Journal of Hazardous Materials 182 (2010) 416–426

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

A new method for assessing domino effect in chemical process industry

Bahman Abdolhamidzadeh[a], Tasneem Abbasi[b], D. Rashtchian[a], S.A. Abbasi[b,*]

[a] Center for Process Design, Safety and Loss Prevention, Department of Chemical and Petroleum Engineering, Sharif University of Technology, Tehran, Iran
[b] Center for Pollution Control and Environmental Engineering, Pondicherry University, Kalapet, Pondicherry 605014, India

ARTICLE INFO

Article history:
Received 11 January 2010
Received in revised form 11 June 2010
Accepted 12 June 2010
Available online 18 June 2010

Keywords:
Accidents
Domino effect
Risk assessment
Process industry
Petrochemical

ABSTRACT

A new methodology is presented with which the likely impact of accident in one process unit of an industry on other process units can be forecast and assessed. The methodology is based on Monte Carlo Simulation and overcomes the limitations of analytical methods, used hitherto, which were inherently limited in their ability to handle the uncertainty and the complexity associated with domino effect phenomena. The methodology has been validated and its applicability has been demonstrated with two case studies.

1. Introduction

Major advances have occurred in process safety science and engineering in recent decades. Each major accident galvanizes the world's scientific community to renew its efforts towards accident prevention. But, whereas rapid strides have been made in the forecasting, consequence assessment, and control of stand-alone events, much less attention has been paid towards knock-on accidents or 'domino effect' wherein one accident in a process unit becomes the cause of another (and at times yet another and still other) accident. But domino effect is not an infrequent occurrence; indeed a large number of major accidents have led to great losses of life and property due to this effect. This is brought out by an inventory made recently by the authors [1] as well as earlier reports by others [2–6]. Some of the more disturbing findings of the author's past accident analysis (PAA) vis a vis domino effect are [1]:

(a) Nearly half of all chain of accidents go beyond the second stage, i.e., the secondary accident causes a tertiary accident. At times, still higher order accidents are caused.
(b) The frequency of domino events, i.e. number of such accidents occurring per year, is increasing. More significantly there is a rising trend in the number of fatalities per domino event.

The reasons behind these trends are not hard to find. With rising population and consequent pressure on availability of land, ever larger number of industries comes to be situated cheek by jowl in industrial complexes, especially in developing countries. For example the 'Manali Industrial complex', about 11 km north of downtown Chennai, India, has a major refinery and scores of downstream petrochemical industries situated one after another in an area of 2.5 km^2. The petrochemical zones at Mahshahr and Asalouyeh in Iran similarly have large industrial clusters. Indeed these types of formations are becoming increasingly common throughout the world, especially so in developing countries.

Even when hazardous industries are located well away from populous areas commercial activity, boosted by the industry, soon leads to development of shops and residential dwellings close to the industry. There is a resultant improvement in infrastructure and appreciation of real estate in areas close to the industry which further stimulates population growth close to the industry. The third factor contributing to a rise in the frequency as well as damage potential of domino events is the increasing number of hazardous chemicals and processes being used across the world with ever larger inventories.

We have tried to determine the nature of the rising trends from the inventory presented by [1] – in the frequency of occurrence of domino event and in the fatality caused per event – and find that these fit not linear curves but power curves. It follows that much greater attention ought to be paid to the risk assessment of domino events than has been paid hitherto, notwithstanding the inherent complexity associated with this issue, and consequently the difficulty in addressing it.

* Corresponding author. Tel.: +91 413 2655263; fax: +91 94432 65262; mobile: +91 94432 65262.
E-mail address: prof.s.a.abbasi@gmail.com (S.A. Abbasi).

0304-3894/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2010.06.049

1.1. Domino effect

It may be pertinent to define 'domino effect' before describing the proposed methodology of assessing it.

The term 'domino effect' has its origins in the game of domino toppling; a domino being a small, flat block, often of wood, marked on one side with two groups of dots representing numbers [7]. If several dominos are arranged in a manner that every falling domino would hit the one placed next to it, and if the domino at the head of the array is made to fall, it may trigger a chain of collapsing dominos with each falling domino toppling the one standing next to it. Hence, in its simplistic sense 'domino effect' means 'one thing leading to another'. In earlier days process safety scientists used the term in this sense to denote cause-effect sequence leading to accidents. For example H.W. Heinrich in 1929 had proposed a 'domino effect technique' based on five labeled 'dominos': lack of control of management, basic causes, symptoms, incident, and loss of lives/property [8]. Each domino represented one event and the technique involved 'lining up' a row of dominoes representing a sequence of events leading to the accident. If all dominoes were to fall one after another the accident was going to occur but if any domino in the sequence was removed, no injury or loss was to ensue.

Later, by-and-by, 'domino effect' came to be used to describe 'knock-on' accidents, or situations wherein one accident becomes a trigger for one or more other accidents. But there are several issues of time, space, proportion, and scale associated with domino effect in process industries due to which a rigorous definition is needed to facilitate development of treatment and control methods.

One of the earliest definitions is due to Lees [9] as per which domino effect represents: a factor to take account of the hazard that can occur if leakage of a hazardous material can lead to the escalation of the incident, e.g. a small leak which catches fire and damages by flame impingement a larger pipe or vessel with subsequent spillage of a large inventory of hazardous material.

It is noteworthy that this definition does not specify that a series of process industry accidents will qualify for the label of 'domino effect' only if they involve separate plant units. But several subsequent definitions do. For example, according to Bagster and Pitblado [10]: *Domino effect is a loss of containment of a plant item which results from a serious incident on a nearby plant unit*. The Advisory Committee on Major Hazards (1984) has given two definitions: *The effects of major accidents on other plants on the site or nearby sites*, and *A loss of containment incident which interferes with the operation of other adjacent plants so that further loss of containment occurs* [11].

Gledhill and Lines [12] have proposed the following definition in terms of the regulations of the European Union's Committee on Control of Major Hazards (COMAH): *A domino event is defined as a loss of containment incident on a major hazard installation which has resulted either directly or indirectly from a loss of containment incident at an adjacent or nearby major hazard installation. The two events must occur either concurrently or in close sequence and the hazard range from the domino event must extend beyond that of the initiating event*. This definition builds upon the Article 8 of COMAH regulation, which is also called 'Seveso II Directive' in which *domino effect* is used to denote *establishments or groups of establishments where the likelihood and the possibility or consequences of a major accident may be increased because of the location and the proximity of such establishments, and their inventories of dangerous substances"*. Some authors within the European Union interpret this definition as being applicable only to situations wherein a loss of containment accident in an industry becomes the cause of a loss of containment accident in another industry. They then distinguish knock-on accidents in different process units of the same industry with the term 'internal domino effect'. But this interpretation isn't consistently followed even within the EU [1], and several scientists, for example Cozanni and coworkers [13,14] and Delvosalle and coworkers [15,16] use domino effect as applicable to even knock-on accidents which occur within an industry.

All the definitions recounted above, except the one by Lees [9], create the impression that if an accident in one part of a plant item–say a pipeline rupture leading to a flammable vapour cloud–causes failure of another part, in turn leading to yet another component failure; it will be outside the purview of domino effect. The most recent definition by the Centre of Chemical Process Safety [17], leaves the issue rather open by defining domino effect as *an incident which starts in one item and may affect nearby items by thermal, blast or fragment impact, causing an increase in consequence severity or in failure frequencies*.

In the treatment described in this paper we have dealt with domino effect in the sense in which it has been defined by Lees [9], Bagster and Pitblado [10], and CCPS [17], but in a separate study [1] we have proposed the concept of 'local domino effect' to deal with chain of accidents occurring within a process unit.

2. Past attempts at assessing the likelihood and possible impact of domino effect

The fact that a fire or an explosion in one hazardous unit can jeopardize other units has always been realized and safety codes exist to prevent escalation. Such codes are reviewed, too, from time to time, especially with reference to fire and explosion hazards [18,19]. But in quantitative risk assessments (QRA) normally done for industrial installations, domino effect is either not considered at all [20] or is done with much less rigour than is warranted by past accident analysis.

The situation is poignantly reflected from the fact that the highly respected and arguably the most frequently referred of all compendia on risk assessment – the *magnum opus* of Lees [21,22], has just a small section on domino effects, encompassing less than 2 pages of the multi-volume treatise. Even the latest (2005) edition of the compendium refers to only one treatment of domino effect, that of Bagster and Pitblado [10]. The other oft-used manual on QRA of CCPS [17] also contains similarly small passage on domino effect. The 'colour books' brought out by TNO (The Netherlands Organization of Applied Scientific Research) on behalf of the EU's Committee for the Prevention of Disasters [23–26] (van den Bosch and Weterings, 1997; CPR, 1999) have exceedingly valuable information on various aspects of risk assessment but nothing at all on domino effect!

One of the earliest and also, perhaps, the most comprehensive study of domino effect is embodied in the Canvey reports [27,28]. In the backdrop of a proposal to construct an additional refinery on Canvey Island, UK, it was decided to investigate and determine the overall risks to health and safety arising from any possible major interactions between existing or proposed installations in the area. The investigators considered several scenarios of some accident setting off further accidents but, interestingly, the term 'domino effect' has not been used prominently in the Canvey Reports. The treatment of knock-on accidents in the reports was based on the premise that the frequency of occurrence of an accident is enhanced by domino effect due to the superimposition of the frequency of failure caused by another accident on the normal failure frequency of a unit.

Thirteen years later, Bagster and Pitblado [10] used data from the Canvey reports to set up a procedure for the treatment of domino effect, based on two premises:

(i) Domino effect increases the consequences of a given incident at fixed frequency (modifies the outcome in an event tree context).

(ii) Domino effect increases the failure frequency of a given incident at fixed consequences (acts as an external event in a fault tree context).

After another long gap in time, Khan and Abbasi [29] synthesized the available knowledge to develop a framework of models for domino effect analysis (DEA). They also evolved a 'DEA procedure', coded it [30], and demonstrated its application to several real-life situations [3,4,31,32]. The DEA has two levels of study; in the level-I study, units are identified within the context of specific industrial lay-out which are, within the realms of credibility, likely to meet with an accident that has the potential to jeopardize one or more other units. In the Level-II study the consequences of the likely accidents are assessed, including the probability of the accident in the 'victim' unit causing further accidents. The methodology continues to be utilized [20,33]. In parallel with Khan and Abbasi [29,30]; Delvosalle and coworkers [16,34] have also reported a methodology which had elements of similarity with the approach of Khan and Abbasi.

In recent years Cozzani and co-workers [13,14,34,35] have built upon the work of the previous authors, bringing in refinements and generating new insights. In a recent study by Reniers et al. [35] a game-theoretical approach has been used to explore the behavior of different industries towards investing in domino effect prevention. It is an interesting and useful study but does not address the issue of forecasting domino effect or assessing its possible impact.

2.1. Analytical formulations and their inherent limitations

There is a common thread which runs through all the past work on DEA: it is based on analytical formulations that were developed to estimate domino effect frequencies, in order to eventually calculate the probabilities of the desired combinations. The basics are common to all of the methods and are explained below:

Any piece of equipment in a complex plant can fail due to the malfunctioning of a process (runaway reaction, overpressure development) or internal defects (corrosion or fatigue). It may also fail due to the impact of escalation vectors (heat load, overpressure or missile impact) from accidents in other neighboring equipment. In probability terms:

$$f_{f,i} = f_f(\text{single equipment}) + f_f(\text{domino failure}) \quad (1)$$

where f_f (single equipment) is the expected frequency of failure of a single equipment, i (event/year) and can be obtained as generic data or can be calculated using conventional fault-tree methods. To it is added frequency of failure due to domino effect; frequency of damage due to a domino effect can be expressed as:

$$f_f(\text{domino failure}) = \text{Prob}_{\text{escalation}} \cap f_{\text{primary}} \quad (2)$$

where f_{primary} is the frequency of the primary event occurrence (event/year) and $\text{Prob}_{\text{escalation}}$ is the probability of escalation given the primary event. For a domino accident to occur, both the occurrence of a primary accident and an escalation vectors are needed. If these two events are assumed to be independent then the joint probability can be expressed as:

$$f_f(\text{domino failure}) = \text{Prob}_{\text{escalation}} \times f_{\text{primary}} \quad (3)$$

However, in reality the two events are not independent from each other. Hence, the analytical formulations used in the methods take this error into account. Of the terms in Eq. (3), f_{primary} may be calculated using conventional methods, but estimation of $\text{Prob}_{\text{escalation}}$ poses problems because in complex and congested process plants there might be not one but several neighboring equipment of whose failure may depend on each other and which can all influence the failure probability of the 'victim' unit. Hence the term $\text{Prob}_{\text{escalation}}$ embodies in it a combination of several other terms. The probability relation for a combination of two events (A and B) is:

$$P(A \cup B) = P(A) + P(B) - P(A \cap B) \quad (4)$$

If three events are likely, the relation becomes:

$$P(A \cup B \cup C) = P(A) + P(B) + P(C) - P(A \cap B) - P(A \cap C) - P(B \cap C) + P(A \cap B \cap C) \quad (5)$$

If larger number of contributive events is to be considered, the probability relation would become proportionately more complex. If there are N different escalation vectors which may trigger secondary events, the number of terms in the relevant probability relation would be $2^N - 1$. This means in estimation of $\text{Prob}_{\text{escalation}}$ for a system with 4 interacting equipment (each one with just a single escalation vector affecting 'victim' equipment) 15 terms will have to be considered in the analytical probability formulation. This number rises to 1023 in a typical plant with 10 interacting equipment. This type of a situation is present in almost all of the real process plants in which QRAs are performed. In fact much more complex situations exist in industrial clusters which are common throughout the world.

It is obvious that developing analytical methods using probability rules would be mathematically very cumbersome and time-consuming for complex systems with large number of equipment. Moreover even if a mathematical model can be developed for a complex case, since the quantities involved in these calculations are characterized by very small place values when used in big analytical formulae, round-off errors would be significant and would make the results erroneous.

It may be noted that the complexities mentioned above would arise even when only the first level domino accidents are considered. The complexities would increase greatly if the estimation of $\text{Prob}_{\text{escalation}}$ was to consider the possibility of escalation to second or higher level domino effect. Due to this complexity in several of the existing methods, higher level domino accidents are neglected. But a past accident analysis carried out by the authors covering accidents from 1910 up to the present [1], reveals that nearly half of all domino accidents proceed beyond the first 'victim' unit. Hence ignoring higher level domino effects is not an acceptable logical simplification and may actually lead to incorrect risk perception.

It would, thus, appear that use of analytical methods to estimate domino frequencies in situations where a large number of units may play a role in initiating and sustaining chains of accidents is fraught with complexity as well as imprecision. But such situations are very common. Hence an alternative approach has been attempted as described in the following sections.

3. A novel approach for the estimation of domino frequencies based on Monte Carlo Simulation

The technique of simulation is based on attempts at imitating a real-life system to reach solutions, especially when an analytical treatment is either not possible due to major gaps in the understanding of the system behavior, or is mathematically too complex.

One of the simulation techniques that has had a great impact in many different fields of computational science is Monte Carlo Simulation (MCS). The term was coined by Ulam and Metropolis in reference to games of chance, which is the main tourist attraction in Monte Carlo, Monaco [36].

MCS enables iterative evaluation of a system using sets of random numbers as inputs. The method is often used for systems which are highly complex, non-linear, or involve more than just a few uncertain parameters. MCS works particularly well when the process is one where the underlying probabilities are known but their interaction is difficult to determine [37,38].

These authors believe that the nature of domino effect phenomena, as it is defined in the context of accidents in chemical process industry, makes itself amenable to treatment by MCS. As can be seen in the previous section, two types of probabilities in domino frequency estimation are required. The first type (which can be defined for every equipment), is the probability of equipment playing a role as initiator in a chain of accidents. This figure is the 'primary accident probability' and can be obtained by performing an event tree analysis or/and a fault tree analysis. Alternatively it can be deduced from generic data [21]. The second type of probability needed for domino effect analysis is the escalation probability. Every primary accident may generate some escalation vectors such as heat load (radiation), overpressure and missiles projection whose impact may trigger a chain of accidents. The probability of this escalation can be estimated from probit models [39]. Estimating domino frequencies involves calculating the combination(s) of both types of probabilities according to different credible scenarios. The calculated probabilities are the inputs to the model. As explained earlier, due to the complexity involved in estimating domino effect frequencies, an analytical model may become extremely complex and a number of uncertain input parameters may be introduced. Therefore MCS is selected among all other options to estimate domino effect frequencies.

In summary the authors wish to exploit the following two advantages of MCS compared to analytical methods:

(a) Whereas analytical methods are usually limited only to the expected values, MCS provides a wide range of output parameters including different probability functions.
(b) Whereas the model used in analytical techniques is usually a simplification, especially for complex systems or combinations, the MCS method is independent of how complex the system is.

Until the mid-1990s there was a disadvantage associated with MCS in terms of its need for increasingly greater computer time with each incremental increase in the targeted precision. But with CPUs of greater and greater processing power becoming available at lesser and lesser costs, this disadvantage has ceased to be of serious consequence.

4. The FREEDOM algorithm

The FREEDOM (FREquency Estimation of DOMino accidents) algorithm (Fig. 1) proposed here by the authors, is based on conducting several hypothetical experiments to simulate the actual behavior of a multi-unit system which may experience domino effect. In this context a system is defined as the combination of equipment present in an industrial unit that may or may not influence the failure of each other. The desired outcome is a failure probability (frequency) of each component of this system.

Among the feedback loops in the FREEDOM algorithm (Fig. 1) is an outer loop which operates for the iterations (experiments) which are performed N times. Through one of the inner loops (0 to T_f with fixed time steps) the average lifetime of the equipment is simulated. The algorithm examines each of the equipment in terms of its failure or non-failure. As is obvious, each equipment in its lifetime can experience the failure mode only once. The desired probability is estimated by counting the number of times that failure occurred for any equipment during numerous 'experiments'.

The steps associated with the operation of FREEDOM (Fig. 1) are:

4.1. Step 1: parameter input

Number of equipment (n), failure probabilities ($P_{\text{primary equipment},i}$) for each equipment in isolation, escalation probabilities (P_{ij}), number of iterations (N), time step (Δt) and the final time (T_f) are specified. Parameter *repeat* is a counter and represents the number of iterations; *repeat* is initialized to one.

4.2. Step 2: initialization of the experiment

The *Failmatrix*, which represents the equipment's failure status at each time step, is initialized to zero. This matrix has n columns (for n equipment) and $T_f/\Delta t$ rows (representing the number of time steps in each experiment). To begin every new iteration (*repeat run*), T is set to zero in step 2.

4.3. Step 3: checking for the initiating event

For each time step and each equipment i (which is selected randomly, so as not to have bias for failure of any particular equipment), the probability of failure ($P_{\text{primary equipment},i}$) is compared with a generated random number (r_1).

If $P_{\text{primary equipment},i} > r_1$, equipment ($i$) is considered failed. To keep the record of this failure its related position in the *Failmatrix* (T,i) is changed to 1.

When equipment (i) fails in a specific iteration (a fixed *repeat* value) in step 3, the algorithm enters step 4 invoking an internal loop (the *repeat* value remains constant during this internal loop).

If $P_{\text{primary equipment},i} < r_1$, step 3 continues with picking another equipment randomly. If no equipment fails in step 3, a new time ($T + \Delta t$), is initialized in step 5. Then the algorithm returns to the start of step 3.

4.4. Step 4: checking domino effect - I

The aim of step 4 is to check whether a failed equipment (i) may cause other equipment (j)s to fail or not. For this purpose, the value of P_{ij} (the escalation probability of equipment i on j) is compared with a new random number (r_2). If $P_{ij} > r_2$, the equipment (j) fails as a (domino effect) consequence of the failure of equipment (i). Accordingly, the *Failmatrix* (T,j) takes the value of "one" to record this failure in that specific iteration.

4.5. Step 5: checking domino effect-II

The algorithm proceeds further to check whether all other equipment fail or not in that specific time step (T). If all equipment fail, the iteration is terminated and a new iteration (repeat + 1) starts in step 6. Otherwise, in the same iteration the algorithm goes forward to a new time ($T + \Delta t$). If $T + \Delta t > T_f$, that iteration is terminated and a new iteration (repeat + 1) starts. Else, the algorithm continues to pick another equipment. This newly selected equipment is checked whether it can initiate domino effect or not by repeating step 3 till all equipment have been checked.

4.6. Step 6: record keeping

A *Summatrix* is used to keep up the accumulated results of all the former *Failmatrices* by summing them in each iteration (*Summatrix* = *Summatrix* + *Failmatrix*). The equipment failure probability is estimated by counting the number of failures occurred for any equipment during N experiments (*Summatrix* arrays) divided by the number of experiment (N). This record is kept in the *Summatrix*.

In step 6, it should also be checked whether the number of iterations reach N to terminate the algorithm or continue with it, repeating steps 2–5 up to N times.

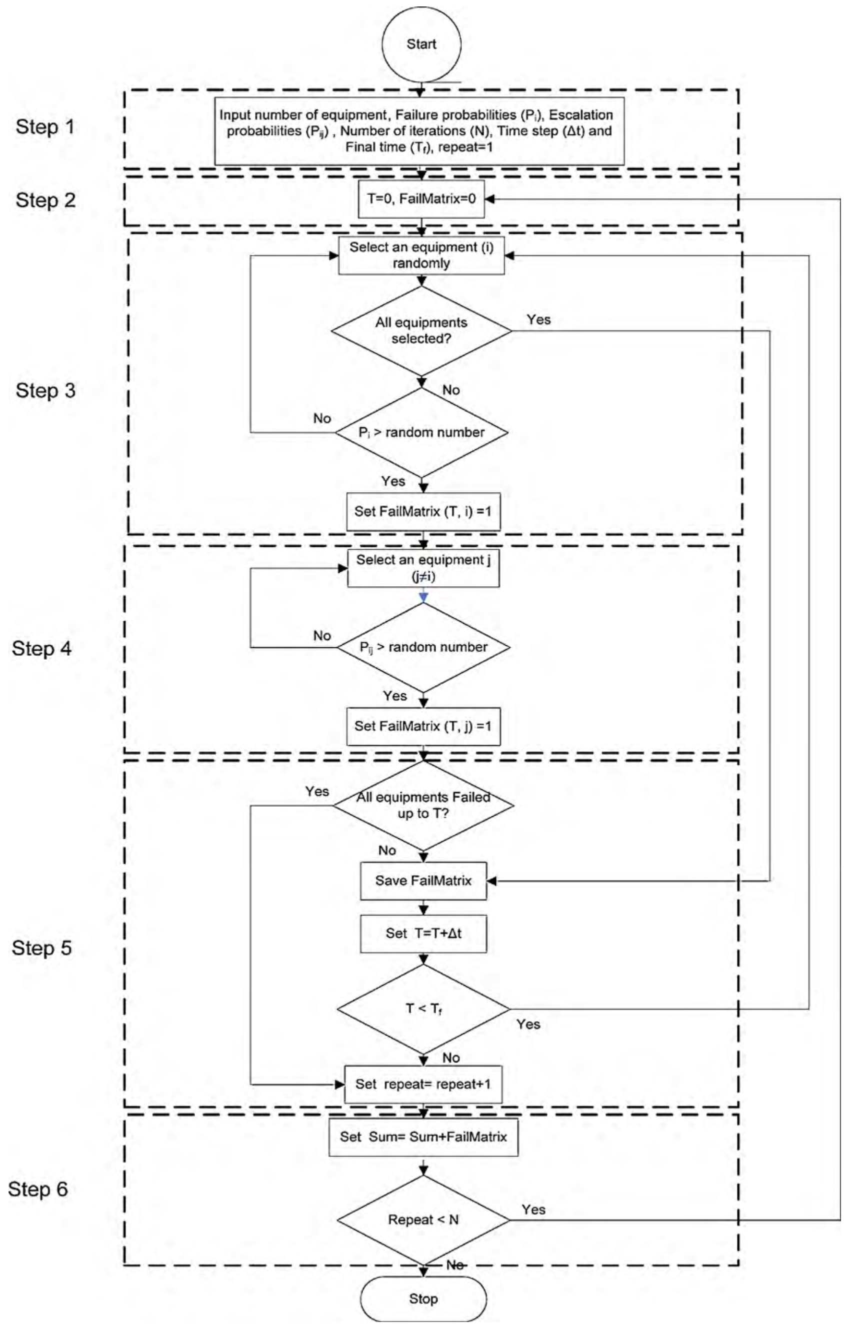

Fig. 1. Flowchart of the algorithm for domino frequency estimation.

It should be noted that an equipment in each iteration (*repeat*) can fail only once. So if in any time interval of an iteration (*repeat*), an equipment fails and its position in *Failmatrix* is changed to one, it drops out of the game for further time intervals of that iteration. Although this delicate constraint is not shown in Fig. 1, it has been considered while developing the code of FREEDOM.

As may be seen, at any time when all components are proved to have failed, the time loop is stopped and a new iteration is started. This considerably reduces the run time of the program. It is also not necessary to save *Failmatrix* for any iteration; the desired 'final *Failmatrix*' is *1/N* of the *Summatrix*. In this way, despite of the highly iterative nature of this algorithm, the computer time is saved.

The main advantage of this algorithm is that it is not constrained by how big or complex the system being simulated is. It is capable of calculating failure probabilities of equipment even in situations which would be too complex for analytical methods.

A software package, also called FREEDOM, has been developed to facilitate the application of the algorithm.

5. Selection of input parameters

The FREEDOM algorithm being highly iterative, the computational time needed in any run is strongly dependent on the number of iterations selected by the user in the initial step of the program execution. Hence the selection of the number of iterations has to be done with care. Whereas an insufficient number of iterations may lead to incorrect results, excessively large number of iterations may increase the processing time without concomitant improvement in the accuracy of the results.

Table 1
Storage characteristics, inventory, and failure frequencies of the tanks used in the first case study.

Equipment no.	Type	Substance	Inventory (ton)	Catastrophic failure frequency (10^{-6})
TK-1	Atmospheric	Naphtha	10,000	1
TK-2	Pressurized	LPG	3500	9
TK-3	Pressurized	LPG	3500	9
TK-4	Atmospheric	Xylene	2000	7

As mentioned before, there are two inner and outer loops in FREEDOM. The inner loop, which is representative of the average lifetime of the equipment, is selected according to the equipment failure rates; this being one of the major inputs to the program (failure probability). The order of the simulation lifetime for the equipment is selected according to the mean time between failures (MTBF, which is inverse of failure rate). The lifetime in the algorithm is selected on the basis of the equipment with the lowest failure rate (largest MTBF). In every iteration, time is made to vary between zero and that selected lifetime within certain reasonable time steps (1 year in this study).

The number of iterations in the outer loop represents the number of iterations carried out to simulate a real situation. Ideally, for a 'perfect' Monte Carlo simulation all possible experiments should be done. The minimum number of iterations is 10,000 but, depending on the conditions of the problem, the number can be 1,000,000 or higher. In the FREEDOM algorithm an inner iterative loop exists; with it the number of iterations can be optimized to achieve a balance between accuracy of results on one hand and computational time on the other. As detailed in the next section, a case study has been carried out. For different values of input parameters, the results of simulation have been compared with the analytical solutions. Effect of different lifetimes and different number of iterations on the accuracy of the simulation has been studied.

Other input parameters such as equipment failure probabilities or escalation vectors are expected to be determined through a conventional risk assessment study which should precede FREEDOM. The study may include several fault/event tree analysis in addition to a detailed consequence modelling for the equipment involved in the case under study.

6. Validation of FREEDOM

A section of an existing industrial plant has been subjected by us to domino effect analysis using the analytical method of Cozzani et al. [6]. The same problem has also been solved by us with FREEDOM to see how well do the results arrived with FREEDOM match with the results of the exact mathematical solution. Subsequently in another case study, FREEDOM has been applied to a real-life situation – the storage farm of a typical large industrial plant.

6.1. The first case study

As the purpose of the first case study is to compare its analytical solution with the FREEDOM-based solution, it has been kept intentionally simple so that it remains amenable to exact analytical solution. It deals with a section of an storage area of a hypothetical industrial plant situated in the southern Iran. To further simplify, a single fail scenario has been associated with each equipment and has been considered as the only possible primary and/or secondary event which can occur. There are four equipment involved: an atmospheric tank TK-1 (containing naphtha), two pressurized spherical tanks TK-2 and 3 (containing liquefied petroleum gas, LPG) and a cylindrical storage, TK-4 (containing xylene). The inventories and storage characteristics have been summarized in Table 1. The layout of the storage area is shown in Fig. 2.

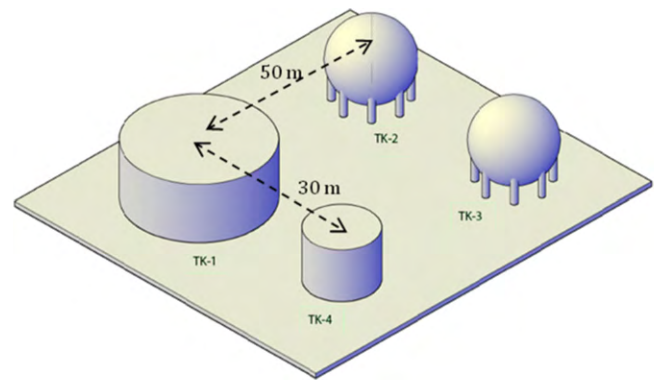

Fig. 2. Layout of the four storage tanks in the case study (distances are shown in meters).

Given the meteorological conditions normally prevailing in that area (average ambient temperature ca. 40 °C; average wind speed ca. 15 m/s: average humidity ca. 60%; stability class D), pool fire (PF) and vapour cloud explosion (VCE) were considered as plausible scenarios of the primary accident. Upon accidental release the materials would form a pool and if immediate ignition occurs a pool fire would result. But if there is no immediate ignition the high ambient temperatures would cause the material to vapourize and form a flammable vapour cloud which would slowly drift downwind. On meeting an ignition source a VCE may occur.

For calculation of the primary accident frequency, an event tree has been developed for each thank. For the tanks that would be impacted by the primary accident and initiate a domino chain, the magnitude of the resulting radiation or overpressure has been simulated by the software PHAST. The escalation probabilities incorporate impacts from heat load and overpressure.

As is often done by others [40], we have used generic failure rates of storage tanks documented in literature [41] to deduce the failure frequencies for TK-1 to TK-4. They are 1E-6, 9E-6, 9E-6, and 7E-6 (event/year) respectively.

The escalation probabilities defined as P_{ij} in this study for the equipment are tabulated in Table 1. These denote the probability that an accident in a certain equipment (e.g. equipment i) would trigger a cascading accident in a target equipment (e.g. equipment j). Decay laws [21] as well as probit models [39] have been utilized to determine the escalation probabilities in the consequence modeling of each tank.

Following the method used by Cozzani et al. [6] for TK-1, and considering the mutual effect of other tanks and its own failure rate, and based on Eq. (1), the formulation becomes:

$$P(fail-1) = 1\times10^{-6} + (0.1\times10^{-6}) + (0.2\times9\times10^{-6}) + (0.1\times7\times10^{-6}) = 4.4\times10^{-6}$$

As there are certain common terms; joint probabilities should be subtracted from the summation according to the probability rules,

Table 2
Comparison of failure frequencies calculated by analytical method and by simulation.

Number of equipment	Analytical solution ($\times 10^{-6}$)	Simulation results ($\times 10^{-6}$)
1	4.39	4.38
2	11.5	11.1
3	12.2	12.1
4	9.79	9.70

as follows:

$$P(fail-1) = 4.4 \times 10^{-6} - [(1.62 \times 10^{-12}) + (6.32 \times 10^{-13}) + (1.26 \times 10^{-12})] + 1.134 \times 10^{-18} = 4.39 \times 10^{-6}$$

It may be seen that when domino effect is taken into account, the failure frequency goes up 4 times.

The failure frequency can be calculated in the same way for other equipment, e.g. for TK-2:

$$P(fail-2) = 1.16 \times 10^{-5} - [(1.8 \times 10^{-13}) + (7 \times 10^{-14}) + (1.26 \times 10^{-12})] + 1.26 \times 10^{-19} = 1.15 \times 10^{-5}$$

The results of simulation are compared with the exact analytical solutions for each tank in Table 2. There is close agreement.

FREEDOM was used to determine failure frequency at a constant N but over different life-times ranging from 1 year to 100,000 years. It is seen (Table 3) that increasing the life time to more than 1000 years does not lead to a great increase in the results' precision, and the change is barely distinguishable beyond $T_f > 100{,}000$.

The nature of the FREEDOM algorithm being such that it conducts numerous random experiments every time it is operated, it is expected that the results of different runs would not to be exactly the same. But if the method is to be relied upon, its results from run to run should not differ markedly, either. To check this, failure frequencies were determined in replicate simulations. The results (Table 4) indicate that when repeated, the simulations yield closely matching results.

In all the runs up to this stage only first level domino accidents were considered. Activation of an inner loop in the FREEDOM software enables the user to consider higher order domino effect. In Table 5 the results of two different runs in different life times are shown in which higher order domino effects were considered. It may be seen that there is an increase in the failure frequencies compared to the failure frequencies of equipment in isolation and also compared to the situation in which only a first level domino effect was considered. The computational time also increased due to greater complexity handled by the algorithm. Because of the stochastic nature of the algorithm, the run time of the program is slightly different from run to run, even when T_f and N are constants.

The extent to which domino effect increases the failure frequency of equipment can be comprehended from Table 6. There is up to a 300% increase in the failure frequencies even when only the first level domino accidents are considered. It follows that ignoring domino effects in risk evaluations will lead to substantial underestimation of the risks.

Moreover, as revealed in a past accident analysis by [1], nearly half of all domino events go past the first victim unit. When that probability is considered, there is an order of magnitude increase in the failure frequencies of equipment. This further underscores the necessity of accounting for domino effect in all risk assessments.

The FREEDOM algorithm can be expanded to accommodate greater complexity than dealt with in this case study. It can deal with multiple initiating events such as both leakage and rupture, heat radiation, overpressure, and missile impact.

6.2. The second case study

In the second case study, FREEDOM has been utilized to estimate risk in the full-scale storage farm of a real-life industrial plant (Table 7). Risk contours have been drawn with and without considering domino effect to identify the influence of the latter.

One of the largest cluster of petrochemical industries in the world and the largest one in the Middle East, is located in Mahshahr,

Table 3
Effect of different life times on the accuracy of the results ($N = 1{,}000{,}000$).

Number of equipment	Analytical solution	Failure frequency ($\times 10^{-6}$) by simulation at different life times, T_f (year)						
		1	10	100	1000	10,000	100,000	1,000,000
1	4.39	9	5.01	4.5	4.31	4.35	4.38	4.38
2	11.5	20	13.5	10.9	11.5	10.8	11.1	11.2
3	12.2	12	10.8	12.0	12.2	12.4	12.1	12.1
4	9.79	12	10.9	10.1	9.76	9.6	9.70	9.72

Table 4
Simulated failure frequencies of three different runs in different life times.

Number of equipment	Number of run	Failure frequency ($\times 10^{-6}$) at different life times, T_f (year)				
		1	10	100	1000	10000
1	1	9	5.01	4.51	4.31	4.35
	2	3.5	4.01	4.59	4.39	4.31
	3	5	4.9	4.21	4.30	4.35
2	1	20	13.5	10.9	11.5	10.8
	2	13	11.1	11.9	11.1	11.3
	3	13	12.1	11.5	11.9	11.3
3	1	12	10.8	12	12.2	12.4
	2	11	9.09	11.9	12.7	12.3
	3	14	13.4	12.4	12.1	12.2
4	1	12	10.9	10.1	9.7	9.60
	2	10.5	11.1	9.98	9.78	9.71
	3	9.5	8.8	9.13	9.71	9.69

Table 5
Simulated failure frequencies of two different runs considering second or higher level domino accidents.

Number of equipment	Number of run	Failure frequency ($\times 10^{-6}$) at different life times, T_f (year)				
		1	10	100	1000	10,000
1	1	1.21	1.03	1.18	1.18	1.08
	2	1.45	1.32	1.19	1.18	1.08
2	1	1.45	1.61	1.67	1.65	1.51
	2	1.85	1.76	1.71	1.65	1.51
3	1	1.8	1.75	1.81	1.78	1.63
	2	1.9	1.84	1.8	1.78	1.63
4	1	1.35	1.53	1.53	1.52	1.40
	2	1.11	1.52	1.52	1.61	1.40
Run time (s)		1108	4170	11,024	27,410	271,533
		1134	4182	11,103	27,319	270,907

Table 6
Comparison of the failure frequency with or without domino effect.

Number of equipment	Failure rate without domino effect ($\times 10^{-6}$)	Failure rate considering first level domino effect ($\times 10^{-6}$)	*a*	Failure rate considering higher level domino effect ($\times 10^{-5}$)	*b*	*c*
1	1	4.38	338	10.8	980	146.6
2	9	11.1	23.3	15.1	67.7	36.1
3	9	12.1	34.4	16.3	81.1	34.7
4	7	9.7	38.6	14.0	100	44.3

a % Difference between failure rates without and with 1st level domino effect.
b % Difference between failure rates without and with higher level domino effect.
c % Difference between failure rates between the 1st level and the next higher level domino effect.

Iran. It covers an area of over 2000 ha. In this zone, among many different industries located close to each other, are two neighboring petrochemical plants: Tondgoyan and Bo Ali. These plants provide a diversity of feed material to downstream industries. The storage areas of the two plants are located side by side. This case study is focused on one of the storage farms which houses 10 tanks (Fig. 3).

If analytical methods were to be used for the 10 items of equipment, the calculation of increased failure frequencies would have been very cumbersome because 511 terms are involved in calculating failure frequency of each equipment.

The accident scenarios, and the basis of their construction, were as detailed in the first case study (Section 6.1). There are two major methods for determining primary failure frequencies. One of these is based on the use of generic failure data. Several reports exist which give generic values for failure frequency of different equipment based on the analysis of past accident data. The authors have reviewed all the reports and have selected failure frequencies on the basis of most oft reported values [12,39,42,43].

The other method uses fault tree to estimate the primary equipment failure frequencies. A top event (e.g. rupture of a tank) is analyzed based on the failure of subsystems that can lead to that top event down to their roots (e.g. instrument and valve failures). Then failure frequency of these subsystems are combined according to probability rules, to determine the top event failure frequency. There are several well-known databases (such as OREDA) for extracting the required failure frequencies.

In this paper the first method has been used to estimate the primary failure frequency of the equipment involved in the case studies. An event tree (ET) was developed for each tank, because there are two possible outcomes of each tank failure: pool fire and VCE. For this step probabilities of early and late ignition were required. These values have been adopted from past reports [17,22,44].

For escalation probabilities a thorough consequence modeling for each tank was performed using PHAST software to calculate the escalation vectors (radiation and overpressure), generated in each tank failure, that would impact other tanks. Then a screening with reference to the threshold values was done to omit the tanks that do not exert domino effect on other tanks featuring in the study.

For the tank failure scenarios in which escalation value exceeded the threshold value, escalation probit was calculated using the most up-to-date relations reported by Cozzani et al. [13]. These relations have been mainly derived from experiments with magnitude of escalation vector (radiation, overpressure) as the input and the probability of damage to target equipment as the output. After calculation of escalation probabilities, escalation matrix was obtained

Table 7
Storage tanks featuring in the second case study.

Series tank number	Plant	Inventory (tonne)	Chemical	Temperature (°C)	Pressure (barg)
1	Bo Ali	23,050	Naphtha	30	0.01
2	Bo Ali	23,050	Naphtha	30	0.01
3	Bo Ali	23,050	Naphtha	30	0.01
4	Bo Ali	11,325	Naphtha	30	0.01
5	Bo Ali	11,325	Naphtha	30	ATM
6	Bo Ali	14,587	p-Xylene	30	ATM
7	Bo Ali	14,587	p-Xylene	30	ATM
8	Tondgoyan	1367	p-Xylene	40	0.003
9	Tondgoyan	1554	Acetic acid	45	0.014
10	Tondgoyan	1554	Acetic acid	45	0.014

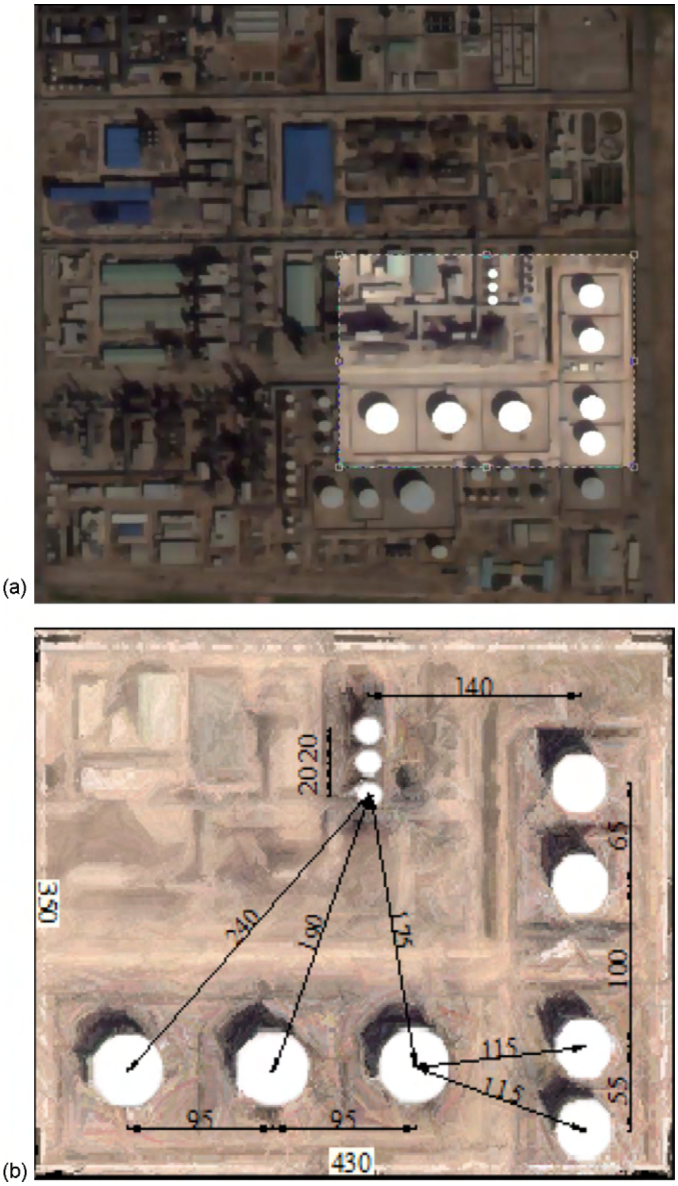

Fig. 3. (a) Location of the 10 storage tanks addressed in the case study, and (b) a closer view of the tank farm showing the distances involved, in meters.

in which each array (P_{ij}) represents the probability of damage to each individual equipment caused by failure in other equipment. According to the number of equipment present in this study (10), the matrix has 10 columns and 10 rows.

It may be stated that the goal of the paper is basically to illustrate the features and the applicability of the FREEDOM algorithm developed by us. The goal is not to actually conduct a domino effect analysis of a specific real-life situation for input to real decision-making. Hence the numerical values of various inputs are not really important here even though we have picked the various values with utmost care.

For the type of tanks involved, 5.88E−8 (event/year) has been reported as the failure frequency of individual tanks [17,44]. Based on this value, and on the escalation matrix and other inputs, FREEDOM was used to obtain failure frequencies in a domino effect situation.

Table 8, which summarizes the results, indicates that the increase in the failure frequencies due to domino effect is significant for several tanks. The data also indicates that failure rates are even higher for the propagation of domino effect to tertiary accident.

Normally, for drawing vulnerability maps, the failure frequency of each event is multiplied by the probability of death due to that event at different points away from the accident epicenter. For a system with 10 items of equipment in any location, the individual risk is given by:

$$IR_{x,y} = \sum_{i=1}^{10} f_i P_{f,i}$$

where $IR_{x,y}$ is the individual risk in a specific location (x,y); f_i is the failure frequency of the equipment i; and $P_{f,i}$ is the probability of death in that location obtained from probit models.

But when domino effect is taken into consideration, the influence of other equipment in increasing the failure frequency of the 'target' equipment is accounted for. This effect is shown by adding a new summation:

$$IR_{x,y} = \sum_{i=1}^{10} f_i P_{f,i} + \sum_{j=1}^{10} \sum_{k=1}^{10} f_j P_{jk} P_{f,k}$$

where f_i is the failure frequency of equipment i (which is estimated by FREEDOM); P_{jk} is the probability of damage to equipment k as a result of an accident in equipment j. The second term in the above equation is for the domino effect.

The death probability, P_{overall}, at any point (after taking into account domino effect), has been calculated as under:

$$P_{\text{overall}} = \min\left\{ \left(P_{\text{primary}} + \sum_{i=1}^{N} V_{\text{domino},i} \right), 1 \right\}$$

It is the summation of death probability arising from primary event at a point with the death probabilities at that point resulting from domino accidents. As may be seen from the above equation,

Table 8
Comparison of the failure frequency with or without domino effect.

No. of equipment	Failure rate without domino effect ($\times10^{-8}$)	Failure rate considering first level domino effect ($\times10^{-7}$)	Failure rate considering higher level domino effect ($\times10^{-7}$)
1	5.88	1.06	3.90
2	5.88	1.07	4.44
3	5.88	1.05	5.78
4	5.88	1.79	5.78
5	5.88	1.82	5.78
6	5.88	1.44	5.48
7	5.88	1.34	5.78
8	5.88	2.50	5.78
9	5.88	3.25	5.78
10	5.88	3.84	5.78

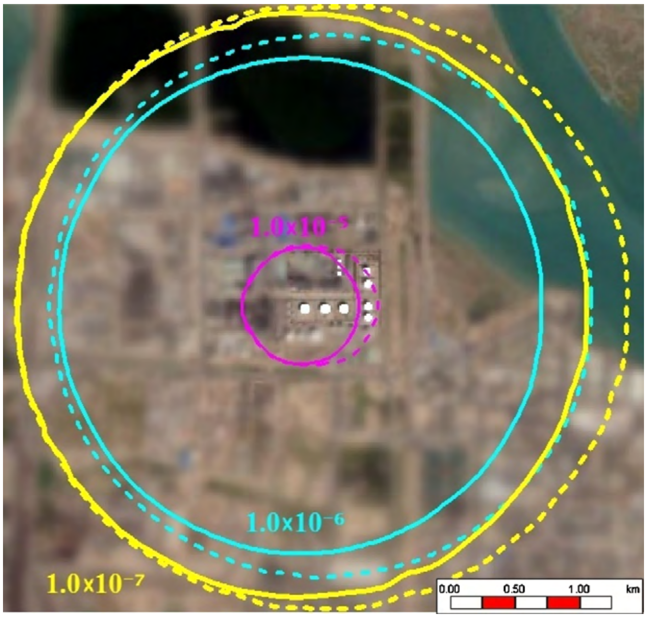

Fig. 4. Individual risk (event/year) for the second case study without considering domino effect (solid lines) and with considering domino effect (dashed lines).

there is an upper limit of 1. Hence the value of death probability will never exceed 1.

Using the above equation, for every (x,y) in the plant under study, *IR* has been calculated and identical values have been connected to form the *IR* contours for scenarios with and without allowing for domino effect (Fig. 4).

These contours are asymmetrical because the units undergoing loss of confinement (the storage tanks) do not have identical sizes and inventories nor are they placed symmetrically. Tanks 4–7 are larger hence pose much greater risk of domino effect then other tanks. As a result of the asymmetry in the sizes and locations of the units, the area under risk by the combination of the units is also asymmetric.

As may be seen, domino effect enhances the areas under risk contours; in other words extra risk is entailed due to domino effect. The societal risk as enhanced by domino effect can be calculated by using reported indices [45–47].

The figures might create an impression that there is only a very small difference in distances between curves showing domino effect (dashed lines) and the ones without domino effect (solid lines). But, given the scale representing these curves, the difference in the distances amounts to hundreds of meters. In the matter of site selection and planning within congested regions frequently encountered across the world, this extent of difference can have major implications. Other authors studying domino effect, for example Cozzani et al. [13], have reported similar extents of difference in risk contours with or without domino effect.

7. Conclusion

Domino effect is a fairly common occurrence in process industry accidents wherein an accident in a process unit becomes the cause of another accident in another process unit. The severity of many process industry accidents, and the consequent losses, are also enhanced due to domino effect. But even as the importance of domino effect has been realized and emphasized from time to time, few methods are available to forecast domino effect situations due to the extreme complexity associated with it. The available methods are all based on analytical techniques which are limited in their ability to handle the complexity.

In this backdrop a method based on simulation has been developed which is described in this paper. The inherent advantages of the simulation technique–iterative evaluation of highly complex and non-linear systems using sets of random numbers as inputs, and the ability to handle more than just a few uncertain parameters – has been exploited to develop an algorithm named FREEDOM (FREquency Estimation of DOMino accidents) and a software of the same name. A case study has been presented which shows that for simpler systems (which are amenable to analytical treatment) FREEDOM is able to arrive at results similar to the ones obtained by analytical techniques. The applicability of FREEDOM has then been demonstrated by another case study which successfully handles a system too complex to be solvable by analytical techniques.

Acknowledgement

TA and SAA thank the Chemical Engineering Programme, Department of Science & Technology, Government of India, for support.

References

[1] B. Abdolhamidzadeh, T. Abbasi, D. Rashtchian, S. A. Abbasi, Domino effect in process industry accidents—an inventory of past events and identification of some patterns, J. Loss Prev. Process Ind., in press, doi:10.1016/j.jlp.2010.06.013.
[2] F.I. Khan, S.A. Abbasi, Major accidents in process industries and an analysis of causes and consequences, J. Loss Prev. Process Ind. 12 (1999) 361–378.
[3] F.I. Khan, S.A. Abbasi, An assessment of the likehood of occurrence, and the damage potential of domino effect (chain of accidents) in a typical cluster of industries, J. Loss Prev. Process Ind. 14 (2001) 283–306.
[4] F.I. Khan, S.A. Abbasi, Estimation of probabilities and likely consequences of a chain of accidents (domino effect) in Manali Industrial Complex, J. Clean. Prod. 9 (2001) 493–508.
[5] S.P. Kourniotis, C.T. Kiranoudis, N.C. Markatos, Statistical analysis of domino chemical accidents, J. Hazard. Mater. 71 (2000) 239–252.
[6] V. Cozzani, G. Gubinelli, G. Antonioni, G. Spadoni, S. Zanelli, The assessment of risk caused by domino effect in quantitative area risk analysis, J. Hazard. Mater. 127 (2005) 14.
[7] J. Crowther, Oxford Advanced Learner's Dictionary of current English, Oxford University Press, Delhi, 1996.
[8] T.S. Ferry, Modern Accident Investigation and Analysis, second ed., Wiley, New York, 1988.
[9] F.P. Lees, Loss Prevention in the Process Industries, vols. 1-2, Butterworths, London, 1980.
[10] D.F. Bagster, R.M. Pitblado, The estimation of domino incident frequencies—an approach, Trans. IChemE 69 (1991) 195–199.
[11] Third Report of the Advisory Committee on Major Hazards, Health & Safety Commission, 1984.
[12] J. Gledhill, I. Lines, Development of methods to assess the significance of domino effects from major hazard sites. CR Report 183, Health and Safety Executive, 1998.
[13] V. Cozzani, G. Gubinelli, E. Salzano, Escalation thresholds in the assessment of domino accidental events, J. Hazard. Mater. 129 (2006) 1–21.
[14] V. Cozzani, S. Zanelli, An approach to the assessment of domino accidents hazards in quantitative area risk analysis. Proc. 10th Int. Symp. On Loss Prevention and Safety Promotion in the Process Industries. Amsterdam, Elsevier, 2001.
[15] C. Fievez, C. Delvosalle, S. Brohez, A methodology and a software (DominoXL) for studying domino effects, Major Risks Research Centre, Faculte Plytechnique de Mons, Belgium, 2002, pp. 1–15.
[16] C. Delvosalle, C. Fievez, F. Benjelloun, Development of a methodology for the identification of potential domino effects in "Seveso" Industries, Proceedings of the 9th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Barcelona, pp. 1–10.
[17] CCPS (Centre for Chemical Process Safety), Guidelines for Chemical Process Quantitative Analysis, second ed., American Institute of Chemical Engineers, New York, 2000.
[18] P.K. Raj, Exposure of a liquefied gas container to an external fire, J. Hazard. Mater. 122 (2005) 37–49.
[19] D. Thiruselvi, Control of domino effect in chemical process industries handling propane: evaluation of minimum viable safe distances among units, MTech Thesis, Pondicherry University, 2009.
[20] T. Abbasi, S.A. Abbasi, The expertise and the practice of loss prevention in the Indian process industry: some pointers for the third world, Trans. IChemE 83 (2005) 413–420.
[21] F.P. Lees, Loss Prevention in the Process Industries-Hazard Identification, Assessment, and Control, vols. 1–3, Butterworth-Heinemann, Oxford, 1996.
[22] F. P. Lees, Loss prevention in the Process Industries—Hazard Identification, Assessment, and Control. (partially edited by S. Mannan) Volumes 1-3, Elsevier/Butterworth-Heinemann, Oxford, 2005.

[23] Methods for Determining of Possible Damage to People and Objects Resulting from Releases of Hazardous Materials (Green Book), CPR 16E, Committee for the Prevention of Disasters, Directorate-General of Labour of the Ministry of Social Affairs, The Hague, 1989.
[24] J.C.H. Schüller, J.L. Brinkman, P.J. Van Gestel, R.W. van Otterloo, Methods for determining and processing probabilities, Committee for the Prevention of Disasters, CPR 14E (TNO 'Yellow Book'), The Hague, The Netherlands, 1997.
[25] C.J.H. van den Bosch, R.A.P.M. Weterings, Methods for the Calculation of Physical Effects, Committee for the Prevention of Disasters, CPR 12E (TNO 'Red Book'), The Hague, The Netherlands, 1997.
[26] P.A.M. Uijt de Haag, B.J.M. AleGuideline for quantitative risk assessment, Committee for the Prevention of Disasters, CPR 14E (TNO 'Purple Book'), The Hague, The Netherlands, 1999.
[27] HSE 1978. CANVEY: An investigation of the potential hazards from operations in the Canvey Island/Thurrock area. HMSO.
[28] HSE 1981. CANVEY: A second report. HMSO.
[29] F.I. Khan, S.A. Abbasi, Models for domino effect analysis in chemical process industries, Process Saf. Prog. 17 (1998) 107–123.
[30] F.I. Khan, S.A. Abbasi, DOMIFFECT (DOMIno eFFECT): User-friendly software for domino effect analysis, Environ. Model. Softw. 13 (1998) 163–177.
[31] F.I. Khan, S.A. Abbasi, Studies on the probabilities and likely impacts of chains of accident (domino effect) in a fertilizer industry, Process Saf. Prog. 19 (1) (2000) 40–56.
[32] F.I. Khan, B.R. Natarajan, S.A. Abbasi, Avoid the domino effect via proper risk assessment, Chem. Eng. Prog. 96 (10) (2000) 63–72.
[33] T. Abbasi, S.M. Tauseef, T. Kannadasan, S.A. Abbasi, Domino effect in process industry accidents, Proceedings of the International Seminar on Emerging Trends in Process Safety and Risk Management, Chennai, 2009.
[34] G. Antonioni, G. Spadoni, V. Cozzani, Application of domino effect quantitative risk assessment to an extended industrial area, J. Loss Prev. Process Ind. 22 (5) (2009) 614–624.
[35] G. Reniers, W. Dullaert, S. Karel, Domino effects within a chemical cluster: A game-theoretical modeling approach by using Nash-equilibrium, J. Hazard. Mater., 2009, doi:10.1016/j.jhazmat.2008.12.113.
[36] N. Metropolis, S. Ulam, J. Am. Stat. Assoc. 44 (247) (1949) 335–341.
[37] R. Billinton, R. Allan, Reliability Evaluation of Engineering Systems: Concepts and Techniques, second ed., Plenum Press, New York, 1992.
[38] D. Vose, Risk Analysis: A Quantitative Guide, second ed., John Wiley and Sons, Chichester, 2000.
[39] V. Cozzani, E. Salzano, The quantitative assessment of domino effects caused by overpressure, Part I, Probit models, J. Hazard. Mater. A107 (2004) 67–80.
[40] H.I. Beerens, J.G. Post, P.A.M. Uijt de Haag, The use of generic failure frequencies in QRA: The quality and use of failure frequencies and how to up-to-date, J. Hazard. Mater. 130 (2006) 265–270.
[41] CCPS, Guidelines for Process Equipment Reliability Data, AIChE, New York, 1989.
[42] N.A. Eisenberg, C.J. Lynch, R.J. Breeding, Vulnerability Model: A Simulation System for Assessing Damage Resulting from MarineSpills, Report CG-D-136-75, Environ Control Inc., Rockville, MD, 1975.
[43] V. Cozzani, F. Gozzi, A. Mazzoni, S. Zanelli, Proceedings of the European Conference on Safety and Reliability, ESREL, Torino, 2001.
[44] G. Fabbrocino, I. Iervolino, F. Orlando, E. Salzano, Quantitative risk analysis of oil storage facilities in seismic areas, J. Hazard. Mater. A123 (2005) 61–69.
[45] F.I. Khan, S.A. Abbasi, Accident hazard index: A multi-attribute method for process industry hazard rating, Process Safety and Environ. Protn. 75 (4) (1997) 217–224.
[46] F.I. Khan, S.A. Abbasi, Multivariate hazard identification and ranking system, Process Safety Progress 17 (3) (1998) 157–170.
[47] T. Abbasi, S.A. Abbasi, The boiling liquid expanding vapour explosion (BLEVE) is fifty and lives on!, Journal of Loss Prevention in the Process Industries 21 (4) (2008) 485–487.