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Quantitative assessment and Consequence modeling of deliberately induced Domino effects in Process facilities

Priscilla Grace George*[1] and V. R. Renjith[2]
[1]Research Scholar, [2]Professor
Division of Safety and Fire Engineering
Cochin University of Science and Technology, Kerala, India
*Presenter E-mail: priscillagrace.mec@gmail.com

Abstract

Process facilities handling hazardous chemicals at elevated temperature and pressure conditions are attractive targets to external attacks. The possibility of an external attack on a critical installation with an intention of triggering escalation of primary events into secondary and tertiary events, thereby increasing the severity of consequences needs to be effectively analyzed. A prominent Petrochemical Industry located in Kerala, India was identified for induced domino effect analysis. In this study, Bayesian network is used to model the development of a domino sequence and to quantitatively determine the occurrence probabilities of domino effect. Moreover, the updating feature of Bayesian networks is used to update probabilities in the light of new evidences. Phast Process hazard analysis software and ALOHA (Areal Locations of Hazardous Atmospheres) software is used for consequence modeling of the security event to obtain the impact zones. Recommendations to manage and reduce the domino effect attractiveness by incorporating inherently safer design concepts and use of appropriate active and passive mitigating barriers are also discussed.

Keywords: Security risk; Domino effect; Process plants; Bayesian networks; Consequence modeling; Phast; ALOHA

1. Introduction

Process industries handling huge amount of hazardous chemicals can be potentially dangerous resulting in catastrophic incidents such as explosions, fire and toxic gas releases with serious adverse effects on people, property and environment. Such Industries involving the storage and transportation of hazardous chemicals are prime targets of security threats. Security risk assessment for process plants was not given serious reflection until the terrorist attack on the World Trade Centre on 11 September 2001. The possibility of inducing a chain of incidents with maximized damage potential makes complex industrial areas a very attractive target for terrorists. Hence complex industrial clusters should be protected against such deliberately induced domino effects (Reniers et al., 2008). Implementing efficient security risk management programs in process industries can help in reducing the attack likelihood and minimizing the consequences of a successful attack (Garrick et al., 2004). Security risk assessments consists of threat analyses and vulnerability analyses involving the consideration of target attractiveness, attack likelihoods and attack consequences. The API standards for security risk assessment (API, 2013) provides guidelines for performing semi-quantitative security risk assessments. (Bajpai and Gupta, 2005) introduced a semi-quantitative method of security risk assessment based on the use of a Security Risk Factor Table (SRFT) as a pre- screening tool for further assessments.

Conventionally, domino incidents are analyzed by two approaches- Event tree approach and Fault tree approach. In the Event tree approach, consequences of a given incident are increased to account for domino effects. In the Fault tree approach, domino effect is incorporated as an external event and failure frequency of a given incident is increased. (Khan and Abbasi, 2001) has developed and demonstrated the application of a computer automated tool for domino effect analysis- DOMIFFECT in an Industrial Cluster in Manali, Chennai, India.

The typical primary incidents for a domino sequence are explosions and fires. The physical effects associated with the primary incidents such as thermal radiation, overpressure and fragment effects can affect nearby units leading to secondary and tertiary incidents. The overall consequence of the domino sequence is much severe than that of the primary incident happening alone. An effective domino effect analysis should include accurate modeling of domino sequence development and a quantitative estimate of occurrence probabilities along with consequence modeling- together identifying the most vulnerable units in the industrial area. Hence, such analyses can be used to reduce the attractiveness of industrial area to external threat agents by determining the units where security measures are to be strengthened. Typically, domino effect analysis has to be performed in the initial stages of design of the industrial area for effective land use planning- thereby assigning adequate safe distances between different units to reduce escalation effects.

Bayesian networks are graphical representations consisting of nodes representing the system variables interconnected by links showing conditional dependencies between them. (Khakzad et al., 2013) has demonstrated the use of Bayesian networks in modeling the propagation sequence of domino effect and determination of domino effect probability at each level. Consequence modeling of the incidents may be performed to determine the impact zones by making use of Phast software and ALOHA software.

The objective of this paper is to analyze the possibility and consequences of a deliberately induced domino effect on a prominent petrochemical industrial area in Kerala, India. A dedicated Bayesian network is developed with nodes representing different units of the industry. The damage potential and the attractiveness of each unit to threat agents depends on the amount and type of hazardous chemicals being stored. The domino propagation sequence is effectively modeled using the Bayesian network. Consequence modeling is performed using Phast software to determine the impact zone of primary incident. Finally, recommendations to reduce the domino effect attractiveness by incorporating inherently safer design concepts and adequate safety barriers are also discussed.

The paper is organized as follows: Section 2 discusses the materials and methods. Section 3 describes the case study and Section 4 discusses the development of domino sequence using Bayesian network and consequence modeling using Phast and ALOHA. Section 5 gives the main conclusions drawn from the study.

2. Materials and Methods

The accident or primary incident in one unit propagating to neighboring units by means of escalation effects are termed as Domino effects. The escalation vectors of primary incident- such as overpressure, heat radiation and fragment effects are compared with threshold values for neighboring units to find potential secondary incidents.

2.1 Bayesian Network modeling of domino sequence

The various units in the industrial area under consideration are represented as nodes to form the Bayesian network. The primary unit for starting the domino sequence is the one most attractive to terrorists depending on its damage potential. The escalation vectors corresponding to this primary incident is determined. The threshold values of surrounding units are compared to the values of escalation vectors to determine the secondary units.

The threshold values for overpressure capable of damaging an atmospheric storage vessel and pressurized storage vessel is 23.8kPa and 42kPa respectively (Cozzani and Salzano, 2004). The threshold value for thermal radiation capable of damaging any storage vessel (both atmospheric and pressurized) is taken as $25 kW/m^2$ (Alileche et al., 2017).

The probit values and escalation probabilities of secondary units given primary incident are calculated. The probability of loss of containment at a nearby unit (P) due to an initiating event in a unit is given by (Mannan, 2012),

$$P = \left(1 - \frac{r}{r_{limit}}\right)^2 \tag{1}$$

Where r is the distance between the units and r_{limit} is the maximum distance at which the initiating event can cause damage.

The units with highest escalation probabilities becomes the secondary units. The primary unit is connected to these secondary units by arcs showing interdependency. This method is then repeated at each level to find the tertiary and further units until propagation ends.

2.2 Consequence Modeling using Phast and Aloha

ALOHA (Areal Locations of Hazardous Atmosphere) and Phast (Process Hazard Analysis Software) are efficient simulation tools for consequence modeling. ALOHA is capable of providing the threat zones corresponding to a chemical release by modeling the atmospheric conditions. The estimated impact zones can be exported and displayed on Google Earth platform. Similarly, Phast is an advanced tool for modeling the incident from release to far-field dispersion.

It also provides extensive modeling for release scenarios such as from leaks, pipelines, ruptures etc. Atmospheric and weather conditions can also be incorporated and detailed reports are available for all possible incidents corresponding to each scenario.

3. Case Study

A prominent petrochemical industry located in Central Kerala, India is selected for the study. The industrial area involves storage of hazardous chemicals such as cyclohexane, Benzene, Low Sulfur- Heavy Stock (LS-HS), Ammonia and Liquefied Petroleum Gas (LPG). Fig 1 shows the google earth image of the chemical storage area.

Figure 1 Google Earth Image of Petrochemical Plant *(Source: Google Earth)*

The quantity actually stored and threshold quantity allowed is listed in Table 1.

Chemical	**Threshold Quantity (Tons)**	**Actual Quantity stored (Tons)**
Benzene	1500	1270
Cyclohexane	1500	1150
Ammonia	60	5000
LPG	15	33

The storage of such flammable chemicals in large quantities are potential sources for explosions and fires. The loss of containment can occur by leaks, cracks or rupture in vessel or pipeline. Since the chemicals are stored in close proximity there is a great chance for domino effect if an undesirable event starts in one unit. Moreover, the industry is located in a municipality housing several industries and is one among the world’s most toxic spots. The population density is approximately 2938 people per square kilometer.

4. Results and Discussions

The petrochemical industry stores 1150 tons of cyclohexane in atmospheric conditions. Induced damage on this vessel can result in vapor cloud explosion creating overpressure effects on nearby Benzene, Ammonia, LS-HS and LPG storage tanks. TNT equivalent Vapor cloud explosion modeling (Casal and Darbra, 2013) results in overpressure values as listed in Table 2, which are then compared with threshold values to find potential secondary units.

Nearby Unit	Distance from Cyclohexane vessel (m)	Overpressure (KPa)
Benzene A	30	170
Ammonia	47	60
Benzene B	58	40
LS-HS	85	25
LPG	150	2

On comparing with the threshold value of 23.8 kPa required for damaging atmospheric vessels, it is found that Benzene tanks, Ammonia tanks and LS-HS vessels comes under domino spell and hence is considered for further analysis.

The secondary incident at Benzene Tank A (Atmospheric vessel) is pool fire due to loss of containment occurring by the impact of overpressure from primary incident. The subsequent thermal radiation at LPG tank, Ammonia tank and Benzene Tank B is estimated by Solid flame model (Casal and Darbra, 2013) and found to be 8.96 kW/m^2, 16.07 kW/m^2 and 92.5 kW/m^2 respectively. Hence, Benzene Vessel B comes under domino spell as the escalation vector value is greater than the threshold value.

The loss of containment from Benzene Tank B resulting in pool fire due to the impact from Benzene Tank A forms the tertiary event. The thermal radiation at LS-HS tank at a distance of 40 m is estimated to be 37.6 kW/m^2.

The domino sequence is modelled as a Bayesian Network using HUGIN EXPERT software and shown in Fig 2. The conditional probability tables (CPTs) are filled by using escalation probabilities calculated according to equation 1. The probability of loss of containment in Ammonia tank, LS-HS tank, Benzene Tank A and Benzene Tank B due to overpressure effects from cyclohexane tank is estimated as 0.39, 0.099, 0.58 and 0.28 respectively. The probability of loss of containment from Benzene Tank B due to thermal radiation from Benzene Tank A is calculated as 0.77. The probability of loss of containment from LS-HS Tank due to thermal effects from Benzene Tank B is 0.34. Moreover, Synergistic effects are also considered when populating the CPTs.

Development of domino sequence using Bayesian network has many advantages such as computation of domino probabilities in each level by appropriately adding logic gates in each level as discussed by (Khakzad et al., 2013). Also probability updating is possible when new information is incorporated onto the network.

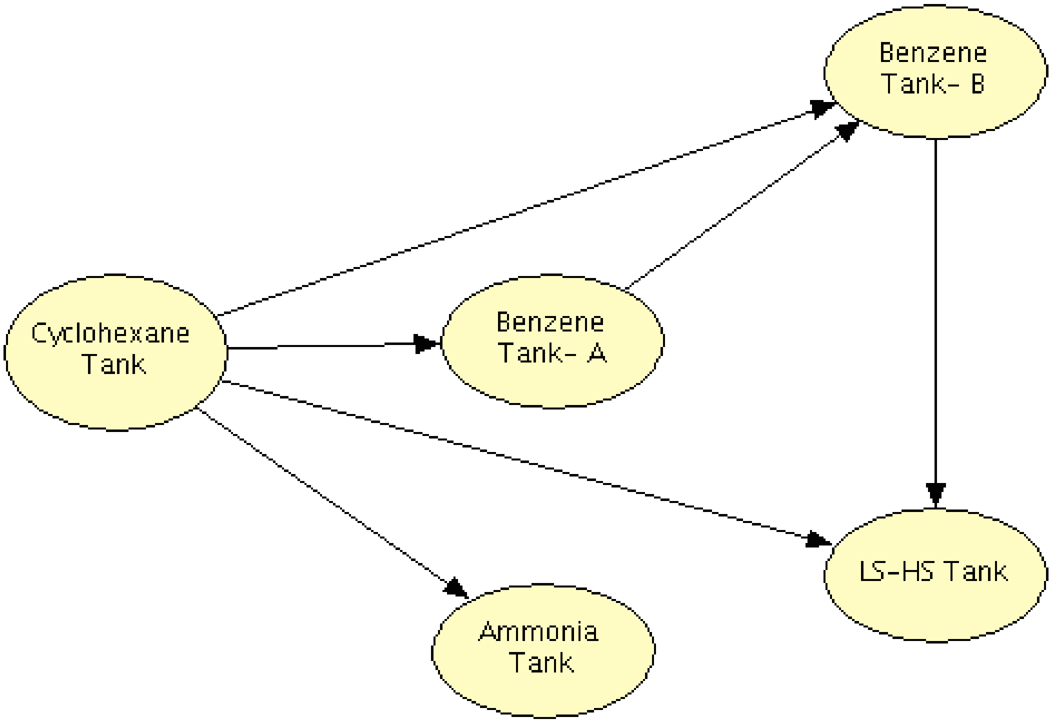

Figure 2 Bayesian Network Modeling of Domino Sequence

The consequence modeling for the above incidents are also implemented using ALOHA software and Phast software. The thermal radiation zone obtained for pool fire from Benzene Tank A is shown in Figure 3. The red zone corresponds to thermal radiation greater than 10 kW/m^2. It is observed that Benzene Tank B is being affected.

Figure 3 Thermal radiation footprint from Benzene Tank A

Phast software provides different analysis results for all possible incidents corresponding to the scenario being represented. The pool vaporization rate Vs time obtained from analysis performed in Phast software is shown in Figure 4.

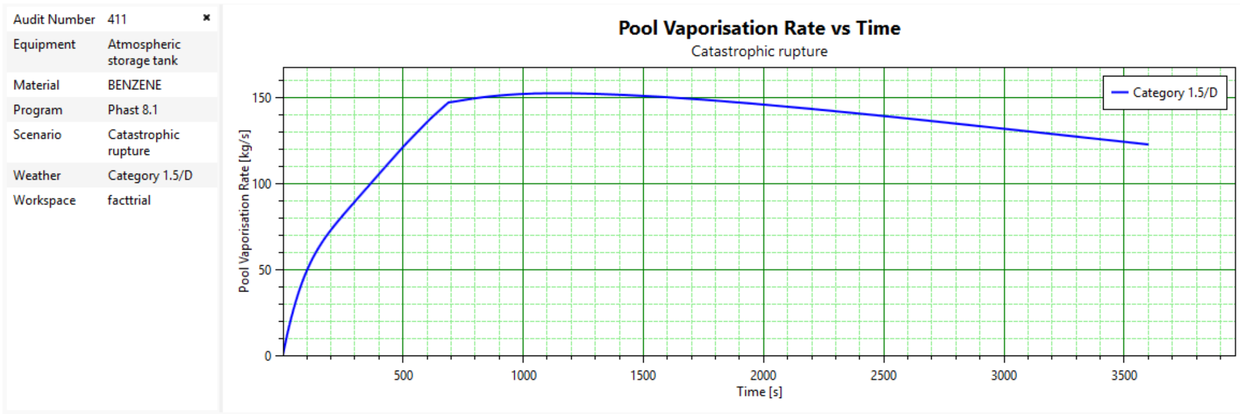

Figure 4 Pool Vaporization rate Vs time for Benzene Tank A

Phast software also provides the toxic dosage per distance corresponding to the catastrophic rupture scenario of Benzene tank A (Figure 5). The toxic dispersion footprint resulting from rupture of Benzene Tank A is shown in Figure 6.

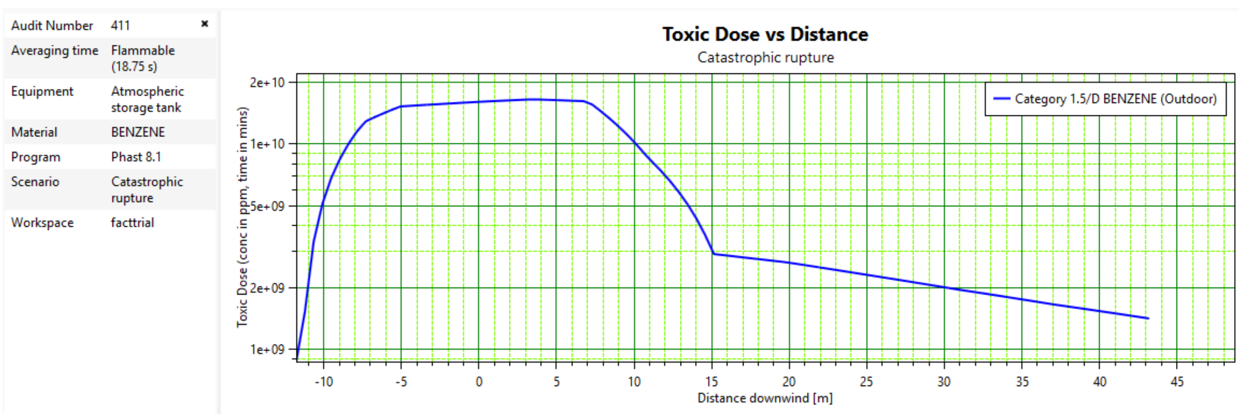

Figure 5 Toxic Dose Vs Distance for rupture of Benzene Tank

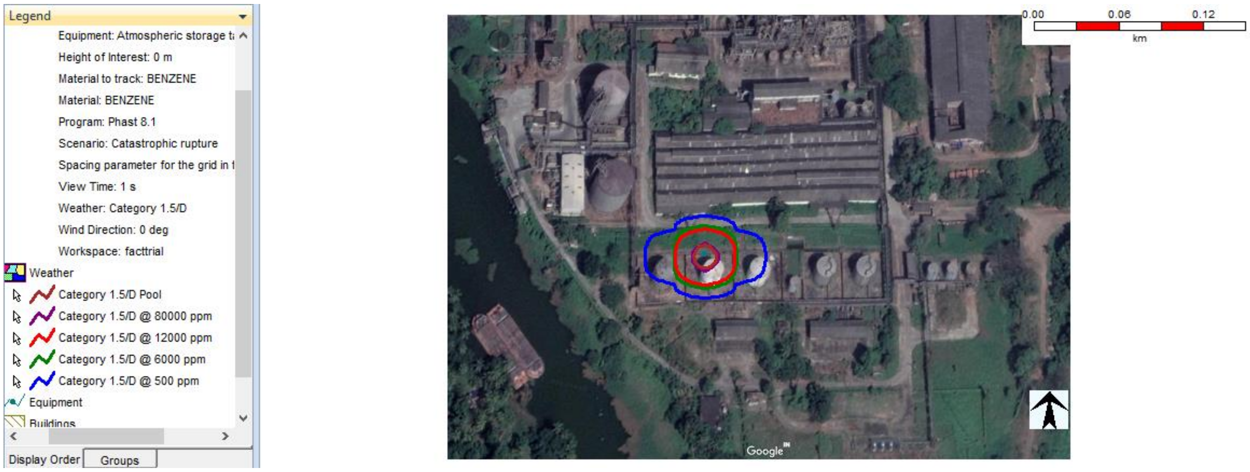

Figure 6 Toxic Dispersion Footprint for Catastrophic rupture of Benzene Tank A

The thermal radiation threat zones corresponding to pool fire incident from Benzene Tank B is shown in Figure 7. The red zone corresponds to thermal radiation greater than 10 kW/m^2. It is observed that LS-HS tank is affected.

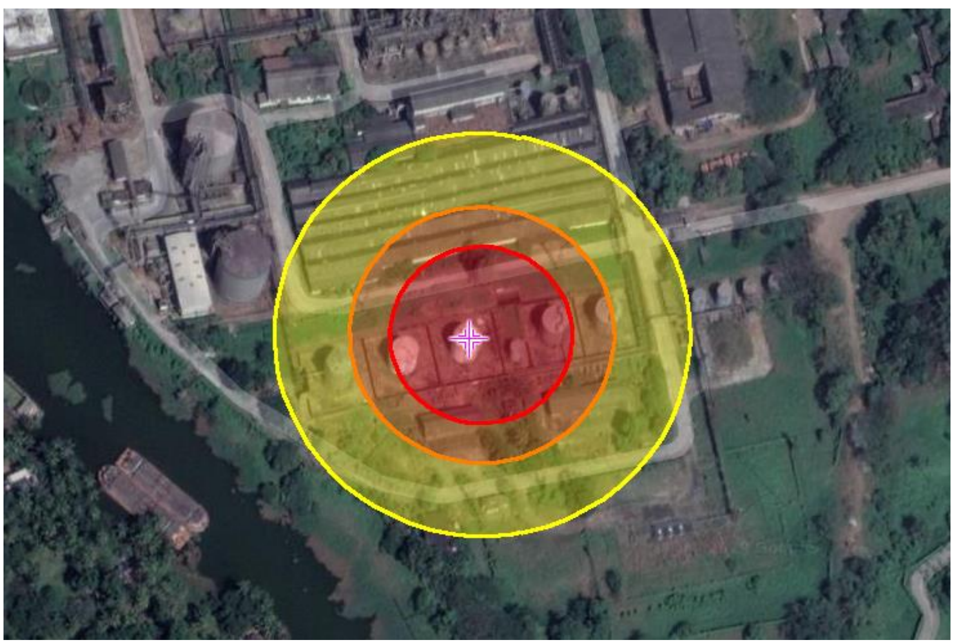

Figure 7 Thermal radiation footprint from Benzene Tank B

5. Conclusions

In this study, the possibility of attacks on critical installations triggering domino effects with increased consequences are analyzed. A prominent Petrochemical Industry located in Kerala, India was identified for the analysis. HUGIN EXPERT software was used to model the Bayesian Network representing the domino sequence. Also detailed consequence modeling was carried out using Phast (Process hazard analysis) software and ALOHA (Areal Locations of Hazardous Atmospheres) software to obtain the impact zones. It is observed that if an undesirable event is initiated at cyclohexane tank, subsequent incidents of fire and explosions are being triggered in nearby tanks with huge consequences. This is a serious concern as this can result in fatalities to surrounding populations as well. Such studies need to be carried out in the design phase of industries to allocate safe distances between units to inhibit domino effects. The escalation vectors for all possible incidents need to be calculated and layout needs to be planned in such a way that escalation vectors do not cross the threshold values for nearby units. Thus the industry should be made inherently safer. This can reduce the attractiveness of the industry to terrorists. Also appropriate active and passive mitigating barriers such as fire extinguishing systems, active alarm systems and physical protection systems needs to be implemented and maintained properly.

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