overall consequence by solvent regeneration section and vacuum system are 1.5% and 1.7% by Bernatik and Libisova [41], but these are 4.8%

Table 12
Ranking of the sections of BEU plant.

Sections of BEU	Khan and Amyotte [11]	Khan and Haddara [3]	Bernatik and Libisova [41]	IAEA-TECDOC-727 [42]	Proposed methodology
Rerun column section	2	1	1	1	1
Extractive distillation column section	5	3	2	2	2
Raffinate column section	3	2	3	3	3
Benzene stripper section	4	4	4	4	4
Solvent regeneration section	8	7	7	5	7
Storage and slop drums	1	6	5	6	5
Vacuum system	6	5	6	7	6
Process condensate system	7	8	8	8	8

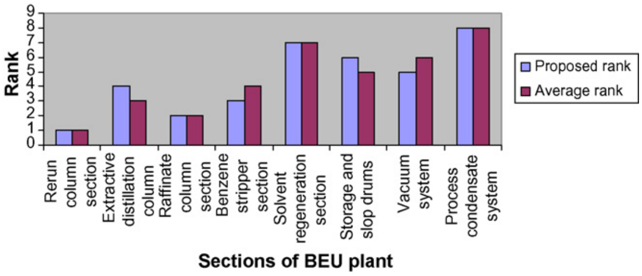

Fig. 14. Proposed ranks vs. average ranks.

and 7.6% by the proposed methodology, respectively. This is because of the non-inclusion of other losses and effects due to flammability and explosiveness in Bernatik and Libisova [41].

As stated in Section 2.1, the proposed methodology considers the consequence categories exhaustively to fulfill the gap in the existing methodologies. As such, different existing methodologies were studied to identify their limitations. Interestingly, the application specific developments have many consequence issues uncommon. For example, Bernatik and Libisova [41] and IAEA-TECDOC-727 [42] consider only fatality for consequence estimation. However, the proposed methodology considers almost all consequence categories, thus is a superset of the existing methodologies as per as consequence categories are concerned. As a result, the average rank of each of the eight sections of the BEU considering the four methodologies taken for comparisons may better reflect the potential capability of the existing methodology. The average rank for each section is obtained by taking average of the ranks of that section that were computed using the existing methodologies. Hence, all the sections were compared with the proposed ranks versus the average ranks. Interestingly, these two ranks for each section match almost exactly (see Fig. 14). Hence, it can be argued that the proposed methodology has an edge over the existing methodologies for overall consequence assessment.

As per as case study application is concerned, although for many sections, the proposed methodology ranks equally the sections, the ranking is a relative measure of importance. But the quantitative assessment of different categories of loss varies. Therefore, the proposed methodology should not be treated as a comparative evaluation only, rather, a scheme of nearly all-encompassing loss categories for quantification of losses.

5. Discussions

5.1. Important considerations for developing a methodology

A few important issues that should be considered while developing a methodology for overall consequence assessment are (i) purpose of the development, (ii) input factors, (iii) application potential, and (iv) precision of the results obtained.

The first significant issue is goal or purpose for which the assessment is established. The hazard with vulnerability and elements at risk (equipment, building, human, etc.) is taken as the consequence in the assessment. The overall consequence methodology is developed with a thorough assessment of all the losses and their aggregation with ease, so that the user can use these overall consequence results for risk assessment and decision-making. Second, for overall consequence assessment, the input factors are all loss categories with their components' costs. Based on literature and upon discussions to plant personnel, almost all loss categories were identified. The estimation of component level costs and their aggregation are explained in Section 2.2.

The third issue is the application potential of the consequence assessment scheme. The magnitude of overall consequence differs from industry to industry. For example, in case of mechanical industries, only production and safety loss can be considered for the consequence assessment. But in case of chemical and nuclear industries, all losses are possible. So, the consequence methodology should have enough flexibility to be applied to all types of applications. The completeness of their methodology by incorporating almost all types of losses makes it applicable to all types of industries. For example, for mechanical industry, a subset of the loss categories is to be considered. To prove the full function of the proposed overall consequence methodology, it was applied to a BEU (petrochemical plant) comprising eight sections. The overall consequence for each section was computed and the results were analyzed. The precision and strength of the developed methodology was tested through comparison with some other existing methods like Khan and Amyotte [11], Khan and Haddara [3], Bernatik and Libisova [41], and IAEA-TECDOC-727 [42] that has been discussed in Section 4.

5.2. Ability of the methodology

The ability a methodology can be measured by satisfying two conditions [43]: (i) methodology should not yield undesired outcome which may arise because of implicit valuation, uncertainty in data or model, and shallow analysis, and (ii) methodology should not be too complicated, too expensive, or lacking required data to conduct.

The explicit valuation is preferred to achieve the desired decisions such as maintenance selection or choice between processes and products. For example, the importance factor in environmental loss proposed by Khan and Haddara [12] is highly implicit in nature which would degrade the overall consequence outcome. But in the proposed methodology all the possible contributing factors are considered in the overall consequence assessment. The data used in the consequence assessment consist of many uncertainties because of expert opinion, subjective information, extrapolated data, and unaccounted data (e.g. mobility of people in human health and safety loss and direction of wind in environmental loss). Due to such uncertainties, the overlap between confidence intervals of overall consequence of two alternatives may lead to wrong decision-making [43]. For example, existing methodologies mentioned in Section 4 considered consequence as point estimate. However, the overall consequence results of the proposed methodology are presented in the form of probability distributions so that the decision-maker is aware of uncertainty while investing the resources. The in-depth and wider analysis may result to better judgment but requires more information and knowledge. The proposed methodology is convenient enough to conduct deeper analysis and to extend the boundary of analysis, if sufficient data are available.

6. Conclusions

In this study, a brief overview of various existing consequence assessment tools and methodologies available in literature was conducted. From these studies, the major losses such as production loss, assets loss, human health and safety loss, and environmental loss were identified and classified for overall consequence modeling. Further, a well-defined methodology for the estimation of losses was developed. The innovative aspect of the proposed methodology is the development of a probabilistic consequence model to estimate and aggregate the major losses. In case of production loss, recycling cost and material wastage cost were considered to make it more realistic. In the calculation of assets loss, the present value and reinstallation cost of the assets were considered. In case of human health and safety loss, moderate and slight injuries were considered in addition to fatality. The environmental consequence index is developed based on fuzzy composite programming. The stochastic nature of the individual losses which was highly neglected in the past studies was considered for the computation of overall consequence.

Then the developed methodology was applied to BEU to estimate the losses of the sections of BEU. The individual losses from each section are aggregated using Monte Carlo simulation to estimate the overall consequence. Finally, the ranking of the BEU sections using proposed methodology was compared with the ranking as obtained by using methodologies proposed by Khan and Amyotte [11], Khan and Haddara [3], Bernatik and Libisova [41], and IAEA-TECDOC-727 [42]. The comparison shows that the proposed method equally performs with other methods. The proposed overall consequence methodology may do better than other available consequence assessment methodologies because of its detailed consideration of (i) all the losses involved in a high-risk industry like chemical industry, and (ii) the uncertainties involved in estimation.

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Appendix A

See Tables A1–A4.

Table A1
Material properties for benzene and *n*-methyl pyrrolidone.

Material property	Benzene	*n*-Methyl pyrrolidone
Toxicity index	3	1
Flammability index	2	2
Reactivity index	0	1
Vapour pressure	75 mmHg @ 20 °C	0.06 mmHg @ 20 °C
Solubility in water	0.18%	2.50%
Viscosity	0.6468 cP	1.67 cP
Half life period	7 days	23 days

Table A2
Hazard potential of SWeHI index values of BEU sections.

Sections of BEU	Hazard potential of SWeHI index
Rerun column section	1263.32
Extractive distillation column section	372.58
Raffinate column section	895.33
Benzene stripper section	814.79
Solvent regeneration section	430.04
Storage and slop drums	2883.93
Vacuum system	538.05
Process condensate system	161.69

Table A3
Dow fire and explosion index values of BEU sections.

Sections of BEU	Dow fire and explosion index
Rerun column section	527.34
Extractive distillation column section	278.94
Raffinate column section	367.82
Benzene stripper section	306.21
Solvent regeneration section	36.33
Storage and slop drums	96.8
Vacuum system	158.3
Process condensate system	26.5

Table A4
Asset value of BEU sections.

Sections of BEU	Asset value ($\times 10^{-6}$ US$)
Rerun column section	4.68
Extractive distillation column section	2.76
Raffinate column section	1.56
Benzene stripper section	1.62
Solvent regeneration section	1.08
Storage and slop drums	1.08
Vacuum system	3.49
Process condensate system	4.56

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