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ORIGINAL ARTICLE

Dynamic Analysis of the Consequences of Gas Release in Process Industries Using Event Tree Technique and Bayesian Network

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ABSTRACT
Storage tanks that contain a wide range of chemicals, compressed gas, and other hydrocarbons play an important role in the process industries. Gas release from these tanks can lead to catastrophic events that can lead to significant financial, human, and environmental consequences. In this study, a compressed gas tank was chosen as the case unit under study. The gas release was taken into consideration as the top event for quantitative and qualitative analyses of the probable consequences using the Event Tree Analysis (ETA) and Bayesian network (BN) model. According to the ETA analyses, 6 safety barriers were identified that could prevent the top event and the success and failure of these barriers led to the 10 final consequences. Among the identified consequences, near misses were known to be the most probable consequences of the top event. The results showed that the presence of safety barriers could significantly reduce the consequences of the occurrence of the top event. BN could fix the static problem of the quantitative risk analysis and provide the capability to determine the most probable consequences of the top event.

KEYWORDS: *Dynamic analysis, Event Tree Technique, Bayesian Network*

INTRODUCTION
Storage tanks that contain a wide range of chemicals, compressed gas and other hydrocarbons play an important role in the process industries[1]. Storing large volumes of flammable and combustible materials in these tanks gives them a higher potential to create numerous hazards [2-3]. In recent years, incidents caused by these tanks have led to the deaths of people, judicial prosecution, and falling the stock value of many companies worldwide [4]. The release of gas from the storage tanks allows them to spread rapidly in the air and, as it is mostly heavier than air, it aggregates on the floor and becomes a major disaster with the slightest spark [5]. The gas release can lead to consequences such as near miss, vapor cloud explosion, flash fire, jet fire, and release of toxic substances [2, 3], which can have huge financial, human, and environmental damage [2]. Among the catastrophic accidents of the process tanks can be pointed to the heavy explosions at propane gas storage facilities in Toronto (2008), the explosion of six spherical tanks in Mexico City (1984), the explosion of chemical storage tanks in Buncefield in England (2005) and LPG tanks accidents in Pune, India (2004) and Tomahawk, the USA in 2008 [6-10].

The detailed analysis of the catastrophic events shows that a large proportion of their damage and the occurrence probability were predictable and therefore preventable if only safety engineering analyses such as quantitative risk assessment and consequence analysis would be performed in a timely manner [11]. Specific techniques have been used to assess risks and

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various methods have been developed by researchers for different conditions. Choosing the right method varies according to the industry under study and goals [12]. Some of the risk assessment methods used in the process industries include Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Bow-tie etc. [13-14]. Process and chemical systems have dynamic and complex procedures that involve various time-related factors, such as seasoning, fatigue of facilities, physical processes, accidental processes, operator response time, etc. Since risk assessment is done statically in the mentioned methods, they cannot determine the dynamic risks of process accidents [15-16]. Since risk assessment is done statically in the methods mentioned, it cannot determine the dynamic risks of process accidents. As a probabilistic inference method under uncertain conditions, the Bayesian Network (BN), by considering the conditional dependencies and common failures, overcomes the constraints of the methods of static nature in risk assessments [17-20]. Performing the probability updates make it as an excellent risk analysis approach in the dynamic systems [21-22].

According to the discussed content, the main objective of the current study was to analyze quantitatively and qualitatively the consequences of storage tank gas release in a process industry using ETA and determine the kind and the way of the connection between the most probable consequences of the catastrophic accident by the BN method.

MATERIALS AND METHODS

Event Tree Analysis: The ETA technique was used to identify the different consequences that could occur in the event of the top event and failure of any safety barriers. It is a very powerful tool for identifying and calculating the sequences of each scenario involved in a potential accident. ETA is an inductive modeling technique that works by making two branches of success and failure at the same time to assess a single event. The purpose of this technique is to determine the first event (top event) and its consequences if the safety systems do not work well [23-24]. ETA is in two forms of qualitative and quantitative. In the qualitative analysis, the top event and its occurrence consequences were identified. The occurrence probability of the top event and performance failure of the safety barriers was determined from the databases such as OREDA, the experts' opinion in this field, similar events, and available documents. Finally, in the quantitative analysis, the occurrence probability of each consequence was calculated using Equation 1.

Equation 1:

$$\text{Pr (Consequence)} = \text{Pr (TE)} \times \prod_{j=1}^{n} \Pr(E)$$

where; Pr (consequence) is the probability of each of the consequence, Pr (TE) is the occurrence probability of the top event, and Pr (E) is the probability of failure or success in safety barriers.

Bayesian Network: After making the ETA model and calculating the probability of the safety barriers and the consequences of the top event, in order to eliminate its static structure for dynamic risk analysis, the model was moved to the BN. This network consists of the qualitative and quantitative components [25]. The qualitative element is shown by the network structure and the quantitative component is presented by assigning conditional probability distribution to the nodes [18]. In BN, in particular, every node in the graph represents an accidental variable and the branches (arcs) show the probability dependencies between the variables.

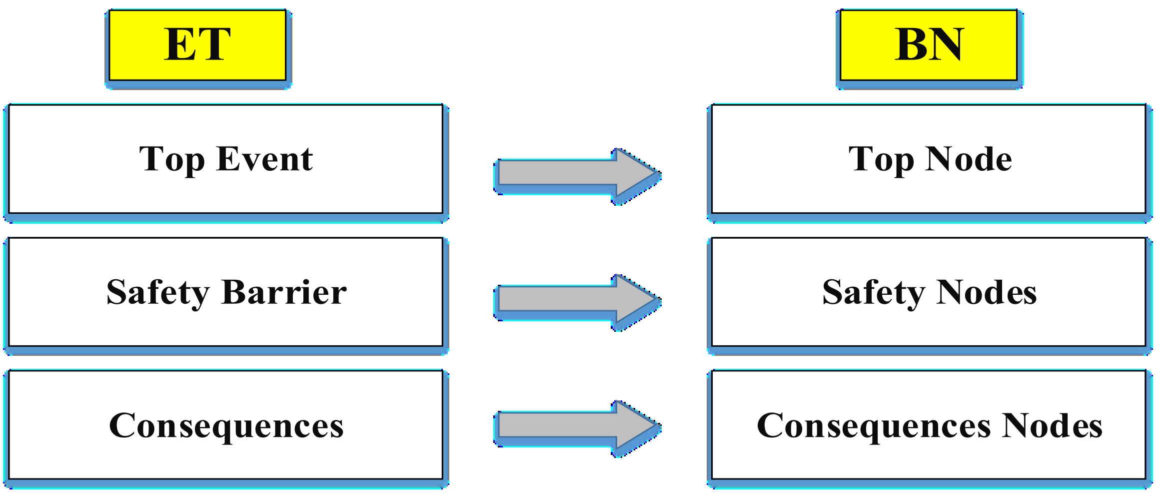

Fig. 1. Mapping algorithm of ET model to BN network

In BN, Equation 2 is used to compute the probability distribution of a set of variables U = $\{X_1, ..., X_n\}$:

Equation 2:

$$P(U) = \prod_{i=1}^{n} P(Ai|Pa(Ai))$$

Pa (Ai) is the parent set of Ai in BN and P (U) displays the properties of BN [18, 26].

BN updates the prior events, based on Bayes theorem, to obtained newer observations of another set of variables, which is called the Evidence (E). Distribution of the probability can be solved using different sorts of reasoning algorithms such as connection tree or variable elimination based on the Bayes theorem.

Equation 3:

$$P(U|E) = \frac{P(U|E)}{P(E)} = \frac{P(U|E)}{\sum_U P(U|E)}$$

In this study, the ETA model was made and analyzed in the GeNIe 2.0 software. The algorithm for mapping ET to BN is shown in Fig. 1. As the figure suggests, the top event, safety barriers, and consequences in the ETA model were considered respectively as the top node, safety barriers node, and the consequences node in the BN model [18]. In order to quantify the model, the obtained probability of the safety barriers was inputted in the BN as the probability of safety barriers node failure based on the mentioned logic, and then, the occurrence probability of each consequence was calculated.

RESULTS

Fig. 2 shows the event tree of the tank gas release (top event). In order to determine the sequence of the events and the different accidents after the occurrence of the top event, the event tree was drawn by considering the six safety barriers of Pressure Relief Valve (PRV), Pressure Safety Valve (PSV), Immediate Ignition Barrier (IIB), Ball Valve (BV), Delay Ignition Barrier (DIB), and Presence/Absence of Congestion. According to the performance of the safety barriers (failure or expected performance), the release from the tank gas was expected to cause 10 final consequences.

After the qualitative drawing of the event tree, in the next step, the probability of the safety barriers and the occurrence of the top event was determined and then, the quantifying process of the event tree was done using Equation 1. Table 1 presents the symbols, descriptions and the probability of the safety barriers and top event. Fig. 3 shows the event tree modeling of the tank gas release using the BN model.

The probability failure of the safety barriers and the top event were inputted in the BN model and then, the probability of the final consequences was determined by the logic available in the BN. Table 2 shows the symbols, descriptions, and the probability of the consequences of the tank gas release.

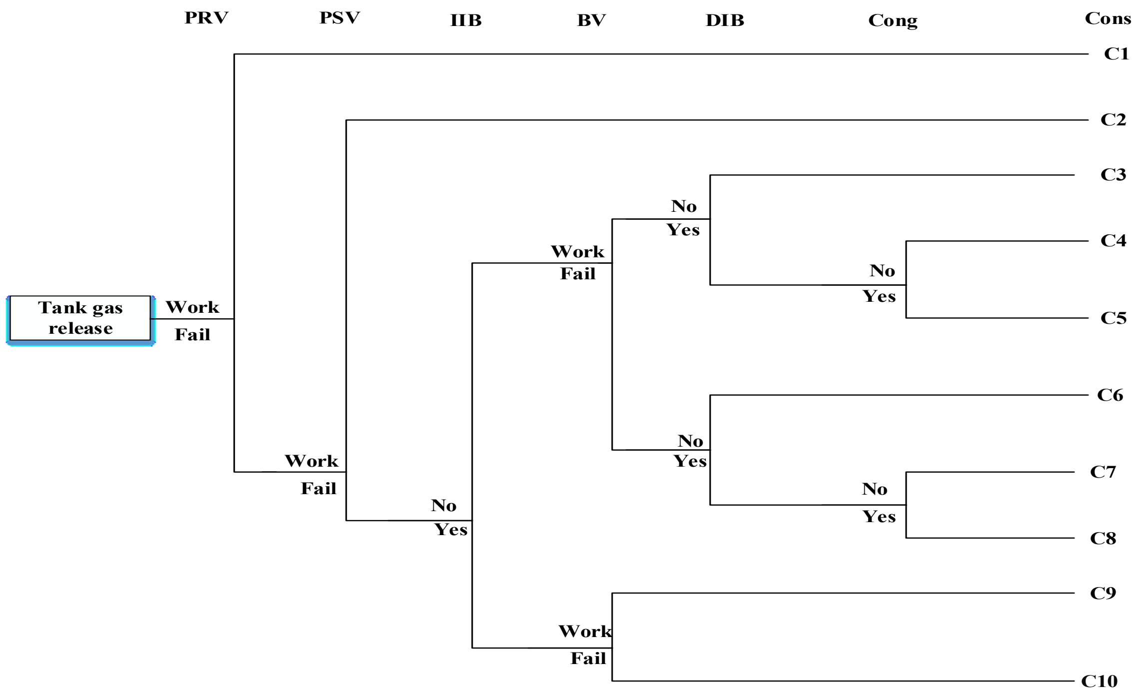

Fig 2. Event tree of the tank gas release

Table 1. Symbols, descriptions, and the probabilities of the safety barriers and top event

Symbol	Description	Failure probability	Success probability
TE	Tank gas release	14.05×10^{-2}	85.98×10^{-2}
PRV	Pressure Relief Valve	4×10^{-1}	6×10^{-1}
PSV	Pressure Safety Valve	19×10^{-2}	81×10^{-2}
IIB	Immediate Ignition Barrier	1×10^{-1}	9×10^{-1}
BV	Ball Valve	3×10^{-1}	7×10^{-1}
DIB	Delay Ignition Barrier	6×10^{-1}	4×10^{-1}
Cong	Congestion	6×10^{-1}	4×10^{-1}

Table 2. Symbols, descriptions, and the probabilities of the consequences

Symbol	Descriptions	Prior probabilities (ET)	Posterior probabilities (BN)	Updated probability (BN)
C1	Near miss	8.04×10^{-2}	8.04×10^{-2}	6×10^{-1}
C2	Safety release	4.53×10^{-2}	4.53×10^{-2}	3.24×10^{-1}
C3	Moderate material release	2.68×10^{-3}	2.68×10^{-3}	1.91×10^{-2}
C4	Flash fire with minor damage	1.6×10^{-3}	1.6×10^{-3}	1.08×10^{-1}
C5	Vapor cloud explosion with minor damage	2.41×10^{-3}	2.41×10^{-3}	1.72×10^{-2}
C6	Major material release	1.14×10^{-3}	1.14×10^{-3}	8.2×10^{-3}
C7	Flash fire with catastrophic damage	6.89×10^{-4}	6.89×10^{-4}	4.92×10^{-3}
C8	Vapor Cloud explosion with catastrophic damage	1.03×10^{-3}	1.03×10^{-3}	8.61×10^{-3}
C9	Jet fire with moderate damage	7.45×10^{-4}	7.45×10^{-4}	5.32×10^{-3}
C10	Jet fire with catastrophic damage	3.19×10^{-4}	3.19×10^{-4}	2.28×10^{-3}

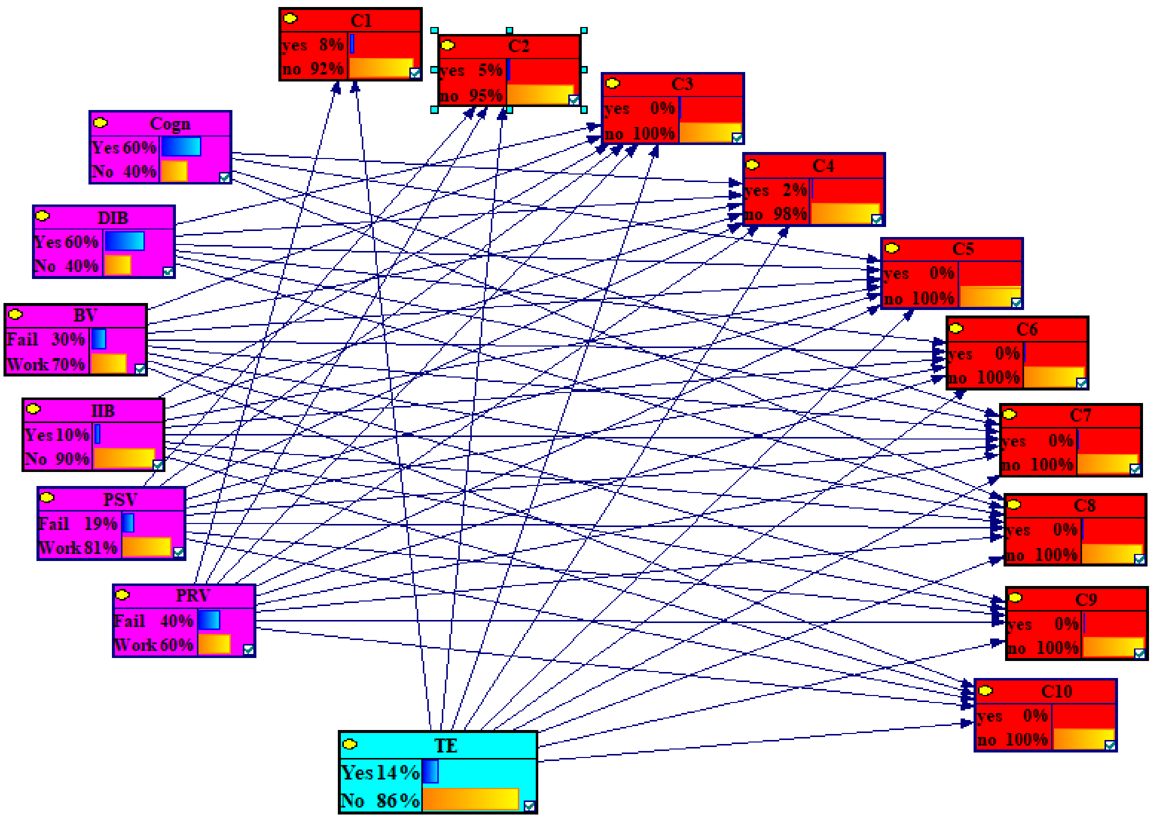

Fig. 3. Dynamic modeling of the tank gas release using BN

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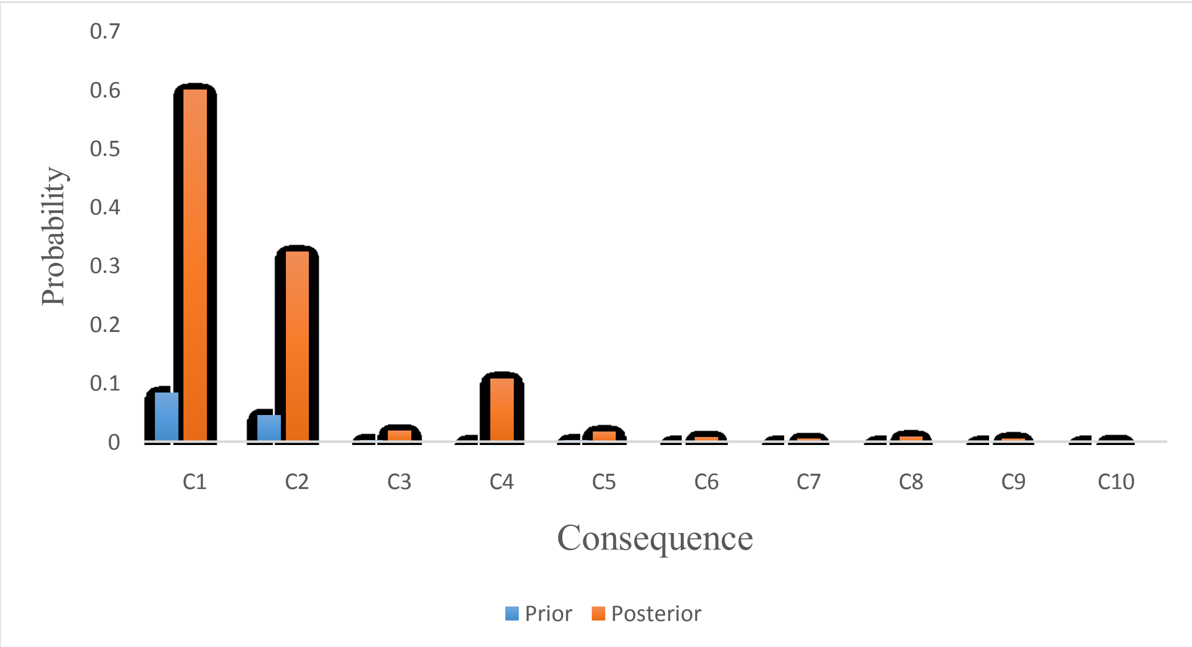

Fig 4. Comparison between the prior and posterior probabilities

In order to update the constructed model, the top node (tank gas release) was taken into account as evidence and the prior and posterior probabilities of all the consequences were updated. The updated results of the BN model are presented in the fourth column of Table 2. In addition, the comparison between the prior and posterior probabilities of the top event consequences is provided in Fig. 4 to identify the most probable consequences.

DISCUSSION

In the studies done by Eun-Soo Hong et al. in 2000 and John D et al in 2009, the ETA technique was identified as an effective method to assess and analyze the consequences of different occurrence scenarios [23, 27]. Although the ETA method provides a powerful tool for the modeling of the consequences of a top event, however; similar to any other conventional risk assessment methods it has some limitations. The most important of which are its staticity and inability to adapt to dynamic events, which is becoming increasingly important in process industries today[28]. According to Fig. 2 and the results of the qualitative drawing of the event tree, 10 consequences could occur in different modes of safety barrier failure or success and the sequence of the events. Immediate or delayed ignition prevention systems, PRV, PSV, BV, and the compression and congestion of the flammable and explosive materials were identified as the safety barriers of the gas release from the return tank. After drawing the qualitative event tree, the probability of success and failure of the safety barriers and the top event was determined. The probability of each of the consequences was calculated as shown in Tables 1 and 2. In this study, in order to eliminate the limitation of the static structure of ETA, the BN model was used. In BN, after acquiring new data and information such as near miss statistics and accidents, the pre-occurrence probabilities of the basic events are updated and in other words, the safety analysis becomes dynamic [17-18]. Sohag Kabir et al. (2018), Idris Sule et al. (2018), and Sou-Sen Leu et al (2013) showed the importance of using BN in analysis and management of the dynamic risk of the process industries in order to get over the limitations of the static risk assessment methods [29-31]. One of the features of the BN is the consideration of the conditional dependency between the failure-type events with common causes that static risk analysis methods, such as ETA are unable to do [32].

According to the fact that there was no dependency between the identified safety barriers to prevent the gas release from the storage tank, the prior probability of the consequences was the same in ET and BN techniques. One of the most important properties of BN is updating the occurrence probability of the top event and its consequences that decrease the uncertainty in the model and the obtained results. By updating the probability of the top event occurrence and its final consequences, it would be possible to identify the most probable consequence of the top event [18]. The updated or posterior probability of each consequence, C_i, is calculated by assuming the occurrence probability (Ci) of the consequence on the condition of the occurrence of the top event (tank gas release) (P (C_i | Tank Gas Release)). Fig. 4 shows the prior and posterior probability values of the top event and the consequences of its occurrence using the BN method.

As observed, C1 (near miss) show the highest increase while updating the probability of the top event from 8.04×10^{-2} to 6×10^{-1}. Therefore, this consequence was studied as the most probable consequence of gas release from the tank and its most important cause is the accurate performance of PRV when the gas release occurs. The C2 (safe release) is the second most probable consequence with the increase from 4.53×10^{-2} to 3.24×10^{-1} and its cause is the failure in the PRV performance and the accurate performance of PSV. Therefore, in the gas tanks, the presence of safety barriers can significantly decrease the consequences of the gas release. The study limitations include “lack of specialized information on the process accidents” and “poor cooperation of many process industries with gas leakage accidents and the resulting consequences”.

CONCLUSION

The current study presents qualitative and quantitative analyses of the dynamic risks in the process industries using the ETA technique and BN. A gas tank was chosen as a case study due to its previous incident records and its critical role in containing hazardous materials in the process industries. Accordingly, gas release from the tank (top event) was considered the case to analyze the probability risk. Analyzing the top event and its occurrence consequences was done using the ETA technique. The event tree results showed that gas leakage from the storage tanks led to the occurrence of 10 final consequences due to the performance of safety barriers. In addition, ETA showed that safety barriers could considerably alleviate the consequences of the top event. In order to update the probability, determine the form of relations between the causes of the consequences and identify the most probable consequence of the top event, the ET diagram was transferred into the BN. Based on the BN analysis; near misses were the most probable consequences of the top event. In addition, safety release was identified as the second most probable consequence of the gas leakage from the tanks.

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