Fuzzy Bayesian estimation and consequence modeling of the domino effects of methanol storage tanks

Mostafa Pouyakian[a], Fereydoon Laal [b]*, Mohammad Javad Jafari[c], Farshad Nourai[d], Sohag Kabir[e]

[a] Department of Occupational Health and Safety Engineering, School of Public Health and Safety, Shahid Beheshti University of Medical Sciences, Tehran, Iran

[b] Social Determinants of Health Research Center, Department of Occupational Health Engineering, Birjand University of Medical Sciences, Birjand, Iran

[c] Safety Promotion and Injury Prevention Research Center, Shahid Beheshti University of Medical Sciences, Tehran, Iran

[d] Principal Risk Analyst, proNEXO Engineering Consultancy, Tehran, Iran

[e] Department of Computer Science, University of Bradford, Bradford, BD7 1DP, UK

*Corresponding author. Ghaffari Blvd, School of Public Health, Birjand University of Medical Sciences, Birjand, Iran. Tel: +985632381651, Email: fereydoonlaal@gmail.com

Abstract

In this study, a Fuzzy Bayesian network (FBN) approach was proposed to analyze the domino effects of pool fire in storage tanks. Failure probabilities were calculated using triangular fuzzy numbers, the combined Center of area (CoA)/Sum-Product method, and the BN approach. Consequence modeling, probit equations, and Leaky-Noisy OR (L-NOR) gates were used to analyze the domino effects, and modify conditional probability tables (CPTs). Methanol storage tanks were selected to confirm the practical feasibility of the suggested method. Then the domino probability using bow-tie analysis (BTA), and FBN in the first and second levels was compared, and the Ratio of Variation (RoV) was used for sensitivity analysis. The probability of the domino effect in the first and second levels (FBN) was 0.0071472631 and 0.0090630640, respectively. The results confirm that this method is a suitable tool for analyzing the domino effects and using FBN and L-NOR gate is a good way for assessing the reliability of tanks.

Keywords: Fuzzy Bayesian network, Domino effect, Atmospheric storage tanks, L-NOR, Methanol, Pool fire

1. **Introduction**

Large quantities of hazardous and flammable materials are stored in storage tanks in process facilities such as the petrochemical industry. Storing liquid fuels in multiple tanks has also created challenges such as fire, explosion, and the release of toxic substances that fire is the most common . Accidents can lead to heavy financial losses, long delays in production, legal complaints, and devaluation of industrial stocks. Despite the publication of standards and guidelines for the safe design, and construction of storage tanks by companies and business organizations and engineering communities such as API, ASME, and NFPA in recent years, accidents still occur in tanks . One of the important issues due to the complexity of process industries is that the occurrence of accidents in these industries is influenced by domino effects.

1.1. Domino effect, accident propagation, and escalation probability

Although significant progress has been made in recent years in the safety and risk analysis of accident scenarios in single units, domino accidents have received more attention in the field of quantitative risk assessment (QRA) due to lower probability, and more complexity and severity . However, catastrophic domino events have occurred in recent years, such as the Texas refinery accident in which vapor cloud explosions (VCE) caused several fires and other explosions . Domino effect analysis has also been investigated to ensure an adequate internal safe distance in high-risk units, because a large accident may cause secondary events in adjacent units as a result of the domino effects .

The occurrence of many process accidents in Iran such as Bou Ali Sina Mahshahr Petrochemical and Kharg Island accidents has also been a domino accident. Therefore, in risk analysis and assessment, it is not only important to deal with the accidents of one equipment or unit, but also the effects of unit or equipment accidents on other units must also be considered, and this is possible by examining the domino effects of accidents . The domino effect occurs when the initial accident in one unit causes other accidents in adjacent units by escalation vectors. These vectors are the same physical effects as heat radiation, overpressure, or projectile fragments by an explosion. Escalation vectors depend on a variety of factors, including the type of initial accident and the distance between the accident center and adjacent units. There are several methods for calculating the escalation vectors, including analytical, integral, and mean models, which are a combination of both analytical and integral models .

Probit methods have been used more widely to estimate the probability of escalation According to the methods presented in previous research , which is due to the simplicity, flexibility, and usability of these methods in a wide range of equipment . To prevent dominoes, the occurrence of fire in a tank or dyke wall and the amount of heat radiation received to adjacent tanks should be analyzed. Therefore, according to the main study scenario (pool fire), the present study intends to evaluate the most probable domino scenario.

1.2. Pool fire in atmospheric floating roof storage tanks and its causes

Pool fire is one of the most common process accidents. When a flammable liquid is spilled on the ground, a pool fire occurs . This type of fire is an asymmetric diffuse flame that is created by the combustion of evaporated materials from the liquid surface . Pool fire plays a very effective role in the occurrence of domino events. Especially in an area of oil tanks, a pool fire can destroy the entire complex. According to statistics, the main cause of 80% of a chain accident with fire origin, was pool fire. A well-known example of chain fire is the Buncefield accident in England in 2005 .

Based on the records of past accidents and research, there is a possibility of various types of fires in storage tanks, but the possibility of pool fire is higher . In a study using databases such as MHIDAS, MARS, ARIA, and research on 225 accidents that occurred since 1960, Darbra et al. (2010) concluded that storage processes have been a major cause of domino events. , and as reported in the study of Romina et al. (2015), fire and explosion were the main types of accidents . In the study of Taveau (2011), 206 accidents occurred in floating roof tanks, of which 145 accidents were fire-type and 61 accidents were explosion-type . The results of the study of Kletz et al., which was conducted to investigate accidents in these tanks, showed that lightning, maintenance operations, and operational errors were the most important causes of these accidents . This study was examined a combination of process, human, organizational, and management factors.

1.3. Fuzzy Bayesian approach

Dynamic risk assessment (DRA) is one of the combined approaches to risk assessment which uses conventional QRA and uncertainty reduction methods . DRA methods use specific data and update mechanisms to review the likelihood of failure of initial public data at the system design stage. New data provided by inspection of the process equipment at regular intervals usually replaces general data to update failure rates using physics-based, structural, mechanical, or condition-based models . Therefore, paying attention to DRA methods will be able to eliminate the shortcomings in QRA methods. According to the above, most risk assessment methods such as fault tree analysis (FTA) and bow tie analysis (BTA) have two important problems, including uncertainty and static structure . There are various methods to reduce these limitations, including sensitivity analysis, probability theory, Dempster-Schafer theory, game theory, possibility theory, and fuzzy sets . In this study, fuzzy logic and Bayesian networks (BNs) were used to reduce uncertainty and make structures more dynamic. Fuzzy theory is used when there is ambiguity and uncertainty and promotes multi-valued, instead of double-valued, logic. Therefore, it is a suitable topic for risk management that deals with qualitative variables and uncertainty . Markowski and Siuta developed a new methodology to improve the identification of representative accident scenarios (RASs), and the results showed the degree of accuracy of the RAS selection process using fuzzy logic . In another study, they used the fuzzy logic approach to the calculation of thermal hazard distances in the process industry .
The BN is a non-circular directional graph for uncertainty conditions consisting of nodes and arcs. Nodes in the BN represent random variables and are connected by directional arcs. Arcs show the usual dependencies and relationships between connected nodes. Conditional probability tables (CPTs) also determine the type and severity of such dependencies. In a BN , the nodes from which the arcs come out and the nodes to which the arcs reach are called the parent and child nodes, respectively. Thus a node can be the child of one node and the parent of another node at the same time. Nodes that have no parents are called "root nodes" and nodes that have no children are called "leaf or central nodes". The other nodes are "intermediate nodes" . Fig 1 shows a typical BN consisting of 4 nodes in which: X1 root node; X2 is an intermediate node; And X3 and X4 are leaf nodes. In addition, node X2 is both the child of X1 and the parent of X3 and X4. Therefore, we assume that this BN is used for failure analysis in a sprinkler system and includes a smoke sensor (flame) (X1), actuator (X2), alarm (X3), and a sprinkler (X4). When a fire is lit, the smoke sensor can activate the actuator (X1 → X2) and sound the alarm (X1 → X3), and then the actuator activates the sprinkler (X2 → X4). To increase system reliability, the actuator can also use the alarm (X2 → X3).

The field of safety risk analysis should be expanded by considering the accident precursors and changes in process parameters (such as level, pressure, flow, etc.). The probabilities of failures and accidents will be predictable with this approach and can be continuously updated in real-time processes. One of the most important techniques for modeling the accident scenario and risk assessment is BTA, which is a combination of FTA and Event Tree Analysis (ETA). These

methods are not suitable for analyzing large and complex systems, especially if those systems contain additional components or show dynamic behavior or time-varying parameters .
Numerous studies have shown that events such as the BP Texas City refinery accident in 2005, could have been prevented by combining a dynamic risk approach with a management framework . However, implementing a DRA approach can be a complex process and requires a variety of resources. Therefore, continuous improvement in any process industry requires the integration of risk assessment methods with management systems .
Although BN has several advantages, the difficulty of determining CPTs is one of its disadvantages . In this study, L-NOR (Leaky-Noisy OR) gates were used to analyze the domino effects of pool fire to reduce the number and complexity of CPTs.
QRA methods often use OR and AND gates, which is a kind of absolute analysis of these logical gates . In various studies, they used L-NOR gates to achieve smaller CPTs. The use of this type of gate has higher diagnostic accuracy than common logic gates . If Noisy-OR gates are used, the size of CPT decreases with the number of parent variables , and using these structures, fewer parameters are required to define CPT .

Therefore, this study intends to provide an approach to analyze the domino effects of pool fire in floating roof atmospheric storage tanks using fuzzy bayesian network (FBN) and probit models, and modify the structure of CPTs in domino analysis using L-NOR gates. In this study, we have performed an analytical comparison of the domino effect in the first and second levels using BTA and FBN techniques in addition to the analysis of human, organizational and process factors.

2. Method

2.1. Specifications of the studied tanks

The present study was performed on methanol tanks of a petrochemical company (three tanks including TK A / B / C). Tanks are quite similar in terms of mechanical structure and stored material. In these tanks, pure methanol is stored and transported to the relevant export port. Methanol is a highly flammable liquid with moderate respiratory and gastrointestinal toxicity. Methanol tanks are atmospheric type and have a floating roof, and each tank has a volume of 64,700 cubic meters of methanol and an internal diameter of 63 meters. Also, the distance between tank 1 and the other two tanks is 37 and 118 meters, respectively.

Fig 2 shows the arrangement of tanks and their location in the petrochemical plant. Methanol is transported to the jetty through pipes to load the tanker using 3 pumps. These tanks have numerous instrumentation equipment including Level Switch (LS), Level Alarm (LT), Pressure Transmitter (PT), Pressure Indicator (PI), Pressure Control Valve (PCV), and, Breather Valve (BV) which has provided to improve safety. PCV provides the necessary nitrogen pressure above the floating roof. The Low Low (LL) and High High (HH) alarms are in the range of -5 to 20 mbar for manual and automatic opening and closing of the nitrogen tank, respectively. BV opens if PCV does not operate and nitrogen pressure is high.

2.2. Research flowchart

This section provides an overview of the current study approach (Fig 3). Determining the probability of failure of tanks and pool fire as well as analyzing the domino effect and calculating the joint probability distribution are two basic steps in this approach.

2.2.1. Determining the probability of failure of tanks and pool fire with FFT and FBN

At this stage, the method of determining the probability of failure of tanks and the occurrence of pool fires are briefly presented. First, hazard identification and risk analysis of selected scenarios were performed using piping and instrumentation diagram (P&ID), process flow diagram (PFD), interviews with experts of different process units, review of past accidents and near-misses of tanks, and hazard and operability study (HAZOP) results in a relevant petrochemical plant. To determine the probability of occurrence of the basic event, expert judgment, and fuzzy theory were performed using linguistic terms. For this purpose, four experts were selected heterogeneously from the relevant petrochemicals who had sufficient information about the system and familiarity with the fault tree structure. Due to the differences of experts in terms of their experiences, knowledge, and different perceptions, a weight factor (WF) was used using Lavasani and Renjith methods to Fuzzification and perception/opinion evaluation of experts was done using triangular fuzzy numbers (TFNs) ($\widetilde{A}=a_1,a_2,a_3$¿ , and 7 linguistic terms (very low (VL), low (L), relatively low (RL), medium (M), relatively high (RH), high (H) and very high (VH) . These fuzzy numbers, under some weak assumptions, directly fulfill the good optimization criteria and the popularity and simplicity of TFNs have made them more widely used .

Then, the Center of area (CoA)/Sum-product approach was used to evaluate aggregated fuzzy failure possibility (AFFP) (Eq 1) and for defuzzification (CFP: Crisp Failure Possibility) (Eq 2). The AFFP values obtained from the consensus stage were converted to a crisp value using the CoA method. In the Yazdi and Zarei study, which aimed to investigate uncertainties in safety risk analysis and compare different approaches, the combined CoA/Sum-product approach was mentioned to be better than other methods in terms of computational complexity, reliability, and time spent on calculation .

$$Z_i = g_x = \sum_{j=1}^{n} w_j f_{ij}, \quad i=1,2,\ldots,n \quad j=1,2,\ldots,m \qquad (1)$$

Here Z_i is the consensus fuzzy number for base events, w_j represents the weight of expert j, f_{ij} also represents the fuzzy numbers of the base event i with respect to expert j.

$$CFP = \frac{\int_{a_1}^{a_2} \frac{x-a}{a_2-a_1} x\,dx + \int_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2} x\,dx}{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1} dx + \int_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2} dx} = \frac{1}{3}\left(a_1+a_2+a_3\right), \qquad (2)$$

Here x is the output variable.

The probability of occurrence of intermediate and top events (TEs) was also calculated from the gate-by-gate method for AND and OR gates .

$$P_{\cup} = 1 - \Pi_{i=1}^{n} \left(1 - P_i\right), \quad (3)$$

$$P_{\cap} = \Pi_{i=1}^{n} P_i, \quad (4)$$

$$P_{TE} = \Pi_{j \in M} \left(1 - \Pi_{BE_{i \in Q_j}} \left(1 - P_i\right)\right), \quad (5)$$

Where P_i is the basic event probability (BE$_i$) and Q_j is a basic event or group of basic events in the fault tree structure ($\forall$ j$\in$ M). P_{TE} is also the probability of the TE.

Finally, the Onisawa relation was used to convert CFP to failure probability (FP) using eq (6). Using this relationship, the CoA output becomes probabilistic . K in this equation is an intermediate variable that depends only on CFP.

$$FP = \begin{cases} \frac{1}{10^K} CFP \neq 0\, K = \left[\frac{1-CFP}{CFP}\right]^{\frac{1}{3}} \times 2.301 \\ 0\, CFP = 0 \end{cases}, \quad (6)$$

Then the probability of occurrence of a pool fire with respect to the probability of an immediate ignition was obtained from Equation (7).

$$P_r(Consequence) = P_r(TE) \times \prod_{j=1}^{n} P_r(E), \quad (7)$$

Here, $P_r(Consequence)$ is the probability of each outcome, $P_r(TE)$ is the probability of the main event, and $P_r(E)$ is the probability of failure or success of the protective layers.

According to Bevi's instructions, the probability of immediate and delayed ignition for flammable and volatile liquids with a flashpoint less than 21 C is 0.065 and 0.935, respectively . In the present study, basic, intermediate, and TEs, immediate, and delayed ignition barriers and consequences, were entered into the GeNIe software version 2.3 as root, intermediate, central (leaf), barrier, and consequences nodes, respectively, based on the study of Khakzad et al. (see Fig 3) and after creating CPTs for different nodes, probability updates were obtained.

2.2. Analyzing the domino effect and calculate the joint probability distribution

In this study, their effects in the studied units were investigated using the Bayesian network and probit methods. In probit methods, both the type of equipment and escalation vector are considered to calculate the amount of probit (Y). In general, Y can be obtained using Eq (8).

$$Y = a + b\ln(V), \quad (8)$$

In this equation, a and b are probit coefficients, which are determined using experimental data and regression methods, and V is the escalation vector or relevant parameters (for example, in the case of radiation flux, the failure time of the vulnerable equipment is considered as time to failure, TTF (s)). After determining Y, the probability of escalation ($P_{Escalation}$) can be calculated using the following equation:

$$P_{Escalation} = \Phi(Y - 5), \quad (9)$$

In this study, to obtain probit values for radiation flux, the probit methods proposed by Cozzani et al. were used . The procedure can be summarized as follows in 9 steps.

Step 1. Select study nodes (three tanks) and identify the domino effect primary unit (Primary Event) using the safety and accident reports, and the results of the existing risk assessment (tank T1).

Step 2. Calculate the resonance vector based on the type of possible scenario using the amount of heat radiation calculated from PHAST software version 7.2 (consequence modeling).

Credible Event Scenario Consequence Modelling (CESCM)

In this study, to estimate the severity of the outcome of the accident scenario and heat radiation, a valid and specific method of process systems called CESCM modeling was used using PHAST software version 7.2. Therefore, methanol leakage from the connection of the tank to the side pipes and pool fire was selected as a scenario and possible outcome. The credible scenario was selected according to the Total standard (GS EP SAF 253) and the diameter of the outlet pipe, for a leakage size of 150 mm (large leakage) . The determined leakage is equal to 20% of the diameter of the outlet pipe according to the Total standard . Table 1 shows the physical and operational characteristics of the studied tanks for modeling.

Table 1. Consequence modeling information

Parameter	**The amount or type**	**Parameter**	**The amount or type**
Nominal capacity (m^3)	64700	relative humidity (%)	62.5
Inner diameter × Cylindrical height (mm)	24100×63000	Temperature ($^{\circ}$C)	40
Material stored	Methanol	Leak diameter (mm)	150
Operating temperature ($^{\circ}$C)	40	Leak Direction	Horizontal
Operating pressure (bar)	0.0013	Dominant wind speed (m/s)	5.2
Flash Point ($^{\circ}$C)	14	Atmospheric stability class	E
IGBS	Nitrogen	Surface roughness (m)	1
Largest Nozzle Diameter (in.)	30	Dominant wind direction	North West
Nozzle height (m)	1		
Roof Type	Cone with an internal floating roof		

Note: IGBS = Inert gas blanketing system

Step 3. Determine the potential secondary unit by comparing the resonance vector with the threshold value (TV). TV is an important criterion for identifying the occurrence of fire dominoes, and dominoes will not occur if the physical effects or escalation vectors are less than this value. Cozzani et al. determined 15 kW/m^2 as the threshold value for atmospheric storage tanks . To determine which units are affected, the initial vectors applicable to adjacent units as a result of the initial event should be compared with the predetermined threshold values. If the escalation vectors are significantly higher than the corresponding threshold, they have sufficient power to damage adjacent units, which leads to a loss of safety or physical integrity. Therefore, primary screening of adjacent units was performed with this comparison, and potential secondary targets are identified .

Step 4. Calculate the amount of probit for pool fire.

$$Y = 12.54 - 1.847 \ln(TTF), \quad (10)$$

$$\ln(TTF) = -1.128 \ln Q - 2.667 \times 10^{-5} V + 9.877, \quad (11)$$

Here Y is the amount of probit, TTF is time to failure (in seconds), Q is heat radiant, and V is the unit volume.

Step 5. Calculate the escalation probability for potential secondary units using the amount of probit considering the initial event and conditional probabilities.

$$P_d = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} e^{-x^2/2} dx, \quad (12)$$

Step 6. Identify the secondary units with the highest escalation probability and draw the arcs.

Step 7. Identify potential accident scenarios and their probability of occurrence for secondary units: we determine the potential accident scenarios and their probability of occurrence for these units by assuming that the secondary units are damaged.

Step 8. Consider the secondary units as the primary unit and repeat the previous steps to determine the next potential units. After creating a probabilistic propagation pattern for the domino effect in the BN and calculating the probability of the initial event and the conditional probabilities of other events, the combined probability distribution for the events involved in the domino effect can be calculated with GeNIe software. A noteworthy point in this study as an innovation is the use of L-NOR gates to determine domino effects. Because there is a possibility of failure of any of the tanks without considering the domino effects.

Therefore, in this study, L-NOR gates were used to modify the CPTs. When a child node is affected by the parent nodes, the overall effect of the parent nodes can be calculated using equations (13) and (14) . If we consider the initial probability X (P_{Leak} or leak probability) as an independent parent, then we use equation (14) to calculate the probability X (considering its parents and initial probability).

$$P(X|Pa(X)) = 1 - \prod_{i \in Pa(X)} (1 - P_i), \quad (13)$$

$$P(X|Pa(X)) = 1 - (1 - P_{leak}) \prod_{i \in Pa(X)} (1 - P_i), \quad (14)$$

Pi is the probability X given that its i^{th} parent is true and the others are false.

Assuming that one of the variables Xi occurs and the other variables do not occur, the occurrence of the child node Y or Pa (X) can be expressed as follows:

$$P_i = P(Y = 1 | \overline{x_1}, \overline{x_2}, \ldots, x_i, \overline{x_{i+1}}, \overline{x_n}), \quad (15)$$

Step 9. Perform a sensitivity analysis by Ratio of Variation (RoV) method: Sensitivity analysis is also used to identify the most important basic events that cause process failure . The RoV method is calculated based on the previous probabilities ($\theta(X_i)$) and the posterior probabilities of the root nodes ($\pi(X_i)$) as follows:

$$RoV_{X_i} = \frac{\pi(X_i) - \theta(X_i)}{\theta(X_i)}, \quad (16)$$

3. Results

3.1. Determining the probability of tank failures

In this study, a bow tie model was drawn according to Fig 4. As the main scenario in this study is the pool fire, the probability of its occurrence was calculated using FFT and FBN.

According to Tables 2 and 3, 58 basic events and 30 intermediate events were identified, which are a combination of process, human and organizational, management factors. Then the probability of occurrence of basic events was obtained using linguistic terms and the opinions of experts and fuzzy logic. Experts included safety supervisor, Master of analyzer and instrumentation, Master of Maintenance Planning, and operation supervisor, which had weight factors of 0.274, 0.235, 0.235, and 0.254, respectively. Weight factors were calculated based on Lavasani and Renjith methods.

After obtaining expert opinions, the corresponding fuzzy numbers were obtained for each linguistic term. The formulation was performed in a spreadsheet and by calculating the values of AFFP, CFP, and variable K using the Eq 1 to 5, FP (FFT) was obtained, the results of which can be seen in table 2. The probabilities were also updated after the transfer of various events in BN and GeNIe software, the results of which can be seen in the last column of the table. Updated values of basic events showed that X12, X51, and X32 had the largest shares in the occurrence of TE. X4, X3, and X2 also had the lowest FP, respectively.

Table 2. Expert opinion, fuzzy and FBN probabilities of root events

event	Description	Expert opinions	FP (FFT)	FBN	event	Description	Expert opinions	FP (FFT)	FBN
X1	BV failure	M, L, L, L	0.000367	0.000367	X30	The same sound frequency related to the alarm	M, L, H, RL	0.002422	0.002422
X2	PCV failure	RL, L, L, L	0.000119	0.000119	X31	Shift work	RL, L, RH, M	0.002352	0.002352
X3	Insufficient supply of N^2	L, L, L, L	4.575E-5	4.5759E-5	X32	Incorrect job description	L, M, H, M	0.004478	0.004478
X4	Failed to send signal	L, L, L, L	4.575E-5	4.5759E-5	X33	High working pressure	L, RH, M, M	0.003468	0.003468
X5	Failure of PT_1	L, L, M, L	0.000294	0.000294	X34	Inadequate standards audits and Procedures	VL, M, M, RL	0.001039	0.001039
X6	Failure of PT_2	L, L, M, L	0.000294	0.000294	X35	Lack of updated instructions and Procedures	L, RH, M, RL	0.002164	0.002164
X7	No HH Alarm on PT	L, M, RL, M	0.001395	0.001395	X36	Insufficient knowledge	M, RL, M, M	0.003334	0.003334
X8	No LL Alarm on PT	L, M, RL, M	0.001395	0.001395	X37	Defects in staff training and awareness	RH, M, M, M	0.007538	0.007538
X9	Failure of PI_1	L, RL, M, L	0.000477	0.000477	X38	Insufficient communication	RL, VL, RH, M	0.001961	0.001961
X10	Failure of PI_2	L, RL, M, L	0.000477	0.000477	X39	Communication failure	L, L, RH, RL	0.000934	0.000934
X11	TSV failure in the downstream line of export	RL, VL, RL, M	0.000653	0.000653	X40	Inadequate monitoring	RL, M, RH, M	0.004606	0.004606
X12	Lack of permit	M, M, RH, RH	0.010298	0.010298	X41	Inadequate safety plans	RL, RH, RH, H	0.012207	0.012207
X13	Wrong permit	RH, L, VL, RL	0.000955	0.000955	X42	Poor decision making	L, L, VH, RH	0.004192	0.004192
X14	Lack of implementation	L, L, M,	0.000494	0.000494	X43	Insufficient job knowledge	L, VL,	0.003582	0.003582

	of permit	RL				of managers	VH, RH		
X15	Defects in the correct execution of permit	VL, L, L, RL	6.213E-5	6.2133E-5	X44	Inefficient management behaviors	L, RH, VH, M	0.007439	0.007439
X16	Defects in the restarting	L, VL, M, M	0.000787	0.000787	X45	Poor communication	L, L, VH, RH	0.004192	0.004192
X17	Failure of LI_1	VL, M, M, M	0.000183	0.000183	X46	Mechanical fatigue	L, RL, RH, M	0.002246	0.00224600
X18	LTHH failure	VL, VL, RH, RL	0.000540	0.000540	X47	Thermal fatigue	L, L, L, VL	2.141E-5	0.00002141
X19	LAH failure	VL, RL, RH, RL	0.001022	0.001022	X48	Insufficient accuracy of leak detector equipment	VL, M, H, RL	0.002352	0.002352
X20	LAHH failure	VL, RL, H, RL	0.001448	0.001448	X49	Inspector detection error	L, RL, VH, RL	0.002193	0.002193
X21	Failure of LI2	VL, L, RH, RL	0.000704	0.000704	X50	Lack of cathodic protection	RL, RL, RH, M	0.003072	0.003072
X22	LTLL failure	VL, VL, RH, RL	0.000540	0.000540	X51	Delay in inspection	RH, RH, RH, L	0.008103	0.008103
X23	LAL failure	VL, L, RH, RL	0.000704	0.000704	X52	Poor inspection	M, RL, H, RL	0.004131	0.004131
X24	LALL failure	VL, L, RH, RL	0.000704	0.000704	X53	Insufficient and inadequate methods of corrosion detection	L, L, RL, M	0.000524	0.000524
X25	Physical disability	VL, RL, H, RL	0.001448	0.001448	X54	Lack of monitoring of welds and joints	L, M, RH, RL	0.002164	0.002164
X26	Low job motivation	L, M, H, RL	0.002877	0.002877	X55	Poor monitoring of welds and joints	L, RL, RH, M	0.002246	0.002246
X27	Insufficient skill	L, M, M, M	0.002276	0.002276	X56	Distraction and disregard for driving principles	VL, VL, M, RL	0.000248	0.000248
X28	Defects in the improvement of the operator skill system	L, M, M, RL	0.001337	0.001337	X57	Lack of necessary skills	L, L, RH, M	0.001679	0.001679
X29	Defects in human activity locking equipment	VL, VL, H, RL	0.000823	0.000823	X58	Unauthorized speed	L, L, M, RH	0.001746	0.001746

Note: BV = Breathing valve; FBN = Fuzzy bayesian network; FFT = Fuzzy fault tree; FP = Failure probability; H = High; HH = High high; L = Low ; LAH = Level alarm high; LAHH = Level alarm high high; LAL = Levl alarm low; LI = Level indicator; LL = Low low; LTHH = Level transmitter high high; LTLL = Level transmitter low low; M = Medium; PCV = Pressure control valve; PI = Pressure indicator; PT = Pressure transmitter; RH = Relatively high; RL = Relatively low; TSV = Temprature switch valve; VH = Very high; VL = Very low.

The various intermediate events (IEs) are also summarized in table 3. FFT and FBN values were obtained according to the type of gate between events and CPT, which are seen in the third and fourth columns of table 3. The results of inductive reasoning of fault tree showed that FFT for TE was equal to 0.11213960 but the FBN calculated the probability of its occurrence being 0.063, which is smaller than the value calculated by the fault tree method. Because the fault tree method calculates the TE probability assuming it is independent, however, the BN method considers the statistical dependence between events when calculating the TE probability. The probability of pool fire according to the method, based on BTA and FBN was equal to 0.007289 and 0.0041266742, respectively.

Table 3. Fuzzy and FBN probabilities of intermediate and TEs

Events	Description	FFT	FBN
I1	Pressure control system failure	0.03408536	0.03358500
I2	Level control system failure	0.03407713	0.03358500
I3	M&OB failure	0.00065556	0.00064200
I4	Preventive maintenance Barrier failure	0.02705241	0.02674700
I5	Vehicle collisions	0.01626913	0.01619300

I6	Failure in IGBS and BV	0.00000000	0.00000000
I7	Heat source during box up conditions	0.00000823	0.00000821
I8	Human Error	0.00000341	0.03358500
I9	Failure in IGBS	0.00000000	0.00000000
I10	Defect in permit	0.01259613	0.01257000
I11	Defects in monitors and alarms	0.00000000	0.00000000
I12	PT Defect	0.00000000	0.00000000
I13	PI Defect	0.00095400	0.00095300
I14	Overfilling	0.00000000	0.00000000
I15	Excessive emptying	0.00000000	0.00000000
I16	LSL Failure	0.00000050	0.00000050
I17	Personal characteristics	0.00793800	0.00791500
I18	Defects in human-system interference Barrier	0.00324500	0.00324300
I19	Defects in the design of Boardman's job and workplace	0.02289413	0.02270500
I20	LSH Failure	0.00000148	0.00000148
I21	Insufficient skills	0.00361300	0.00360900
I22	Incorrect work schedules	0.02054213	0.02040100
I23	Organizational Barrier Failure	0.03378300	0.03333900
I24	Managerial Barrier Failure	0.01940500	0.01926800
I25	Insufficient knowledge	0.01087200	0.01084600
I26	Improper communication	0.00289500	0.00289300
I27	Fault in leak testing	0.00454500	0.00453900
I28	Corrosion	0.01583000	0.01575100
I29	Failure to monitor the destruction of welds and joints	0.00441000	0.00440500
I30	Failure to detect corrosion	0.01275800	0.01271800
TE$_{\textbf{Methanol leakage}}$		0.11213960	0.06300000

Note: BV = Breathing valve; FBN = Fuzzy bayesian network; FFT = Fuzzy fault tree; IGBS = Inert gas blanketing system; M&OB = Managerial and organizational barrier; PI = Pressure indicator; PT = Pressure transmitter; LSH = Level switch high; LSL = Level switch low

3.2. Analyzing the domino effect and calculating the joint probability distribution

3.2.1. Consequence modeling and heat radiation

Fig 5 shows the area affected by different amounts of heat radiation in terms of distance from the accident site. According to the figure, the amount of heat radiation caused by a methanol tank is constant up to a distance of 68 meters and is equal to 50 kW/m^2, which is the highest amount of heat radiation due to the failure of a tank. According to Fig 6, the affected spaces due to heat radiation of 37.5, 12.5, and 4 kW/m^2, were equal to 169.06, 116.02, and 72.048 meters, respectively.

3.2.2. Analysing the domino effect

The studied tanks are located on a straight line with the same distance between them and were considered as three study nodes. Based on the results of risk assessment, storage tanks have an initial FP of 0.11213960 and 0.063 based on the results of FFT and FBN. The amount of heat radiation at a distance of 107.8 meters was equal to 15.8 kW/m^2, which is more than the TV. Therefore, due to the distance of 37 meters between the two tanks, the fire created in tank 1 (T1) will cause a domino effect in the first level. The distance from tank T1 to tank T3 is 118 meters.

Tables 4 and 5 show the probabilities of exacerbating the domino effects of initiating events. Node T2 is a potential secondary node, its escalation probability is shown in Table 5. The results of the combined escalation effects of the two tanks T1 and T2 in the second level of dominoes are also given in this table.

Table 4. The probability of escalation of domino effects caused by T$_1$ tank failure if ($P(T_2 \vee T_3|T_1)$

T2					**T3**			
Initiator or primary event	**Heat radiation (kW/m^2) & Distance (m)**	**Ln$_{ttf}$**	**Probit value (Y)**	**Probability (P)**	**Heat radiation (kW/m^2) & Distance (m)**	**Ln$_{ttf}$**	**Probit value (Y)**	**Probability (P)**
T1	50 (37)	3.738	5.635	0.737	11 (118)	5.446	2.481	0.0059

Note: T = Tank

Table 5. The probability of escalation of domino effects caused by T$_1$ tank failure if ($P(T_3|T_2) \wedge P(T_3|T_1, T_2)$)

Initiator or primary event	**T3**			
	Heat radiation (kW/m^2) & Distance (m)	**Ln$_{ttf}$**	**Probit value (Y)**	**Probability (P)**
T2	50 (37)	3.738	5.635	0.737
T1 & T2	61	3.514	6.049	0.852

Note: T = Tank

Therefore, according to the above, the results can be presented in the following table.

Table 6. Conditional probability of tank 3 due to fire or safety of tanks 1 and 2

Row	**T1**	**T2**	**T3**
1	Fire	Fire	Fire

2	Fire	Safe	Safe

Note: T = Tank

Also, it can be concluded that:

$$P(U)=P(T1)\,P(T2|T1)\,P(T3|T2,T1), \quad (17)$$

Here P (U) is the joint probability. The chronological or sequential probability sequence of events will also be T_1, T_2, and T_3. It is noteworthy that, if the domino effect does not occur, there is still a possibility of an accident in T3, which is the initial probability of T3. Therefore, L-NOR gates were used, the results of which can be seen in table 7. Conditional probabilities between nodes in the previous step were calculated using the probit equations and used together with the initial tank probabilities to complete the CPTs and update the probabilities. Table 7 shows the probability of a domino accident caused by a pool fire using the BTA and FBN methods at the first and second levels.

Table 7. Probability of a domino accident caused by a pool fire in the first and second level

Method	P_{leak}	First level	Second level
BTA	7.2890E-3	0.0126073650	0.0116507438
FBN	4.1266E-3	0.0071472631	0.0090630640

Note: BTA = Bow-Tie analysis; FBN = Fuzzy bayesian network

The results of the Domino effect sensitivity analysis based on the RoV method are shown in Fig 7. Three nodes are in the same direction and line, but due to a better representation of the causal relationships between them were drawn with a slight change. According to the results, in case of fire in tank T1 and co-occurrence (T1 and T2), RoV values for tank T2 and T3 were equal (101.989, 138.913) and (57.234 and 77.730), respectively.

4. Discussion

The present study provided an approach for analyzing domino effects and risk assessment using FBN. In this study, we tried to reduce uncertainty by using FBN and modifying CPTs. As mentioned earlier, there is uncertainty in the various stages of risk assessment studies. Markowski et al. (2010) discussed in a study the sources and types of uncertainty in process safety analysis (PSA) as well as methods to deal with them . Unfortunately, for some basic events, there is no failure rate or it is not highly reliable . The use of fuzzy logic and expert opinions can address this problem. BN is a reliable method in evaluating process safety analysis that has features such as graphical representation and strong reasoning , which will be discussed further below.

The study of domino accidents has become an interesting field for researchers due to its importance in various industries, especially process industries. There are different methods for estimating domino effects. In this study, probit methods, consequence modeling, and CPT modification with L-NOR gates were used to investigate the domino effects. Kadri et al. (2013) proposed a hybrid method that quantitatively evaluates the effects of a domino event using probabilistic models and physical equations . Kourniotis et al. (2000) examined a statistical approach to analyze the domino effect. In this approach, past events were statistically analyzed to better understand the pattern of dominoes, consequences, and materials, and the results were updated based on new information about the accident using Bayesian inference . Cozzani and

Salzano's approach was to analyze the domino effect of excessive blast pressure using probit models . Abdolhamidzadeh et al. (2010) proposed a simulation-based method. This methodology is called FREEDOM and can evaluate very complex and nonlinear systems but can not manage more than a few uncertain parameters . |In a study, Khakzad and Reniers (2017) estimated the risk of dominoes caused by tank fires and suggested the best design and location of tanks according to various factors in the study using BN and analytic hierarchy process (AHP) methods .

In this study, the domino effects of three tanks containing methanol with similar volume and characteristics that were located in the same direction and distance were investigated. The results showed that in case of fire in the first tank, the first and second levels of dominoes occur and the second and third tanks are involved, respectively. The amount of heat radiation exceeds the threshold and escalation effects will occur.

Various studies have provided different values for the threshold, ranging from 9.5 to 38 kW/m^2 . If a higher heat radiation threshold value is considered between the storage tanks, the safer distances will be higher and the results will be more conservative. The study of Cozzani et al. (2006) also considered the TTF in determining this threshold that this failure time is affected by active and passive control barriers. Lees also considered 37 kW/m^2 as the TV . Irrational consideration of this threshold will lead to a loss of resources and increase costs while also providing higher safety. Therefore, the threshold or intensification threshold in this study, like the study of Cozzani et al. (2006) for atmospheric storage tanks, was considered 15 kW/m^2 . If the heat radiation is less than this value, a domino accident will not occur. In this study, the escalation vector was greater than the TV.

The important point is that even if the domino effect does not occur, there is still the possibility of an accident in the tanks. Therefore, P_{leak} in the studied tanks was equal to 0.00012 which was obtained from the results of risk assessment. Despite the many advantages of BN, such as the ability to process uncertainties over conventional methods, it also has disadvantages such as the difficulty of determining CPTs . In this approach, L-NOR gates were used to modify the structure of CPTs . If this type of gate was not used in studies, the size of CPTs will be much larger and the calculation of probabilities will be very complicated .

In this study, a comparison between BTA and FBN was performed to analyze the domino effects. Given the advantages of the FBN approach in reducing uncertainty and dynamism, it can be said that this approach provides more realistic results in risk assessment and analysis of domino effects. Considering events with common cause failures (CCFs) and conditional probabilities in BN were other advantages . While FTA and BTA statically examine probabilities, the FBN approach considers dynamic aspects while computing probabilities. FBN results showed that defect or absence of permit and delay in inspection and incorrect job description were important causes of methanol leakage. According to the human factors analysis and classification system (HFACS) approach, the root of these basic events is the defect of organizational and management factors .

5. Conclusion

In this study, a FBN-based approach was presented to analyze the domino effects of atmospheric storage tanks. The variables affecting accident risk, and FTA and BTA approaches are dynamic and static, respectively. Therefore, the use of BN, which is dynamic in nature and has unique features such as considering conditional relationships between events, deductive and inductive reasoning, makes the created model more realistic and reduces uncertainty. In this approach, as a new topic in the study of domino effects, due to the initial probability of failure of each tank, L-NOR gates were used to modify the structure of CPTs, and conditional probabilities between nodes were calculated using probit equations. Thus, the BN model of the study can reduce uncertainty and examine complex causal relationships and sequential dependent failures.

On the other hand, the lack of a database for different failures, numerous social and cultural differences, and different equipment specifications, always make systems uncertain. Therefore, the use of fuzzy logic in this study to calculate the failure rate helped reduce uncertainty. In this approach, all factors affecting the occurrence of consequences, including organizational, management, human, and process factors were examined. The results of a case study showed that the use of L-NOR gates and their mapping to BN reduced the uncertainty, complexity, and size of CPTs. FBN and L-NOR gate combination is an effective way to evaluate the reliability of tanks.

The probabilities of occurrence in FFT and BTA results were greater than the FBN in DRA and domino analysis. Therefore, considering the characteristics of the FBN approach, the results were more realistic than the FFT and BTA results.

Disclaimer: None

Declarations of interest: None

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References

Fig 1. The usual BN.

Note: X = Node.

Fig 2. Arrangement of tanks and their position in the studied petrochemical plant.

Fig 3. The framework of the proposed method.

Note: AFFP = aggregated fuzzy failure possibility; BaN = barrier node; BN = bayesian network; CFP = crisp failure probability; CN = central node; FBN = fuzzy bayesian network; IE = intermediate event; IN = intermediate node; L-NOR gate= leaky noisy OR gate; MN = main node; Pleak = leak probability; RN = root node; RoV = ratio of variation; TE = top event; Y = probit value.

Fig 4. Bow-Tie diagram for atmospheric storage tanks.

Note: X = basic event; I = intermediate event; The full colour version of this figure is available online.

.**Fig 5.** Heat radiation caused by pool fire according to the distance from the accident site

Fig 6. Space affected by pool fire radiation.

Note: The full colour version of this figure is available online.

Fig 7. Sensitivity analysis of the domino effect of the studied tanks, (a): Overview, (b, c): Sensitivity analysis of T1 and T2 tanks separately and together.