Safety investment optimization in process industry: A risk-based approach

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Abstract

Process plant safety is a critical indicator of organizational performance. Adequate investment into safety practices to avoid future accident cost is therefore a beneficial strategy. The current approach to such investments in the process industry is driven largely by simple risk-based heuristics, insurance market premiums, organizational culture and management judgment. There is, however, an absence of an overarching methodology to assist such an effort. Therefore, there is a need for developing a robust decision-making framework for enabling systematic and optimal allocation of financial resources across all significant risk elements within a process plant.

The present work proposes a safety investment optimization (SIO) framework for a typical process plant. Such an optimization approach targets maximal reduction of risk values across all potential hazards within the constraint of a given safety investment budget at the incipient stage of establishing a plant such that it saves future cost to company by reducing the risk from accidents. At the same time the framework takes into account the need to comply with the regulatory requirements imposed by the government. Additionally, access to insurance market as a strategy to transfer risk is also integrated. Finally, the residual risks are managed through investments in selective safeguards while ensuring that the benefits over-weigh the cost of such an exercise. For illustrating the application of the framework, a representative process plant with a select number of risk scenarios is chosen and all steps suggested by the framework are demonstrated quantitatively. It is anticipated that the proposed SIO framework will help optimal resource allocation for managing the risks implicit in a typical process plant.

1. Introduction

Safety in a chemical plant is a significant consideration not only because of employees’ right to work in a safe environment but also due to the need to control public exposure to risk. Hazards are intrinsic to process operations and have the potential to cause serious business interruptions when actualized through incidents. More than 7500 accidents have been reported across the world in chemical process industry since 1960 till date (Tauseef et al., 2011). Further, the incident database FACTS- Failure and ACCidents Technical Information System (FACTS, 2017), reports more than 25,000 accidents and near-misses involving hazardous material in past 90 years. This underscores the unquestionable need to manage process risks so as to reduce both human and property losses by investing appropriately in safety measures. Yoon et al. (2000), for example, has analysed the outcome of safety investment in a representative chemical industry. It is demonstrated that by investing sufficiently into safety, one may save the direct cost of future accidents as well as help the company build a safer work environment.

For a typical process industry, several safety investment decision-making problems may exist, and it is generally difficult to decide with due precision how much investment into safety is “good enough”. Some examples of such decision-making problem are: whether a company should buy fireproof jackets for its employees or not; whether a fuel storage tank should be fireproofed or not, etc. Such decision-making problems become more intricate as the number of options/safeguards to mitigate a particular hazard increase. For example, instead of fire-proofing a fuel storage tank, company may consider implementation of a critical alarm system. Typically, for a process plant, where there are multiple such decision-making problems, one has to make investment decisions within a constrained budget. In such scenario, there is a need for adopting an overall safety investment framework which can help allocate resources in an optimal manner. This may ensure that return on investment through avoidance of accidents is maximized while at the same time reducing the residual operational risk to acceptable levels.

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This necessitates a theoretical exploration and development of a strategy for optimizing safety outlay across all credible risks arising from industrial operations.

The approach to optimization of safety investment may vary with the type of industry mainly due to variation in the nature of risk and data availability. For example—a dominant risk faced by the construction industry is possible loss of man-hours. The data on cost-effectiveness of preventive measures i.e. reduction in lost man-hours per dollar spent is relatively more accessible in the construction industry compared to the chemical process industry (Hallowell, 2011). As a result, it is comparatively easy to allocate available resource based on calculated value of return on investment towards reducing loss of man hours.

Several authors have attempted to propose approaches to optimizing safety investment in CPI. Sato has suggested use of a method which assigns weight to each proposed safeguard based on Analytical Hierarchy Process involving a survey-based approach (Sato, 2012). A linear mathematical expression for the degree of risk reduction is formulated in terms of investment across all available hazards, the aim of the exercise being the maximization of the degree of risk reduction within a given financial constraint (AIChE, 1994). A shortcoming of this method is that it assumes that the degree of risk reduction for a particular hazard varies linearly with investment level, which may or may not be true for practical scenarios. Based on utility theory, Khazad and Reniers (2017), has proposed a Bayesian approach-based method to cost-effectively allocate safety measures. This approach maximizes the utility function which can take inputs of societal risk as well as of monetary value of risk. It uses “Limited Memory Influence Diagram (LIMID)” to graphically represent hazards and connects utility nodes to visualize each accident scenario. For all safeguards, the method calculates the utility value. The investment which maximizes the utility function is chosen as the solution. Though this method is based on probabilistic risk calculations, it becomes relatively difficult to apply as the number of risk sources in a plant increase.

A method to provide financial decision support for practical risk management setting was also proposed by Aven and Hiriart (2011). This method is based on the formulation of a mathematical model for total cost function comprised of safety investment and expected accident cost. Total cost function is further translated in terms of safety investment by obtaining the relationship between expected accident cost and safety investment. The minimum value of total cost to company is found by differentiating total cost function with respect to safety investment. However, in order to implement this method, one needs to have sufficient information to formulate a mathematical function comprised of reduction of losses and of accident frequency in terms of safety investment. Also, the total cost function needs to be continuous in order to derive the result by an analytic approach.

An automated tool named Cost Efficient Safety for Major Accidents (CESMA) was developed by Reniers and Brijs (2014) that may potentially help organizations to choose the most cost-effective safeguard based on available accident frequency and consequence. Along similar lines, there are tools like Safety pays (OSHA, 2017) which is a web-based system for calculating the impact of occupational accidents on an organization’s profitability. Further Linhard (2005) has reviewed a “Return on Health, Safety and Environmental Investments” (ROHSEI) Model which has resulted in the development of a software product to help decision makers in assessment of workplace risk. While the tool is generally helpful in assessing a variety of health and safety problems it is not typically possible to arrive at a comprehensive solution to plant-wide safety investment optimization. More recently, Yazdi et al. (2019) have proposed a methodology for designing an optimum safety maintenance investment plan by employing a fuzzy dynamic risk-based method. While the methodology would be applicable for maintenance scheduling, it needs to be explored if it may be extended to choose an optimal combination of safeguards for mitigating a risk scenario.

The present work is aimed at addressing some of the gaps that exist in the current literature as reviewed in the foregoing paragraphs. The contemporary practice of allocating safety investments in the CPI process is dependent on a number of factors including results of qualitative or quantitative risk analysis for the plant, organizational approach to risk control and insurance market premiums. In addition, the stringency of national risk regulation is a major determinant of process safety investment. The objective of the present work is to integrate these above-mentioned considerations towards formulation of a risk-based framework which may be employed to optimize organization-wide safety investment at the inception of operation. We consider that such a method needs to address all representative risk sources for a plant and also allow compliance with relevant risk regulations of the land. Additionally, access to insurance market as a strategy to transfer risk is also accounted for. It may be noted that in this context safety investment implies outlay that is to be considered over and above that which is required as per standard engineering practices relevant to basic plant design. Essentially the proposed safety investment framework aims to maximize the overall degree of risk reduction such that it complies with local acceptance risk criterion while also ensuring enhanced financial benefits in comparison to investment.

Section 2 of this paper describes the proposed safety investment optimization framework. Section 3 presents a case study which demonstrates the application of the proposed framework. The paper is concluded by outlining the principal findings of the study and the future outlook.

2. Safety investment optimization framework

As noted above, all accidents which may occur in future are costs to the organization. These may potentially be reduced or eliminated through timely and adequate financial investment in improving safety through design, hardware changes or addressing human factors. For a given risk source, the Total Cost (Ct) to company may be expressed as sum of Safety Investment (I) and Monetary Risk (MR) value. The parameter MR may in turn be given by the product of accident frequency (f) and monetary consequence encountered in the form of property and business loss (L). With initial safety investment, Ct is expected to decrease either due to reduced f or L, which results in a lower value of MR. On the other hand at very high levels of I, reduction in MR does not occur in proportion to the magnitude of safety investment, which leads to an increase in Ct (Kletz, 1999).

Thus, there exists an optimum value of safety investment. Once the safety investment is decided for a particular risk source, there remains the additional task of apportioning the total available safety investment budget optimally across all the plant risk sources. Thus, there is a need to consider a resource allocation model to achieve the most cost-effective (hence optimal) risk reduction across all plant risks.

There are essentially five approaches to risk management (Williams, 1971): (i) avoidance of risk; (ii) loss prevention and reduction; (iii) retention of risk; (iv) non-insurance transfers; and (v) third-party insurance. In the present context we assume that the first approach is not an option that is available, as presumed benefits of operation are higher than the risk entailed. Also, non-insurance transfers (e.g. surety bonds, fidelity bonds) which are available to the finance industry are not generally applicable to process industry. The approach proposed in the present work essentially weighs three safety investment options - loss prevention and reduction, retention of risk (residual risk) and insurance, subject to the constraint of a pre-fixed financial resource. The key idea of behind the strategy is to consider the opportunity for optimal investment in overall plant safety to obtain secure returns by reducing the monetary risk of both human and property losses.

The proposed framework for optimizing the allocation of a given safety investment budget is illustrated in Fig. 1. The first step is to identify hazards and consequent risk sources in a plant and develop a representative list based on the initial, expanded one. Next, the hazards are modelled along with application of relevant failure frequencies to derive the Individual Risk (IR) as well as Societal Risk (SR) distribution.
around the facility in question. For convenience we limit ourselves to the consideration of only IR in this communication. Based on the estimated IR contours, it is ascertained if the public IR at plant boundary is acceptable vis-a-vis local governmental regulations. If not, then fractional risk contributions of each hazard towards total IR value at plant boundary are estimated. This is used to determine the allocation of financial resources needed to implement preventive measures to cost-effectively mitigate hazards such that IR at plant boundary is rendered acceptable. The principle of this allocation is that hazards contributing more to the total IR are prioritized for application of risk reduction measures. Once the regulatory requirements are met, and if further funds are available, market-based insurance cover for select remaining risks is procured. Lastly, any additional funds, if accessible, are used to selectively invest into safeguards for managing still outstanding risks such that benefits in terms of avoidance of corresponding accidents are higher than the latter’s cost. In the subsections that follow, each element of the SIO framework are detailed further in qualitative and quantitative terms.
2.1. Screening of accident scenario

Hazard identification is the first step to application of the proposed SIO; it may be done, for example, using Hazard and OPerability- HAZOP study or equivalent methods (Sato, 2012). In a typical process plant, there may be a large number of probable risk sources. Considerable time and effort may be needed to consider each of them for the purpose of computing the effective public risk arising from all of them. Hence, there is a need for limiting the number of risk scenarios to a manageable number towards obtaining a representative and yet a realistic set.

The initial list is reviewed to identify those incidents that are too small to be of concern i.e., consequences are too small or the frequency is too remote for it to be realized (AIChE, 1989). Removal of these incidents from the initial list produces a revised list. It is necessary to compress this revised list further by combining redundant or similar incidents. This leads to a condensed list. This may be reduced additionally by grouping similar incidents from subsets and, wherever possible, replacing each subset with a single equivalent incident. The grouping can be accomplished by consideration of similar inventories, compositions, discharge rates, and discharge locations. The final list formulated in this manner is considered to be the representative list (AIChE, 1989).

2.2. Meeting risk acceptance criteria

Based on the representative accident scenarios, the next step of SIO is to compute the public IR profile of the plant and compare with a relevant risk acceptance criterion (RAC). Various types of RACs have been proposed in the literature (Kausand, 2013). For the purpose of the present work we suggest the application of the so-called As Low As Reasonably Practicable or ALARP criteria (HSE, 2017). ALARP is used by regulators to control public risk, i.e., to those in the immediate vicinity of the process plant. This involves weighing the risk against the difficulty, time and money needed to control it. If risk is more than a certain highest level defined by regulators, then it is designated as intolerable and it has to be reduced to a lower level irrespective of the required investment. At the same time below a certain lower level, the risk is defined as broadly acceptable; if the estimated public IR is below this value an organization is not required to invest into further risk reduction. The ALARP region lies between the two above limits of ‘intolerable’ and ‘broadly acceptable’ levels. If the estimated risk is found to lie in the ALARP region it is recommended that the organization attempts to reduce it towards the broadly acceptable level as much as may be feasible practically. Alternatively, it is needed to be shown that any additional investment needed to bring down the risk further is grossly disproportionate with the corresponding number of public deaths averted. As indicated in (Fig. 1), in case the computed IR falls above the ALARP region, one needs to then consider the scenarios which contribute the most significant fractions of the total IR (say, for example >50%) and cause it to exceed the higher ALARP limit. On the other hand, the scenarios which pose insignificant (say, for example 10%) cumulative IR at plant boundary, may not be considered for purpose of this exercise. Once the high-risk scenarios are selected, all associated safeguards (suggested by, for example, a HAZOP study) which may be used for reducing public IR need to be enumerated. For instance, if the safeguard is expected to reduce the accident frequency, one may carry out a Layer of Protection Analysis (LOPA) (Crowl and Louvar, 2002). Each option is assessed by re-calculating the IR at the plant boundary resulting from the implementation of the specific safeguard, or a combination of safeguards. Out of all possible combination of safeguards, that which entails the lowest cost, and which leads to reduction of risk to within ALARP limits maybe considered for actual implementation.

2.3. Choosing an insurance policy

Once the local risk regulation criterion is complied with, the proposed SIO involves the consideration of the residual risk from identified sources, and its partial transfer through insurance of plant assets that may potentially be damaged by the concerned accident. Insurance may be sought for whole process plant cumulatively over the various residual risks selected to be insured. Generally, low frequency/high consequences risk sources are insured since potentially they can cause catastrophic losses and significant business interruption. However, first such risk sources need to be controlled by lowering their risk (typically through reduction of accident frequency or potential loss that they may entail) by pro-active implementation of specific safeguards (Abrahamsen and Asche, 2010). This is addressed in the primary phase of the SIO exercise at outlined in section 2.2. The risk that still remains as a residue may be insured.

An organization’s decision in this regard may largely be driven by insurance premiums available from the market (Ellins, 1999). The cost of safety investment may be weighed against benefit of risk absorption offered by insurance companies. If the benefit to cost ratio is favourable, procurement of insurance would be justified. It may be noted that organizations can also explore opportunities for securing lower insurance premium by proactive investment into safeguards (Linhard, 2005).

To compare competing insurance policies for mitigation of the same hazards, one can treat the former as individual safeguards and compare them using a cost-effectiveness analysis. Results of such analysis are, however, purely based on financial considerations; it does not include management’s perception of acceptable risk level. To include such a factor, expected utility theory and worry value factor model may be used (Williams, 1971).

2.4. Cost-effectiveness analysis (CEA) for choice of safeguard

In order to assess a safeguard, both i.e. money invested in installing the safeguard and money saved in the form of avoidance of accident have to be considered, the latter representing the benefits. It may be noted that benefits may include reduction in plant asset and business interruption losses, and in human fatalities due to implementation of safeguard. Monetary value of human deaths averted can be calculated using ‘Value of Statistical Life (VSL), i.e., the economic value of human life (Madheswaran, 2007). We define cost-effectiveness as the ratio of benefits to costs:

\[
\text{Cost effectiveness} = \frac{\text{Benefits}}{\text{Cost}} \tag{1}
\]

The approach to assessment of cost-effectiveness is mentioned at the lower part of Fig. 1.

2.4.1. Cost of safeguard

The cost of the safeguard \( C_s \) is comprised of two parts-the fixed cost \( C_{st} \) and the recurring cost \( C_{sr} \) (Reniers and Audenaert, 2009). For example, the price of a gas-detection system is its fixed cost while its annual maintenance corresponds to the recurring cost. Since the recurring cost is incurred in future, it needs to be discounted as value of money decreases with time. The discounted cost or Net Present Value (NPV) is calculated using following expression (Gaviou et al., 2009):

\[
\text{NPV} \quad C_s = \frac{C_{st}}{1 + r} + \frac{C_{sr}}{r} \tag{2}
\]

Here, \( \text{NPV} \) Net Present Value

\( C \) Cost

\( r \) Discounting rate (or factor)

\( t \) Time period

The parameter \( r \) depends on various factors like an organization’s risk-taking ability, inflation rate and risk profile of the project (Dyk and Hu, 1989). There is no perfect value of discounting rate (DR). However, it is usually assumed to be weighted average cost to the company. It can
vary significantly depending on the afore-mentioned factors, and can range from 1% to 12%. [Inventopedia, 2015]. Dyke and Hu (1989) have presented a comprehensive study on the method of computing the discounting rate by including the effect of a number of critical determinants such as: temporal interest rate variations, the time period over which the DR is to be averaged, and adjustment for inflation. They conclude that significant variations in the value of DR may result due to the effects of the afore-mentioned parameters. The reader may also refer to more recent reviews by Spackman (2004), Moore et al. (2013), and Akbulut and Seclimits (2018). These studies address, in particular, the method of calculation of DR suited especially for application in cost-benefit analysis.

The expression for total cost ($C_t$) of installing a safeguard can then be written as follows:

$$C_t = C_{if} \sum_{i=1}^{n} \frac{C_{ii}}{1 + r}$$

(3)

2.4.2. Benefits of avoidance of accident

To calculate the monetary benefit of accident avoidance, one needs to estimate the value of monetary risk associated with a hazard. As noted earlier, monetary risk (MR) may be defined as product of frequency (f) and monetary consequence of accident (L). Expected monetary benefit is simply the reduction in MR, i.e., Δ(fL), resulting from the implementation of a safeguard. However, it is important to exclude insurance-covered losses while assessing MR. Monetary benefits can also be comprised of three parts-direct ($B_d$), indirect ($B_i$) and immeasurable/intangible ($B_i$) (Reniers and Brijs, 2014). Direct benefits are those which are associated with property or immediate monetary losses. Examples include non-collapse of installing unit, non-loss of raw materials. Indirect benefits may include non-absenteeism of labour, non-business interruption etc., (Reniers and Audenaert, 2009).

Unlike cost, benefits may also include intangible or non-measurable components, which are usually difficult to quantify. Examples of such components are: non-deterioration of company image, employee satisfaction, talent attraction etc. It may be important to consider such factors into calculation as these may significantly impact company’s business in the long-term. For this purpose, use of “Disproportion Factor” (DF) has been proposed. It was originally introduced to ascertain whether cost and benefits are in right proportion and meets the definition of ALARP (Goose, 2006). The disproportion factor is also termed as the gross disproportion to reflect an intended bias in favour of safety. The so-called proportion factor (PF) indicates the ratio of the costs to the benefits. The PF may be compared with the disproportion factor (DF) so as to determine if the risk reduction measure is “grossly disproportionate” or not. In other words, there is disproportion, when the cost of a potential safety measure grossly exceeds the magnitude of the safety benefits obtained when the measure is adopted. A detailed analysis of the above concept has been provided by Goose (2006). Thus, the “Proportion factor” (PF) which is defined as below has to have value greater than DF.

Proportion factor = \frac{Total Costs}{Direct benefits \times Indirect Benefits} = \frac{C_t}{B_d \times B_i} \frac{C_{if}}{DF}

(4)

The parameter DF may be computed using the following expression (Talarico and Reniers, 2016):

$$DF = \log N_{avg} \log 10^{\text{EV}} \log \frac{N_{max}}{N_{max}} 3$$

(5)

where, $N_{max}$ Worst case scenario for potential causalities, $N_{avg}$ EV/ΣFR, ΣFR the sum of failure rates of accidents (/yr), EV Expected loss of life per year Cumulative area under F-N (Frequency vs. Number of Human Fatality) curve used in societal risk.

The three terms in eq. (5) are called the “how factors”, which are referred to as “how bad”, “how risky” and “how variable”, respectively. The scheme of calculation of DF using the three terms has been demonstrated by Goose (1999, 2006). These factors are computed starting from the following values: (i) the sum of the failure rates, expressed in events per year (ΣFR), (ii) The expectation value (EV) which is also called Potential Loss of Life and represents the average number of casualties expected per year, (iii) The maximum potential fatalities ($N_{max}$), which are the worst-case scenario concerning the number of fatalities for a single event; (iv) The ratio of EV to ΣFR, representing the average number of fatalities per event ($N_{avg}$). The value of DF is necessarily greater than 1 because otherwise it would mean a bias against safety. It is usually less than 10 and should never exceed 30 [Goose (1999), HSE (2019)].

Since DF is always greater than 1.0, the total cost should be more than the sum of calculated direct and indirect benefits value. In general, it may be difficult to obtain exact estimates of cost, and certainly of benefits of implementation of specific safeguards for mitigating risk as the latter needs to include what has been referred to above as “intangible or non-measurable components”.

In the present work, the total benefit ($B_t$) is estimated as DF-times the sum of direct and indirect benefits:

$$B_t = B_d + B_i + B_i \cdot DF$$

(6)

As indicated above, the non-measurable benefits are generally difficult to quantify. For simplicity, and for including the non-measurable benefit component (i.e., $B_{inst}$) in the cost-benefit analysis, it is equated to DF $B_d + B_i$. This is expressed in an equivalent manner by eq. (6). The greater the risk, the greater is the DF. It is to be expected that higher the risks, greater would be the total benefit when appropriate safeguards are implemented in order to reduce risks to a given level. As may be evident from eqn. (6), DF is higher when risk (i.e., accident frequency and/or consequences) are high. Thus, total benefits would then be – in some measure – proportional to the risk, i.e, DF. Eq. (6) indicates that total benefits will increase with DF as non-measurable benefits are high. Hence, even high cost of safeguard may sometimes be justified for reducing loss due to accidents.

In principle however, the application of the SIO proposed in the present work, does not necessarily depend on the inclusion of the non-measurable benefit. The analysis demonstrated through the case study in section 3 below, would remain valid even if only the direct and indirect benefits are estimated and employed; however, the value of the total benefit would be lesser in magnitude than that computed using eq. (8) below, which incorporates the non-health and safety benefits.

As mentioned above, for calculating the overall benefits, one needs to also account for human fatalities that may be simultaneously averted by implementing a particular safeguard. Monetary value of human deaths averted can be calculated using ‘Value of Statistical Life’ (VSL), i.e., the economic value of human life (Madheswaran, 2007). Number of expected deaths is calculated by integrating the product of individual risk and population density throughout area of exposure. The parameter “Deaths averted” is the difference between the number of expected deaths before and after implementing safeguard. Multiplying this value with VSL gives the value of corresponding benefits. This is surmised by eqn. (7).

$$\Delta = \int_A f \cdot PF_{x,y} \cdot d\gamma$$

$$d\gamma \cdot d\alpha \cdot VSL$$

(7)

where: f Frequency of accident

$PF_{x,y}$ Probability of fatality at point $(x,y)$

$d\gamma$ Population density at point $(x,y)$

$d\alpha$ Differential area
Various methods to calculate VSL are suggested in the literature (Franks et al., 2002). Nevertheless, use of VSL remains controversial as it is debatable whether assigning monetary value to a life is morally defensible or not. On inclusion of all the components of benefits discussed above, the total expected benefit is given by:

\[ B_i = \Delta P_i \sum_{j=1}^{n} \left( L_{0,i} - L_{1,i} \right) \int_{A}^{B} \frac{PF_{x,y} d_{x,y}}{1 - r^j} \text{ VSL} \, dA \, f_0 \, DF_0 \]

\[ \sum_{j=1}^{n} \left( L_{0,i} - L_{1,i} \right) \int_{A}^{B} \frac{PF_{x,y} d_{x,y}}{1 - r^j} \text{ VSL} \, dA \, f_1 \, DF_1 \]

(8)

\[ L_{0,i} \] Estimated direct losses without safeguard (excluding insurance covered losses); \( L_{0,i} \) Estimated indirect losses without safeguard (excluding insurance-Covered losses); \( PF_{x,y} \) Probability of fatality at location \((x, y)\) without safeguard; \( f_0 \) Frequency of accident without safeguard; \( M \) Plant life (in years); \( \Delta P_i \) Reduction in insurance premium (due to implementation of safeguard), \( DF_0 \) is the disproportion factor in absence of the safeguard. Subscript ‘1’ denotes the value of all the concerned parameters that obtain on implementing the safeguard.

The various terms in eq. (8) may be paraphrased as follows. Installation of a safeguard is expected to reduce the risk of an accident and hence would logically command a reduction in the concerned insurance premium to be paid. This aspect is reflected by the first term \( \Delta P_i \). Next the terms \( L_{0,i} \) and \( L_{1,i} \) stand for direct and indirect losses associated with the accident and hence represent “cost” terms. As also explained above, the term \( \int_{A}^{B} \left( PF_{x,y} d_{x,y} / 1 - r^j \right) \text{ VSL} \, dA \) is an estimate of the expected cost of human fatalities due to the accident obtained through a product of the expected number of fatalities over a given area “A” and a representative Value of Statistical Life (VSL). The sum total of the accident cost is multiplied by accident frequency “f” and to yield the expected accident cost. The expected cost when multiplied with the disproportion factor \( DF \) leads to an estimate of the total benefit. The second and third terms of eq. (8) together represent the difference of the net benefit without and with the particular safeguard; this difference is expected to be positive, as the expected total cost of the accident in presence of the safeguard will be lower than that in its absence.

Direct losses include property damage, immediate medical expenses, and any other related penalties. Indirect losses will include capacity lost, business interruption loss, loss of work time, new recruitment and training cost etc. It may be noted that frequency of the accident is reported in per annum units; hence, as shown in eq. (8), there is a need for discounting it. Once costs and benefits are estimated using eqs. (3) and (8) respectively, these can readily be used in the cost-effectiveness analysis (CEA) algorithm which is described in next section.

2.5. Algorithm for CEA

As mentioned earlier, each accident scenario screened during the application of the pro-sided SIO may, in principle, be mitigated by using multiple, competing safeguards or combination of safeguards. Once all of the possible safeguards for controlling a particular risk source have been identified (say, using HAZOP) the corresponding costs and benefits may be computed (eqs. (3) and (6)). One may then use a suitable computer algorithm to select the most cost-effective safeguard or a combination thereof simultaneously across all risk sources screened in the first step of the SIO framework.

The computer program developed for CEA in the present work is based on the well-known algorithm employed for the “Knapsack Problem” (Singh, 2014). Knapsack is the name of the function used in the computer program. The program essentially maximizes total benefit across all risk sources subject to a pre-defined, fixed investment budget.
derive from a HAZOP study that has to be conducted at the primary stage of the SIO application. For the purpose of present illustration, we assume here that three different safeguards can be used to mitigate scenario 2 (i.e., S21, S22, S23, where Sj represents to jth safeguard for ith scenario); while two different safeguards (S31, S32) are available for mitigation of scenario 3. The net present value of cost of each safeguard are assigned a set of values (Table 3), and are to be regarded as representative for the present purpose. Table 3 also shows the extent as well as the nature of mitigation obtained by implementing each safeguard. Once more the allocated values are assigned arbitrarily; though, in principle, all these parameters may be estimated from actual scenario and relevant data.

For reducing total IR, various possible combinations of safeguards are considered feasible. Six possible options are shown in Table 4 along with the total costs and the consequent IR at the plant boundary. From the total IR values reported in Table 4, it may be evident that combinations S22, S31, or S23, S31 should be appropriate for the given situation as these reduce the total public IR to less than 10^{-6} yr. However, the more economical of the two combinations is that of S22, S31 costing $15,000; hence this combination of safeguards may be implemented to achieve regulatory compliance. This procedure essentially completes the first phase of application of the SIO.

The next step is to choose the appropriate insurance cover for the residual risks. This analysis can, in principle, be carried out with help of the approaches mentioned in section 2.3. However, presently for the purpose of illustration, we assume that an insurance policy worth $50,000 is bought by comparing the risk transferred to insurer and the cost of insurance premiums. It may be noted that such an insurance cover need be procured to manage the risks unattended to at the end of the foregoing exercise of aligning the plant boundary risk with local regulations.

At this point, an outstanding amount of $35,000 ($100,000 - $15,000-$50,000) is still available for investing into additional safety measures across all residual risks of relevant sources. As argued earlier in section 2.4, this step of the SIO process is essentially based on considerations that any investment at this point may be sought only if the probable benefits outweigh the safeguard costs. In continuation with Table 3, Table 5 enlists a set of values of safeguard costs for the four scenarios assumed for illustrating the attendant cost-benefit analysis as suggested by the present SIO framework. It is to be noted that S22 and S31 have already been chosen earlier to be implemented in order to comply with regulatory requirement; hence they are not considered in the cost matrix of Table 5.

We demonstrate below the suggested decision-making procedure based on the calculation of the benefit to cost ratio for the example case of implementation of safeguard associated with scenario 1 which has not been considered earlier, and hence constitutes a residual risk.

We assume that the cost of buying the specific safeguard S1 is $7700 and maintenance cost is $200 per annum, while the discounting factor is assumed to be 5%.

![Algorithm for cost-effective optimization of safety investment.](image-url)

**Table 1**
List of selected incidents.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Installation</th>
<th>Containment</th>
<th>Frequency (/yr)</th>
<th>Total capacity</th>
<th>Scenario description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Atmospheric tank</td>
<td>Octane (highly flammable liquid)</td>
<td>1.0 \times 10^{-7}</td>
<td>4200 MT</td>
<td>Formation of vapour cloud which is ignited resulting VCE involving 1200 MT</td>
</tr>
<tr>
<td>2</td>
<td>Double walled dome roof tank</td>
<td>Ammonia (liquefied toxic gas)</td>
<td>4.0 \times 10^{-6}</td>
<td>10,000 MT</td>
<td>Release of 50 MT toxic vapour from 20.0 m height</td>
</tr>
<tr>
<td>3</td>
<td>Tonner</td>
<td>Chlorine (liquefied toxic gas)</td>
<td>4.0 \times 10^{-6}</td>
<td>1 MT</td>
<td>Catastrophic rupture releasing 1.0 MT Chlorine</td>
</tr>
<tr>
<td>4</td>
<td>LPG Bullet</td>
<td>Butane (LPG)</td>
<td>1.0 \times 10^{-5}</td>
<td>30 MT</td>
<td>BLEVE involving 25 MT of LPG</td>
</tr>
</tbody>
</table>
Table 2
IR contribution of scenario at plant boundary.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>IR at 750 m</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>S21</td>
<td>5000</td>
<td>9.9 $10^8$</td>
<td>3.2 $10^6$</td>
<td>1.5 $10^6$</td>
<td>1.7 $10^6$</td>
</tr>
<tr>
<td>S22</td>
<td>10,000</td>
<td>9.9 $10^8$</td>
<td>3.2 $10^6$</td>
<td>1.5 $10^6$</td>
<td>1.7 $10^6$</td>
</tr>
<tr>
<td>S23</td>
<td>20,000</td>
<td>9.9 $10^8$</td>
<td>3.2 $10^6$</td>
<td>1.5 $10^6$</td>
<td>1.7 $10^6$</td>
</tr>
<tr>
<td>S31</td>
<td>5000</td>
<td>9.9 $10^8$</td>
<td>3.2 $10^6$</td>
<td>1.5 $10^6$</td>
<td>1.7 $10^6$</td>
</tr>
<tr>
<td>S32</td>
<td>8000</td>
<td>9.9 $10^8$</td>
<td>3.2 $10^6$</td>
<td>1.5 $10^6$</td>
<td>1.7 $10^6$</td>
</tr>
</tbody>
</table>

Table 3
Total IR at plant boundary after implementing safeguards.

<table>
<thead>
<tr>
<th>Safeguard</th>
<th>Safeguard Cost ($)</th>
<th>Mitigation measure</th>
<th>Total IR at r 750 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>S21</td>
<td>5000</td>
<td>Frequency reduction by one-fourth</td>
<td>2.4 $10^6$</td>
</tr>
<tr>
<td>S22</td>
<td>10,000</td>
<td>Frequency reduction by one-fourth</td>
<td>2.0 $10^6$</td>
</tr>
<tr>
<td>S23</td>
<td>20,000</td>
<td>Ammonia release limited to 35.0 MT</td>
<td>1.7 $10^6$</td>
</tr>
<tr>
<td>S31</td>
<td>5000</td>
<td>Frequency reduction by one-third</td>
<td>3.9 $10^6$</td>
</tr>
<tr>
<td>S32</td>
<td>8000</td>
<td>Chlorine release limited to 0.5 MT</td>
<td>4.6 $10^6$</td>
</tr>
</tbody>
</table>

Table 4
Total IR at plant boundary after implementing safeguards.

<table>
<thead>
<tr>
<th>Safeguard</th>
<th>S21</th>
<th>S22</th>
<th>S23</th>
<th>S31</th>
<th>S32</th>
<th>S33</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost ($/yr)</td>
<td>10,000</td>
<td>15,000</td>
<td>25,000</td>
<td>33,000</td>
<td>18,000</td>
<td>28,000</td>
</tr>
</tbody>
</table>

Total IR at r 750 m

<table>
<thead>
<tr>
<th>Scenario</th>
<th>S21</th>
<th>S22</th>
<th>S23</th>
<th>S31</th>
<th>S32</th>
<th>S33</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4 $10^6$</td>
<td>9.5 $10^7$</td>
<td>7.2 $10^7$</td>
<td>3.9 $10^6$</td>
<td>3.9 $10^6$</td>
<td>3.9 $10^6$</td>
</tr>
</tbody>
</table>

Table 5
Cost ($) matrix.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Safeguard 1</th>
<th>Safeguard 2</th>
<th>Safeguard 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10,000</td>
<td>5000</td>
<td>3000</td>
</tr>
<tr>
<td>2</td>
<td>5000</td>
<td>-</td>
<td>20,000</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>8000</td>
<td>10,000</td>
</tr>
<tr>
<td>4</td>
<td>30,000</td>
<td>50,000</td>
<td>40,000</td>
</tr>
</tbody>
</table>

Total Safeguard Cost (USD)

\[
7700 \sum_{i=1}^{31} \frac{200}{0.05} \approx 10000
\]

It may be noted that the above safeguard cost corresponds to the first element of the cost matrix in Table 5.

In principle, the total direct and indirect losses (which have already been defined following eq. (8)) from the accident from risk source 1 can be estimated based on plant design and relevant operational details using techniques of quantitative risk analysis amongst others (AIChE, 1989); however, for the present work the following illustrative values are assumed:

Direct losses $20 M USD;
Indirect losses $30 M USD (not covered through insurance)

Additionally, a representative VSL amounting to $0.25 M is fixed (Madheswaran, 2007). Further we consider that no reduction in insurance premium (PI) is available for this safeguard option as the insurance cover has been purchased for other risks; accordingly, \( \Delta P I \) 0 (which is determined by insurer and market conditions). Lastly, the implementation of safeguard 1 is assumed to reduce the accident 1’ frequency by a factor of 1/5.

As part of calculation of benefits, DF needs to be estimated. Prior to that, the societal risk curve, i.e., the cumulative frequency (F) versus number of fatalities (N) plot (AIChE, 1989), is prepared using the corresponding data presented in Table 6. The resultant plot is shown in Fig. 4.

To calculate expected loss of life (EV), area under the F-N curve is needed. This is calculated by integrating the product of probability of fatality and population density throughout area of exposure as shown in equation (13).

Table 6
Cumulative frequency versus number of fatalities.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Frequency (/yr)</th>
<th>Number of Fatalities (N)</th>
<th>Cumulative Frequency (/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0 $10^7$</td>
<td>200</td>
<td>1.0 $10^7$</td>
</tr>
<tr>
<td>2</td>
<td>4.0 $10^6$</td>
<td>198</td>
<td>4.1 $10^6$</td>
</tr>
<tr>
<td>3</td>
<td>4.0 $10^4$</td>
<td>61</td>
<td>4.041 $10^4$</td>
</tr>
<tr>
<td>4</td>
<td>1.0 $10^5$</td>
<td>31</td>
<td>4.141 $10^4$</td>
</tr>
</tbody>
</table>
Fig. 4. F–N curve for Disproportion Factor Calculation.

\[ N_i \int_{A_i} PF_{x,y} dA_i \]  
(13)

Number of fatalities \((N_i)\) along with its corresponding frequency is computed using eqn. (13) and the resulting numbers tabulated in Table 6; finally, the F–N curve is plotted using the tabulated data (Fig. 4).

- \(F_N\): Number of fatalities for all accident outcome case ‘\(i\)’ for which \(N_i > N\)
- \(PF_{(x,y)}\): Probability of fatality at point \((x,y)\) due to accident outcome case ‘\(i\)’.
- \(d_{(x,y)}\): Population density at point \((x,y)\) based on assumed grid size.
- \(dA_i\): Differential area affected by accident outcome case ‘\(i\)’.
- \(F_N\): Frequency of all incident outcome cases affecting \(N\) or more people
- \(F_i\): Frequency of incident outcome case ‘\(i\)’.
- \(N_i\): Number of people facing fatality from incident ‘\(i\)’.

The expected number of deaths from scenario ‘1’ is thus: \(\int IR r d_i\).  

\(2 \times \pi r d_{i} 2 \times 10^{-5}\), where \(d_{i}\) is the population density corresponding to the location grid.

The DF value is next calculated using eqn. (6) for which the numerical values of the associated parameters are as follows:

\[\sum_{Q} FR\] Sum of failure rates, expressed in events per year  
0.0004141

\(EV\) Area under the F–N curve (Fig. 4) 0.023
\(N_{max}\) 200 (from scenario 1)
\(N_{av}\) \(EV/\sum_{Q} FR\) 55

Thus, DF \(\log(55) \log(2300) \log(200/55)\) 3 \(8.66\)

Expected loss without the safeguard \(S_{11}\) is estimated using the first term in square bracket in eqn. 8, (i.e., in absence of the safeguard) as:

\[\sum_{i=1}^{20} 4.8 \times 10^{-6} - 2.0 \times 10^{-1} - 3.0 \times 10^{-2} - 2.0 \times 10^{-5} - 2.5 \times 10^{-6} \times 0.05^{-5}\]

\[\sum_{r} 2822 \]

2822

With a frequency reduction to 1/5 of the original value, the expected monetary loss with safeguard \(S_{11}\) is \(2822/5\) $564. Since the frequency of the accident is reduced with the safeguard, the DF needs to be recalculated in the same manner as outlined above. However, as may be easily demonstrated, the value of DF remains practically unchanged. Using equation (8), the net total benefit is 0 $2822 564 8.66 $19,550.

In principle, the benefits associated with each of the safeguard corresponding to the other risk scenarios can be calculated similarly. A set of representative values is indicated in Table 7 in way of illustration. While the benefit accruing from implementation of safeguard \(S_{11}\) is shown as \$19,550 (as obtained from foregoing calculation) the other benefit values are assigned arbitrary values. Once more (as in Table 5 of cost matrix), since \(S_{22}\) and \(S_{31}\) already have been implemented in the earlier phase of SIO, they are not considered in the benefit matrix, i.e., Table 7.

One can now enter the cost and benefit values for all the safeguards in Tables 5 and 7 in the CEA (Knapsack) program assuming a constrained investment budget of $35,000. The result of such a run shows that a combination of \(S_{22} S_{33} S_{31}\) yields the maximum benefit of $189,250 with the corresponding benefit/cost ratio of 5.40 which is highest amongst all possible values. This essentially completes the application of the SIO methodology as the entire safety budget is utilized fully and no further investment in additional safeguard for mitigation of residual scenarios is possible.

The overall SIO is essentially similar to the classical optimization problem in which the extremum of an objective function is sought subject to constraints. In the present method the optimized function is a ratio of total “Benefit” \((B_i)\) to total “Cost” \((C_i)\) associated with the implementation of a single or a combination of safeguards subject to the constraint of the quantum of available safety investment fund. This is illustrated in the overall safety investment optimization framework presented in Fig. 1. The final optimization for obtaining the most cost-effective, i.e., the least costly, combination of safeguards for a particular risk scenario is carried out using the optimizer “Knapsack” program.

4. Conclusions

Investment into safety can affect organizational business performance in significant manner. It is, therefore important to allocate monetary resources across various risk sources in a manner such that it saves future cost by avoiding accident. While several research papers have reported such an effort, none of them can be conveniently adopted to arrive at a comprehensive solution to plant-wide safety investment optimization in order to mitigate all identified, credible accident scenarios. Besides, the need for regulatory compliance at the same time is not also addressed in the approaches reported so far. The safety investment optimization framework proposed in the present work attempts to address these specific lacunae. It first suggests an approach to reduce the public individual risk at the plant boundary to within regulatory limits based on a quantitative risk assessment (QRA). Thereafter, an analysis for selection of appropriate insurance policy is carried out for residual risks leading to a transfer of the risk to insurer. Once an appropriate insurance policy is selected, the problem effectively translates into a business-decision in which the aim is to secure the best return on safety investment through a probabilistic cost-benefit analysis across all possible combination of available safeguards not considered in the

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Safeguard-1</th>
<th>Safeguard-2</th>
<th>Safeguard-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>19,550</td>
<td>12,800</td>
<td>8000</td>
</tr>
<tr>
<td>2</td>
<td>42,850</td>
<td>–</td>
<td>87,400</td>
</tr>
<tr>
<td>3</td>
<td>–</td>
<td>7300</td>
<td>59,000</td>
</tr>
<tr>
<td>4</td>
<td>90,000</td>
<td>125,000</td>
<td>80,000</td>
</tr>
</tbody>
</table>
earlier phases of the investment exercise. A simplified case study has been presented in way of illustrating the approach to application of the proposed SIO method. The case study is based on a process plant with a select list of four risk sources. The first layer of QRA computations shows that the public IR exceeds the tolerable limit. The SIO thus suggests the most cost-effective combination of safeguards that ensure regulatory compliance. The case study next illustrates the choice of an insurance cover for mitigating the residual risk. Thereafter, based on the availability of additional safety budget, a cost-benefit analysis over the residual safeguards applicable across the various probable accident scenarios is demonstrated. This leads to the identification of the combination of safeguards that secure the maximum expected benefit to the organization. In essence this step allows the organization to move beyond mere regulatory compliance. In the process of reducing risk further through targeted investments the organization is able to secure the best return on such investments.

The case study has relied on relevant parametric values that are partly sourced from literature and through personal communication with industry professionals, and are partly assumed. It is argued that the optimality of safety investment allocation is likely to be significantly influenced by true values of as well as variations in the magnitude of the critical parameters. These, for example, include accident consequences and frequencies, cost and effectiveness of safeguards, and value of human life. The various parametric assumptions employed in this work notwithstanding, it is expected that the approach adopted will provide a conceptual aid to the critical problem of safety investment which as of today is largely empirical, and is founded on experience and judgment of the decision-makers. In the future, some extensions of the present work may be undertaken. For instance, the proposed framework takes value of statistical life (VSL) into consideration while calculating benefit. However, as depicted in case study, its contribution to the total benefit is relatively small, and it does not seem to impact most of the investment decision irrespective of number of likely human fatalities. Methodologically, it is useful to include VSL, but realistically, further work is needed to integrate value of life in framework in a more justified manner. Further, currently, the method for allocation of pre-defined safety budget has been presented. However, further work may be undertaken to derive a solution to the reverse problem, i.e., the estimation of the optimum amount of safety investment needed for an enterprise.

CRediT authorship contribution statement

Sandip Roy: Conceptualization, Methodology, Software, Writing - original draft, Visualization, Investigation, Software, Validation, Writing - review & editing. Ankit Gupta: Conceptualization, Methodology, Software, Writing - original draft, Visualization, Investigation, Software, Validation.

References


