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Dynamic risk assessment of storage tank using consequence modeling and fuzzy Bayesian network

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A R T I C L E I N F O

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A B S T R A C T

Accidents in process industries cause irreparable economic, human, financial and environmental losses annually. Accident assessment and analysis using modern risk assessment methods is a necessity for preventing these accidents. This study was conducted with the aim of Dynamic risk assessment of tank storage using modern methods and comparing them with traditional method. In this study, bow tie (BT) method was used to analyze the Leakage event and its consequences and model the cause of the outcome, and the Bayesian network method was used to update the probability rate of the consequences. Then, four release scenarios were used. Possible selection and release outcome were modeled using version 5.4 of ALOHA software. Finally, according to the degree of reproducibility of possible consequences and risk number modeling for the four scenarios were estimated. The results of modeling the cause and effect showed that 50 Basic events are effective in chemical leakage and Pool fire is the most probable consequence due to chemical leakage in both BT and Bayesian network (BN) models. Also, the modeling results showed that Leakage 50 mm diameter has the highest Emission rate (80 kg/min) and Leakage of 1 mm have the lowest emission rate. The results of risk assessment showed that the estimated risk number in both models is in the unacceptable range. In this study, an integrated approach including BT, Fuzzy Bayesian networks and consequence modeling was used to estimate the risk in tank storage. The use of these three approaches makes the results of risk assessment more objective than conventional methods. The results of outcome modeling can be used as a guide in adopting accident prevention and emergency preparedness approaches.

1. Introduction

Along with the increasing growth of industries, the use of hazardous chemicals has also increased significantly. Fire, explosion, and

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release of toxic substances are the most likely harmful consequences in these industries. Which, in addition to causing harm to employees, significant financial and environmental damage, can also affect nearby residents. The Bhopal disaster, which occurred in 1984 due to a methyl isocyanate leak, killed more than 2,000 people in the nearby town, and thousands of people died of disease years later. This incident is a clear example of an accident that led to large-scale human damage without fire and explosion and even with the factory remaining intact [1]. Therefore, the consequences of the release and leakage of hazardous toxic substances have always been of great importance in safety and health programs [2]. Secondary, industrial accidents may also occur as a result of natural disasters, therefore investigating accidents due to possible leakage of storage tanks and how to deal with them in emergency situations in emerging countries such as Iran is an important preventive measure [3]. Emergencies usually include toxic gas leaks, explosions, fires, chemical spills, and hazardous leakage of explosive and flammable gases [4,5]. Toxic and flammable chemicals are generally released due to the rupture of tanks, transfer pipes and other fittings. This accident usually has harmful consequences and, in many cases, can be prevented.

According to Zarei et al. [6], the first effective measure to prevent such an accident is the quantitative risk assessment of these sites so that the necessary preventive and control strategies can be designed and implemented based on the results of these studies. Two parameters play a major role in risk analysis. The first parameter is the probability of occurrence and the second parameter is the severity of the consequence. The probability of an event, the possibility of an event occurring or the defect leading to the event over a period of time. The severity of the consequences of an accident means the harmful effects of that accident [7].

In cases where a scenario has never occurred or occurs with very low frequency during lifetime, there is insufficient historical failure data to estimate the probability of failure in system components [8]. One of the methods of determining the probability of failure in the conditions of uncertainty is the use of fuzzy theory. The theory of fuzzy set of probabilities was first introduced in 1989 by Lotfizadeh [9]. In this study, fuzzy set theory was used to estimate the probability of basic events.

Predicting accident probability is the most important step in safety analysis. There are many ways to determine probability in risk analysis. Among the probabilistic methods for predicting the probability of accident and analyzing the accident are Fault tree method, Event tree method, Bow tie method and Bayesian network method [10]. Although, risk assessment methods have an important role in identifying risks and hazards, they have limitations made them difficult in analyzing the risk of complex and reciprocal systems [11]. The Fault tree method is widely used in the field of risk analysis, and error detection [12]. The standard fault tree is not suitable for analyzing large systems, especially if the system with high error, common cause errors, or primary events that interact with each other. Most importantly, the Fault tree method considers all events independently, which is usually not valid [13].

Therefore, due to the static nature of Fault tree and Event tree methods, these methods are not compatible with dynamic environments. Dynamics of the environment can be due to changes in environmental conditions (temperature, pressure, etc.), operation and changes in attitudes toward accidents and quasi-accidents. The shortcomings of conventional methods in dynamic risk analysis and the application of Bayesian methods in risk assessment and safety analysis were considered in the late 1970s [14,15]. Bayesian method is an effective method for situations where there is little data available and different information and is also a good framework for determining the range of probabilities for cases such as decision making in uncertain conditions [16].

There are two types of problem knowledge: a. Objective knowledge based on the formulation of the engineering problem (e.g. by mathematical modeling and simulation), and b. Knowledge extracted from experts is often incomplete, imprecise, fragmented, unreliable, ambiguous, and contradictory [17,18]. Fuzzy logic may be useful when the dominant uncertainties are due to a lack of knowledge [17].

Therefore, in this study, fuzzy logic and Bayesian Networks (BNs) were used to reduce uncertainty. Fuzzy logic is used in conditions of ambiguity and uncertainty and multi-valued logic is used instead of two-valued. In other words, it can deal with uncertainties and inaccuracies where there are no clear boundaries [17].

Uncertainty refers to a situation in which the probability of events cannot be measured due to the lack of sufficient information in oxygen tanks. In the study of Markowski et al., various methods were also mentioned to reduce uncertainty, including expert methodology, sensitivity analysis, statistics, and fuzzy logic [19,20].

Paragraphs on uncertainty reduction were added to the text. In the limitations section, it was mentioned that the uncertainty in this study is not quantifiable and measurable. Sentences related to reducing uncertainty were revised and spoken more gently in this context.

In modern safety approaches, outcome prediction or modeling is used as an important part of the accident prevention program or to reduce potential losses and determine the severity of consequences. Consequence modeling is mainly done using mathematical equations. Studies have recommended consequence modeling as a suitable tool for the design and safe operation of hazardous industrial units [21]. In addition, the results of these assessments form an important part of an organization's risk management decision-making framework for accident prevention. However, modeling the emission of pollution has its own requirements and the role of various factors must be properly considered. Factors such as: characteristics of the released material, characteristics of the production process, characteristics of the external environment (including climate and topography of the region) [22].

Various tools such as software are used to model the outcome. One of the most suitable modeling software to release toxic substances, fire and explosion is ALOHA software [23]. Developed in collaboration with the US Environmental Protection Agency, the US Oceanic and Atmospheric Administration and the Office of Chemical Prevention and Emergency Preparedness, the tool has a database of information on 1,000 pure and mixed substances. This software is for various applications in the field of safety, including assisting with chemical crisis management, access, storage, information management and airflow mapping in the event of an accident, assessing compliance of activities with environmental regulations related to maintenance and Chemicals, risk management, etc. are used. However, the accuracy of the results can be reduced due to some parameters such as high atmospheric stability, very low wind speed and with frequent changes in wind flow, the presence of certain materials, the presence of fire reactions, etc. [24].

Despite some limitations, its use can provide good results. Consequence modeling of material leakage with this software has been done in various studies. Yang et al. studied the modeling of leakage consequences from Propylene Storage Tank with this software [23]. Predrag Ilic et al. modeled the leakage consequence of chlorine with ALOHA and used it to prevent future accidents and integrate it into risk assessment [25]. Modeling the consequences of ammonia gas emissions and preparing an emergency response plan were studied in the study of Afonso Henrique da Silva Júnior et al. [26]. Therefore, consequence modeling of such industries can play an effective role in reducing human and environmental losses [27].

In the tablecloth industry, various paints and solvents, including acetone, are used as paint evaporators in the painting and dyeing industries to create various patterns and designs. Because, these materials are stored in large tanks, there is always the possibility of possible leakage from these sources. Therefore, the prevention of possible accidents and the preparation of emergency response plans require that leak modeling of the leakage of these materials be carefully considered.

In the studied industry, risk assessment and consequence analysis is done in a completely traditional way using the usual methods of risk assessment, considering the nature of the process of this industry and how the process units operate, the use of more up-to-date methods can be a suitable solution for Identification, evaluation and evaluation of possible risks is one of the most important illuminating aspects of this study is the use of combined methods in this industry, which may be able to take a special look at this type of industry and use more up-to-date methods in quantitative risk analysis and evaluation. To some extent lead to a reduction in the rate of accidents in this type of industry.

Therefore, the purpose of this study is to provide a method for dynamic risk assessment of acetone-containing tanks. The Event tree method was used to determine the probability of major events due to acetone leakage and the Bayesian network method was used to update the probability of final consequences. ALOHA software was used to determine the severity of the consequences of acetone leakage.

2. Materials and methods

This study was conducted in the printing hall of one of the tablecloth production companies in Tehran. In the printing hall, various patterns and drawings are printed on the table. Paint evaporating solvents such as acetone are used for this purpose. Fig. 1 shows the method of performing Dynamic risk assessment of acetone tanks.

2.1. Cause – effect modelling of accident scenario

2.1.1. Fuzzy-BT method

Bow tie diagram depicts the risk under consideration in a simple and understandable way. The advantage of this method is to show the possible scenarios in the assessment of a risk and the logical connection between its causes and consequences in a diagram, scenarios that would be depicted in any other way more complicated. With the help of this method, it is possible to determine the most important scenarios and control risk and reduce unwanted events [28]. Bow-tie diagram consists of five main elements: basic events,

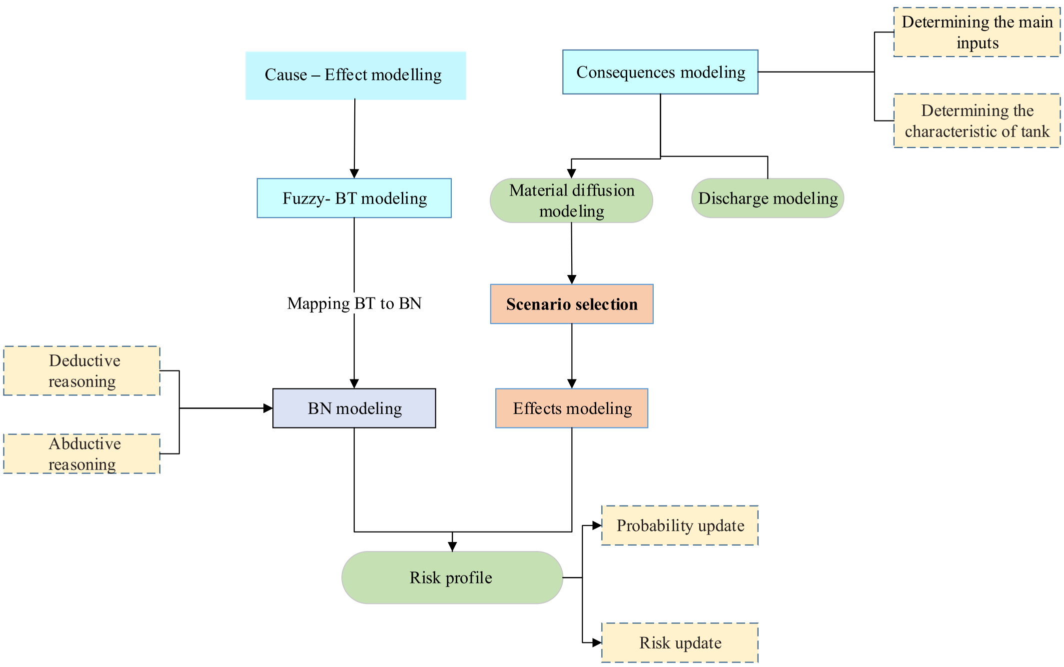

Fig. 1. Study method.

fault tree, initiating event, event tree and output event [29]. This technique is one of the most effective methods in risk management and assessment, the right side of this technique is the Event tree and the left side is the Fault tree [30]. In this study, the Fault tree method was used to identify the basic events in the occurrence of acetone leakage from storages [31]. The probability of the final event was determined by knowing the probability of occurrence of the basic events and according to the type of gate used. In order to identify and calculate the order of occurrence of potential scenarios involved in the accident, the Event tree method was used.

Due to the unavailability of failure frequency data, the results of experts' opinions were used through a questionnaire to calculate the failure probability of events. In this study, the fuzzy numbers corresponding to the qualitative input and results data were used using a 7-point linguistic term including very low, low, fairly low, medium, fairly high, high and very high opinions [32].

In the conducted studies, there are various techniques for the consensus of experts' opinion, such as linear survey, maximum-minimum Delphi method, sum-product, max-product. In this study, the sum-product algorithm and equation (1) were used for consensus among experts [33].

$$Z_i = \sum_{j=1}^{n} w_j f_{ij} \quad \mathrm{i} = 1, 2, \ldots, \mathrm{m} \quad \mathrm{j} = 1, 2, \ldots \mathrm{n} \tag{1}$$

In this regard, Zi is the probability of fuzzy failure, Wi is the weight of expert j, fij is the possibility of fuzzy failure expressed by experts j, n: the total number of experts and m is the total number of events.

To make decisions in a fuzzy environment, de-fuzzing fuzzy numbers is a very important method. According to the experts, the obtained number is still a possibility that should be diffused. There are several methods for dephasing, including the CoA surface center method, max-min, the center of the largest surface, Weighted average, Mean max, and Bisector [34,35]. In this study, the max-min method which presented by Chen and Hwang [33] has been used.

Then, the corresponding fuzzy values were determined using Zhang et al.'s method [36], so that after defining and selecting the experts according to the criteria of organizational rank, experience, results, and age, the weighted average of the experts was determined. Trapezoidal fuzzy membership functions were used to fuzzify the data, and equation (2) was used for the purpose of fuzzifying and converting fuzzy numbers into crisp failure possibility(CFP).Then, in order to convert the CFP into probability numbers, the equation provided by Onisawa (Equation (3)) was used [37].

$$CFP = \frac{1}{3} \times \frac{(a_4 + a_3)^2 - (a_4 + a_3) + (a_1 + a_2) - (a_1 + a_2)^2}{a_4 + a_3 - a_2 - a_1} \tag{2}$$

$$FP = \begin{cases} \frac{1}{10^K} & \mathrm{CFP} \neq 0 \\ 0 \quad \mathrm{CFP} = 0 \end{cases} \quad \mathrm{K} = \left[\frac{1 - CFP}{CFP}\right]^{1/3} \times 2.301 \tag{3}$$

2.1.2. Bayesian Networks

Bayesian network is a graphical model to show the relationship between the desired variables. The Bayesian network is a non-circular directional diagram [38]. Bayesian networks not only use Bayesian theory to update probabilities, but also, have a fully flexible and compatible feature for dynamic modeling of a wide range of accident scenarios. The Bayesian network uses a set of variables to calculate the coefficient probability distribution [39,40]. According to Bayesian law, if we divide the sample space S into n sets E_1,E_2, …,E_n and set A is a subset of the sample space, then the probability of E_k occurring is determined by condition A from Equation (4) [39].

$$P(E_k|A) = \frac{P(E_k \cap A)}{P(A)} = \frac{P(E_k) \times P(A|E_k)}{\sum P(E_i) \times P(A|E_i)} \tag{4}$$

2.1.3. Algorithm for transferring BT bow tie diagram to Bayesian networks

After plotting the BT diagram and determining the probability of base events by using the Fuzzy set theory, in order to eliminate its shortcomings, this model must be transferred into the Bayesian networks. The Bayesian BN network approach offers more valuable results in risk analysis than BT due to its ability to update old probabilities and consider common cause defects and failures in a system [41]. Therefore, in order to overcome the limitations of BT, a bow tie diagram was transferred according into the algorithm proposed by Khakzad et al. [42].

2.2. Consequences modeling of accident scenario

ALOHA software version 5.4 was used to model the release of these materials. This tool is based on the Gaussian model of continuous diffusion and floating air pollution ducts. According to the standard method guide, internal validation of the method must be done before use. For this purpose, the method was validated by implementing the scenarios presented in the method guide instructions [43]. To model the release from the storage tanks of these materials, it is necessary to collect some information as the main software inputs from various sources. Atmospheric parameters of the desired location are considered as one of the software inputs, so at the beginning of the review of the required information such as average season temperature, air flow velocity, prevailing wind flow direction, latitude and longitude, stability category and others. The required parameters were collected from the Meteorological

Organization, databases, Internet and etc. Information about the acetone storage tank was obtained from data on the shape of the source, the physical dimensions and the amount of material which contain the industry documentation. Fig. 2 shows the P&ID of the tank in question. Summer simulation time, wind speed of 5.5 mph, tank volume of 2200 L, relative humidity 50%, air temperature 80 °F, tank type horizontal.

2.2.1. Scenario selection

The diameter of leakage holes is determined according to the size of the pipes connected to the tanks as well as the transfer pipes of the two studied materials [44]. By examining the conditions, scenarios were examined for Acetone 4. Leakage diameters in the 4 selected scenarios were considered equal to 1, 5, 10 and 50 mm, respectively. For each scenario, a specific code of the same name with the material and diameter of the leakage was specified (Table 1).

2.2.2. Effects modelling

At this stage, various consequences of an accident that could cause casualties were evaluated. The effects of chemical leakage in the two groups of toxicity and fire were investigated and modeled. The toxicity of the material was assessed using a criterion. In the present study, ERPG and AEGL criteria were selected as toxicity assessment criteria. The AEGL standard is set by the US Environmental Protection Agency and identifies three levels. These identified levels are related to population exposures at the levels of AEGL densities of chemicals [45]. Finally, using ALOHA input data, the hazard radius at intervals of 1,2,3 ERPG was determined as completely separate-colored lines. The safe range and concentration of acetone were obtained at different times after releasing from the output of software graphs. In fire modeling, the release of flammable material and exposure to sparks have several possible consequences. The occurrence of these results depends on the time of the spark and its position, and also the phase of the material, the type of release and the environmental conditions.

2.3. Risk estimation

To calculate the probability of injury (grade 1 or 2 burns) or death as a consequence of a specific dose, Equations (5) and (6) are used [46].

$$\text{Pr} = C_1 + C_2 \ln D \tag{5}$$

Where, C_1 and C_2 are constant values that are determined according to Ref. [46] and D is the dose of heat radiation [47] ($w^{4/3} s.m^{-8/3}$).

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} \exp\left(-\frac{u^2}{2}\right) du \tag{6}$$

The risk of the final consequences is calculated by multiplying the probability of occurrence by the severity of the outcome of each scenario. In this study, Bayesian networks were used as an innovation to update the probability of root events and ALOHA was used to estimate the final consequences and predict the amount of heat radiation [48]. Updates are attained by obtaining data on the severity of accidents, human failures and equipment in Bayesian networks. In order to estimate the probability of mortality according to the heat flux estimated by ALOHA software, Equations (5) and (6) were used [49,50]. The severity rate due to the occurrence of each of the consequences was determined from Equation (7) [50].

$$N = D_p A P \tag{7}$$

In this relation, N is the number of deaths (number of deaths/accidents), Dp is the population distribution (person/square meter), A is the area of the affected area (square meters), P is the probability of death.

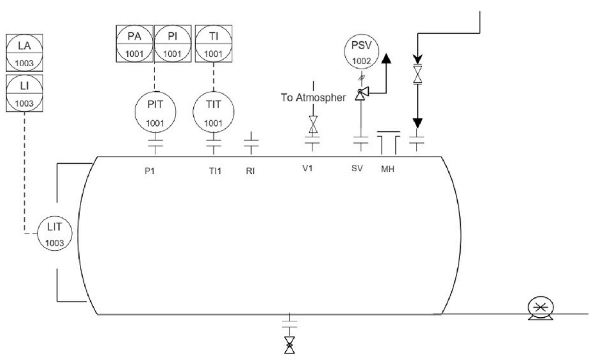

Fig. 2. P&ID diagram of an acetone tank.

Table 1
Characteristics of the studied scenarios of Acetone.

Leakage Diameter (mm)	Material Type	Code	Scenario
50	Acetone	A-50	1
10	Acetone	A-10	2
5	Acetone	A-5	3
1	Acetone	A-1	4

3. Results

3.1. Drawing a BT diagram

BT diagram related to Leakage Acetone from the tank according to Fig. 3 was drawn in the specialized panel with the presence of relevant specialists and operational people. After qualitative drawing of the BT diagram focusing on acetone leakage from the storage, the probability of the final event and the consequences of the acetone leakage were estimated. Given that the flash point of acetone is −18 °C [51]. And according to the BEVI guidelines for substances with a flash point of less than 21 °C [52]. In materials with a flash point below 21 °C, the final consequences of falling in the event of a safety barrier failure (instantaneous spark, delayed spark and enclosed space) include pool fire, flash fire, vapor barrier explosion and safe release of chemicals. Fig. 3 shows Bow Tie Diagram Possible Scenarios. In BT bow tie diagram, Event tree was drawn according to BEVI instructions and acetone flash point. The event tree due to acetone leakage was drawn according to the flammability of acetone according to Juan et al. [53]. As shown in Fig. 3, the basic events are denoted by an X and the middle events are denoted by an IE. Table 2 shows the description of the intermediate events and final outcomes.

In the fault tree, events X37, X38, and X39 all three are the basic events of IE13 (Stress factor). These events can have an effect on each other. In this study, it is assumed that these three basic events are independent. X11 is the base event of the house type.

3.2. Determining the likelihood of basic events and safety barriers

As mentioned, in order to calculate the probability of failure of the main event, it is necessary to determine the failure rate of the root events. Fuzzy set theory is used to determine the probability of root events and safety barriers. In this method, a heterogeneous group of 7 people was used, including safety, process, repair and instrumentation experts. Table 3 shows the description of the basic events and the safety barriers and their probabilities.

3.3. Bayesian network modeling

Bow tie diagram analysis leads to the identification of those root events that cause the occurrence of the main scenario and ultimately the related consequences. Although, the bow tie method is a strong analysis of the causes of accidents, it has limitations that can

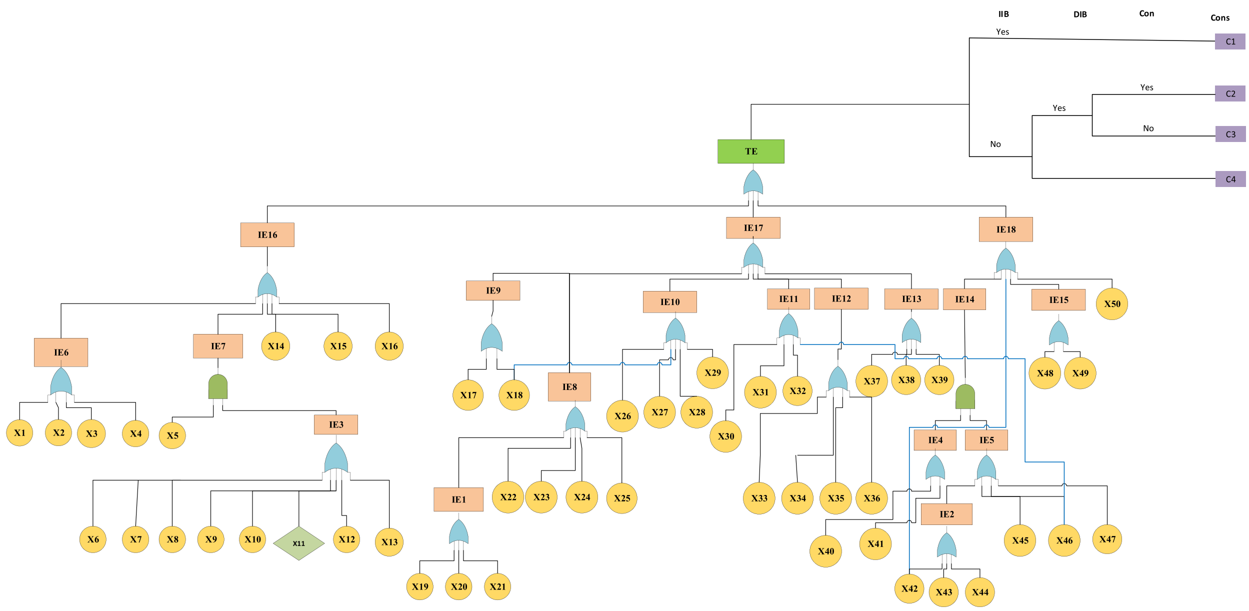

Fig. 3. Modeling the cause of acetone leakage consequences with the BT model.

Table 2
Description of the intermediate events and final outcomes.

Event	Description	Event	Description
TE	Leakage Acetone Tank	IE12	Corrosion
IE1	Gasket defect	IE13	Stress factor
IE2	Power outage of the Marshaling system of instrumentation equipment	IE14	Rising pressure
IE3	Improper operator performance	IE15	Obstruction of connected pipes
IE4	Main equipment defects	IE16	Human Causes
IE5	Defective control equipment	IE17	Mechanical Causes
IE6	Defects in the communication system	IE18	Process Causes
IE7	Defects in inspection and operation of equipment	Cons	Consequents
IE8	Improper fastening	C1	Pool fire
IE9	Create tiny cracks	C2	vapor cloud explosion (VCE)
IE10	Equipment wear	C3	Flash fire
IE11	Defects in the valves	C4	Safe or toxic release of substances

Table 3
Description of the basic events and the safety barriers and their probabilities.

Symbol	Basic Event	Failure Probability	Symbol	Basic Event	Failure Probability
X1	Wireless battery drain	0.00159956	X26	Improper use of equipment	0.00107895
X2	Wireless electronic defect	0.00178649	X27	Inability to replace worn equipment	0.00140281
X3	not using wireless	0.00193642	X28	The nature of the chemical	0.00144212
X4	Insufficient number of wirelesses	0.00199067	X29	Inspection defects in burn detection	0.00121899
X5	Improper management performance	0.00195434	X30	Damage to the gasket	0.00148594
X6	Fear of explosion and fire	0.00180302	X31	Maintenance defects	0.00136144
X7	Lack of timely notification of the control room	0.00193642	X32	External blows	0.00097949
X8	Hearing loss	0.00177011	X33	Cathodic protection defect	0.00142889
X9	Lack of sufficient skills and experience	0.00149968	X34	Loss of anti-corrosion layer	0.00157036
X10	fatigue	0.00138676	X35	Abrasion	0.00133352
X11	Job Stress	0.00158489	X36	Defects in corrosion inspection	0.00120781
X12	Turn taking	0.00119674	X37	Shear stress	0.00130918
X13	Inadequate and ineffective training	0.00141579	X38	Axial stress	0.00118304
X14	Deliberate error in executing instructions	0.00136144	X39	Tangential stress	0.00159956
X15	Permit defect issue	0.00130918	X40	Closing even after the tank	0.00142889
X16	Unwanted foot collision with valves	0.00155597	X41	Do not operate input pressure switches	0.00140281
X17	Defect in welding	0.00121899	X42	Defective performance of earth system	0.00113501
X18	temperature changes	0.00124451	X43	Equipment wear	0.00145546
X19	Improper gasket placement	0.00149968	X44	Lightning	0.00140281
X20	Creating curvature in the gasket	0.00137404	X45	Software defects	0.00148594
X21	Equipment wear and tear	0.00138676	X46	Defects in control valves	0.00133352
X22	Threaded connections are broken	0.00130918	X47	Lack of calibration of instrumentation systems	0.0013213
X23	Leak detection defects	0.00142889	X48	Cold weather	0.0011722
X24	Unprincipled redesign	0.00128233	X49	Defects in the filtration of impurities	0.00166341
X25	Improper assembly of equipment	0.00151356	X50	Incorrect initial design	0.00137404
IIB	Immediate ignition barrier	0. 1354200	Con	Confinement	0.4256000
DIB	Delay ignition barrier	0.2950000			

have a significant effect on the risk analysis. In order to overcome the limitations of the bow tie method, the diagram was drawn according to the algorithm presented by Khakzad et al. [42] in most Bayesian networks GeNIe software is used. Fig. 4 shows the Dynamic model of the Leakage of acetone from the tank.

3.3.1. *Inductive reasoning*

One of the common features of BT model and BN model is inductive reasoning. As it can be seen in the BT bow tie approach, the probability of the top event (TE) occurring is that of the acetone leak 0.0468547. However, the results of the Bayesian BN network model showed that the probability of the main event is 0.047965137, which is less than the value obtained in Bow-tie BT. The results of the Bayesian networks showed that in the acetone leakage scenario, the consequences would be pool fire, vapor cloud explosion (VCE), flash fire, and safe release of chemicals, the probability of which is shown in Table 4.

3.3.2. *Deductive reasoning*

One of the characteristics of Bayesian networks is the ability of deductive reasoning. This ability is very important in dynamic risk analysis. This advantage makes the network structure dynamic and allows updating of the probability of occurrence of base events by receiving Accident pre-data. By updating the probability of occurrence of baseline events and final outcomes, it will be possible to

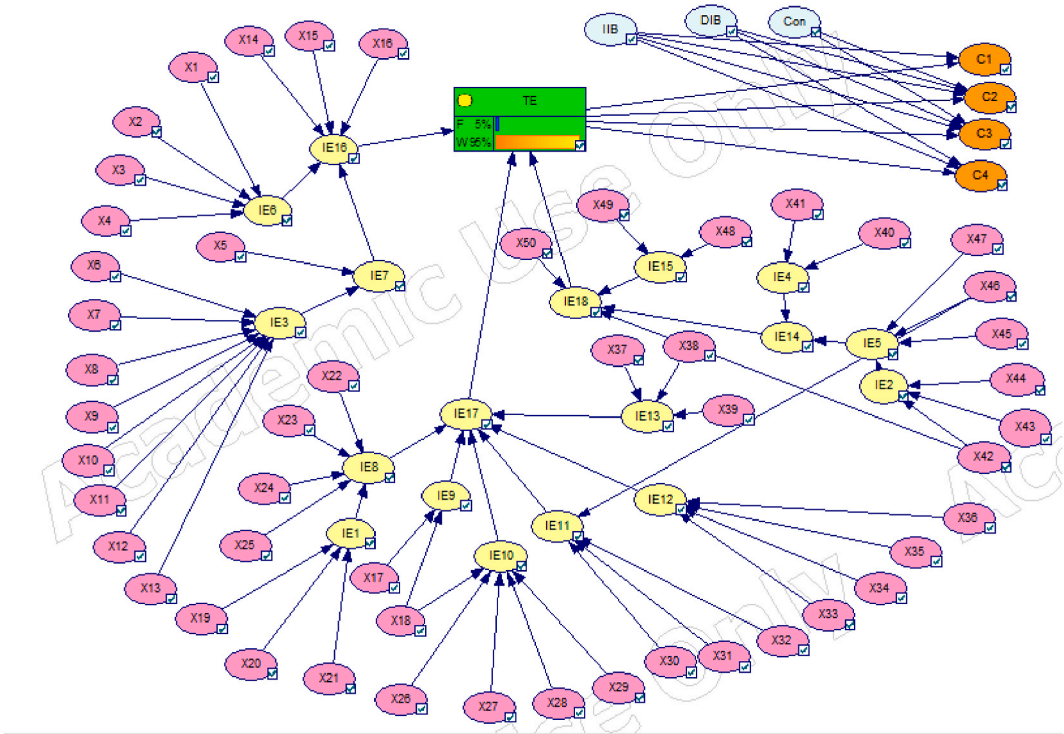

Fig. 4. Dynamic modeling of the Acetone Leakage scenario with the Bayesian network.

Table 4
Probability of final consequences with BT and BN approach.

	Prior probabilities (BT)	Prior probabilities (BN)	Updated probability (BN)
TE	0.04685470	0.04796513	1
C1	0.00634510	0.00649543	0.13542000
C2	0.00507900	0.00081551	0.01700220
C3	0.00687110	0.14028991	0.01700220
C4	0.04051230	0.00191615	0.03994800

select the most critical baseline event that has the largest share in the occurrence of the main event [54]. The last column of Table 4 shows the updated probabilities of final consequences using the Bayesian network. As can be seen, Pool fire has a probability of 0.13542, which is the highest value compared to other consequences.

3.4. Consequence modelling

Material release rates in the 4 studied scenarios are presented in Table 5. The results show that in the first hour in scenario A-50, the maximum amount of material is 80 kg and in scenario A-1 and the minimum amount of material is 0.35 kg of acetone.

Fig. 5 shows the consequence of the A-50 acetone release scenario. Accordingly, the release rate of acetone reaches its maximum after about 8 min, and then follows a steady trend. The amount of contamination density in different areas and 60 min after the beginning of material release in different scenarios is shown in Table 6. For scenario A-50 and for AEGL-1, a range of 80 m and 400 m, respectively, is considered as a danger zone. As the leakage diameter decreases, these ranges also decrease.

Fig. 6 shows the results of scenario study No. A-50 for an acetone source with a leakage diameter of 50 mm. The results showed that 1 h after the accident, the area of AEGL3 where there is a risk of death will include a space with a length and height of 50 m (in the

Table 5
The amount of material released in the first hour after the accident.

Acetone				Material
A-1	A-5	A-10	A-50	Scenario
0.35	0.9	3	80	released material kg

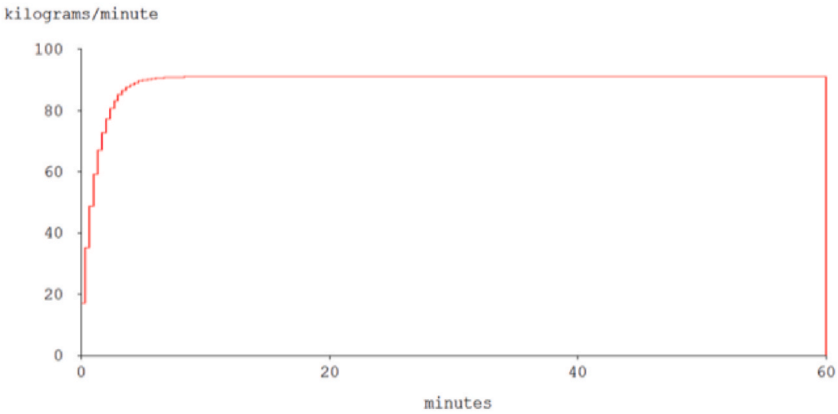

Fig. 5. Acetone release rate in scenario A-50.

direction of the wind). In addition, the density of material released up to a height and height of 70 m is higher than the AEGL2 range, which can increase the risk of permanent injury and reduced abilities. During the same period, AGEL 1 area will be expanded to a space with a horizontal length of 400 m and a height of 80 m.

As shown in Table 7, the danger radius due to material distribution varies for different ERPGs and in different scenarios. Accordingly, this radius for ERPG 3 is greater than the other two.

The range of heat radiation caused by material fires released in different scenarios is presented in Table 8. As can be seen in the scenario with a leakage diameter of 50 mm, the maximum heat flux is estimated.

According to Fig. 7, in the event of scenario number A-50, heat radiation is lethal in the range of 220 m and has the ability to scatter in the range of 312 m. In this scenario, heat radiation within 500 m will cause pain in the exposed people.

3.5. Risk assessment

After modeling the outcome by ALOHA and estimating the probability of consequences due to acetone leakage, the risk number due to pool fire acetone was estimated in four scenarios in both Posterior and prior approaches. As mentioned, possible scenarios due to fall and in case of failure of control barriers include flammable vapor cloud, pool fire, sudden fire and safe release of chemicals. According to studies, the criteria for assessing the outcome of a fire is 4 kW/m2 (pain threshold for 20 s) and 37.5 kW/m2 (100% death in 1 min or 1% death in 10 s). The average population density in the tank farm is 9 people. Table 9 shows the pool fire risk assessment in the tank area. As can be seen in Table 9, the highest probability of death is related to Pool fire with a leakage diameter of 50 mm with a probability of 3.34.

Table 10 shows the results of the studied scenario risk in two approaches: Posterior risk with Bow-tie method and Bayesian networks and risk prior or updated using Bayesian networks. The highest risk numbers in the BT and BN models are related to the Pool fire scenario with a Leakage diameter of 50 mm with a probability of 0.0211923and 0.021694736. The results of Rick's update on Bayesian networks showed that the pool fire risk is equal to 0.4523028.

4. Discussion

Dynamic risk prediction in tanks is one of the safety challenges in process units. Two parameters play a major role in risk analysis. The first parameter is the probability of occurrence and the second parameter is the severity of the consequence. The probability of occurrence indicates the number of times that an accident occurred in a period of one year, and the severity of the consequence means the number of casualties or damages resulting from the occurrence of that accident.

Table 6
Length and height of materials released in different scenarios by different compression ratios (m).

Acetone				Material	
A-1	A-5	A-10	A-50	Scenario	
L = ND	L = ND	L = 80 L = 20	[b]L = 400	AEGL-1	Hazard area
H=ND	H=ND		H = 80	>200 ppm	
L = ND	L = ND	L = ND[a]	L = 70	AEGL-2	
H=ND	H=ND	H=ND	H = 70	>3200 ppm	
L = ND	L = ND	L = ND	L = 50	AEGL-3	
H=ND	H=ND	H=ND	H = 50	>5700 ppm	

[a] ND (not shown): danger radius less than 10 m.
[b] L and H are also length and height, respectively.

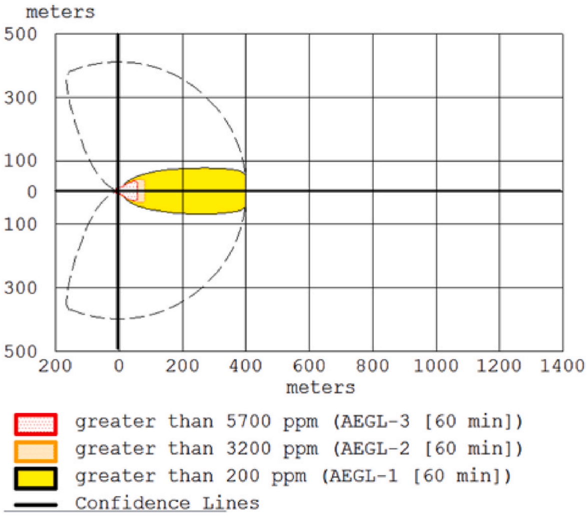

Fig. 6. Material release from an acetone tank with a Leakage diameter of 50 mm.

Table 7
Danger radius due to the distribution of released materials in different scenarios (square meters).

Acetone				Material	
A-1	A-5	A-10	A-50	Scenario	
ND	28	42	50	ERPG1	Hazard area
19	36	58	70	ERPG2	
56	85	103	115	ERPG3	

Table 8
Heat radiation hazard range of materials released in different scenarios (square meters).

Acetone				Material	
A-1	A-5	A-10	A-50	Scenario	
148	190	202	220	>10.0 kw/sq m	Radiation range
212	256	282	312	>5.0 kw/sq m	
378	413	456	500	>2.0 kw/sq m	

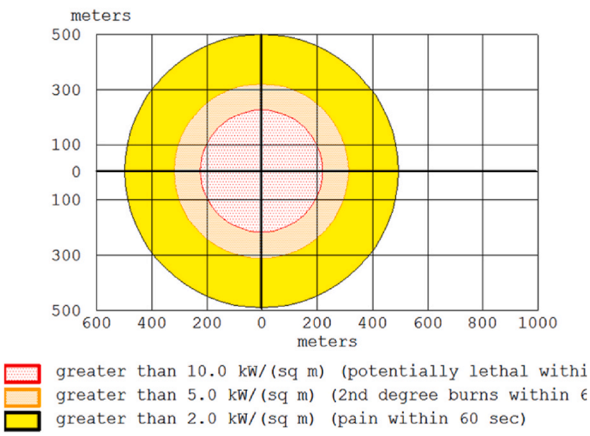

Fig. 7. Radiation ranges from fire in scenario A-50.

Table 9
Results of evaluation of the effects of the consequences of the studied scenario.

Number of casualties	Probability of death	Population density (person/square meter)	Affected area (square meters)	Consequence (pool Fire)
3.34	0.022	0.001	151976	A-50
0.21	0.0017	0.001	128124	A-10
0.11	0.001	0.001	113354	A-5
0.06	0.0009	0.001	68778	A-1

Table 10
Risk profiles with Posterior (BT and BN) and prior (BN) approach.

Consequence (Pool fire)	Consequence repeatability (event/year)			Mortality (person/event)	Social risk		
	Prior probability BT	Prior probability BN	Posterior probability BN		Prior probability BT	Prior probability BN	Posterior probability BN
A-50	0.006345	0.0064954	0.13542	3.34	0.0211923	0.021694736	0.4523028
A-10				0.21	0.0013324	0.00136404	0.0284382
A-5				0.11	0.0006979	0.000714497	0.0148962
A-1				0.06	0.0003807	0.000389726	0.0081252

Today, most studies to design accident prevention and control strategies in industries focus on this stage of the risk management process, because the severity dimension of the accident is often catastrophic and in the event of an accident leads to irreparable financial, human and environmental damage to industry. Therefore, the appropriate and efficient approach is to focus on reducing the likelihood of such an accident. The methods used in this step have shortcomings and limitations that can be very effective in the results of risk assessment.

Several methods have been proposed for cause-and-effect analysis and modeling. Slelt et al. [55] used an obstacle block diagram to investigate the hydrocarbon release incident on oil rigs. Delvosalle et al. [56] used Bow-tie BT to identify catastrophic scenarios in process units. Among the cause-and-effect analysis and modeling methods, Bow-tie BT has proven to be an efficient method because it demonstrates the ability to combine the causes and consequences of an accident in a graphical model [57].

The results of this model in storage led to the identification of 50 root events and 18 intermediate events affecting acetone leakage in storage. The probability of the Top event, the acetone leak, was calculated to be 0.0468547. In the scenario of acetone leakage from the storage, the final consequences of leakage, considering that this material is in the group of flammable and volatile materials according to BEVI instructions, i.e. the flash point is less than 21 °C, including pool fire, sudden fire, and vapor cloud explosion. (VCE) and safe release of chemicals. Therefore, in the event of a delayed ignition, a flash fire or explosion may occur. Generally, after ignition, the flame returns to the liquid pool and leads to a pool fire. In some cases, due to the density or large size of the flammable cloud, the flame moves rapidly forward, which can lead to an explosion. In the Stone Leakage scenario, the flash fire event was identified as the most likely final outcome with a probability of 0.006871per year (Table 4). The probability of a vapor cloud explosion (VCE) 0.005079 is the probability of pool fire 0.006345 and the probability of safe release of chemicals is 0.04051. As stated, the probability of fire eruption is higher than other consequences, which can be caused by the operating conditions of acetone and the vapor pressure of the substance.

Although the special capabilities of the BT bow tie method have been demonstrated in quantitative risk analysis [42,57], new studies show that this model has limitations. Bayesian network method was used to eliminate these limitations in this study. Table 4 shows the results of inductive reasoning of the BT bow tie method and the Bayesian BN network. As can be seen in the BT bow tie approach, the probability of the top event (TE) occurring, that is, the acetone leak, is 0.0468547. But the results of the Bayesian BN network model showed the probability of the main event being 0.047965137, which is more than the value obtained in Bow-tie BT. The reason for this discrepancy could be due to the conditional dependence between events with common causes that Bow-tie BT does not have this capability. The results of Bayesian networks showed that in the scenario of acetone leakage, the consequences of pool fire, vapor cloud explosion (VCE), flash fire and safe release of chemicals with the probability of occurrence of 0.00649543, 0.00081551, 0.14028991 and 0.00191615 are possible consequences of acetone leakage in tanks.

In the analysis of Bayesian networks, sudden fire has the highest probability of occurrence among the possible consequences of acetone leakage, which results are similar to the results of the bow tie diagram. One of the unique features of Bayesian network is Deductive reasoning. Deductive reasoning results of Bayesian networks updating Bayesian networks in the acetone leakage scenario, shows the probability of 0.13542 for pool fire, which was identified as the most probable consequence of acetone leakage in storage. If sudden fire was identified as the most likely outcome in the inductive analysis.

In this study, using ALOHA software, 8 possible leakage scenarios from acetone storage tanks were investigated and the hazard radius at the desired distances, safe range and acetone concentration at different times after release were obtained.

The results showed that the release rate of the material depends on the Leakage diameter more than all the parameters. Accordingly, the larger the leakage diameter, the higher the emission rate and the lower the emission rate in smaller diameter leaks. Therefore, Leakage 50 mm diameter had the highest emission rate (80 kg/min) and Leakage 1 mm had the lowest emission rate (in g/min). The importance of leak diameter along with the pressure inside the tank, volatility and material properties can also affect the amount of diffusion over time. For acetone, the diffusion rate reaches its maximum emission rate after 8 min (Fig. 5). The study of Zarei et al. showed that the leakage diameter is the most important parameter in modeling the outcome of hydrogen storage and with increasing leakage diameter, the rate of material release and consequently the risk of fire or explosion has increased [49] which confirms the results of the present study.

For the 50 mm Leakage scenario of the acetone tank, the risk range of death (ERPG1) and the range of the risk of permanent injury and reduction of individual abilities (ERPG2) were 50 and 70 m^2, respectively. The larger the distance, the farther away the tank is from Leakage, and the concentration of material at these distances can affect exposed individuals. Toxicity and material properties play a very important role in determining these distances, so that at higher ERPG values, the impact intervals are less. The results of Mortazavi et al.'s study showed that ERPG1 and ERPG2 for toxic chlorine gas in summer were 11 and 6.5 km, respectively, and ERPG 1.2 for this substance is 1 and 3 ppm, respectively. This result well shows the importance of the effect of substance toxicity on exposure intervals. The results of their study also showed that these distances are different from each other in the summer and in the winter, which is due to the stability of the air layers [58].

Tseng et al., 2012 also showed that in modeling the outcome, the parameters of wind speed, weather stability and total emission time can affect the dispersion of vapor cloud in different scenarios [59]. Zarei et al. also reported that the distance affected by the explosion of hydrogen gas during the day was longer than at night [49]. Therefore, these parameters such as summer weather stability, assessment of the possibility of leakage during the day and the degree of toxicity caused by acetone can also be considered effective in obtaining the results of the current study.

The results showed that in Leakage diameter, most of the thermal radiation has the ability to kill at closer distances, and at longer distances, it has the ability to burn and cause pain. For scenarios with low leakage diameters, these distances are not significant (Table 8). Leakage diameter (described earlier), nature of material (explosiveness and flammability), weather conditions, emitted energy rate (in kilowatts), etc. can be mentioned as factors influencing the influence of distances [49,60]. The importance of determining these distances is that if people are placed in these distances, the probability of damage due to heat radiation and in the presence of flammable or explosive sources, and the probability of fire or explosion increases.

Quantitative risk analysis is a powerful method of risk assessment, it is one of the few methods that expresses risk as individual risk and social risk [61]. In this study, in order to assess the risks, the UK risk criterion was used, which is mostly used in domestic and foreign risk studies. According to this criterion, the acceptable risk is 10^{-6}, the tolerable is 10^{-5} and the unacceptable risk is 10^{-4} [62].

Table 10 shows the results of risk assessment with two bow tie approaches BT and Bayesian BN network. As can be seen, the risk number estimated by the Bayesian BN network is lower than the BT bow tie method. The difference between the results of Bayesian and Bow-tie networks is due to the characteristics of Bayesian networks, including the consideration of events with common causes, the conditional dependence between events and safety barriers, and the existence of conditional probability tables in Bayesian networks.

In Social risk scenario A-50, the tanks are more than other scenarios. In all scenarios are in the unacceptable range. Therefore, it should be noted that the placement of dangerous people or substances in these areas can lead to health and economic damage. Therefore, it is important that the distances obtained are included in emergency plans. Especially when the next designs are done, these results can be used well for locating tanks. Therefore, the importance of the location of operators, personnel and office buildings, care and maintenance personnel, and the general population of the community should be considered in the design of these tanks.

Brown et al. have also recommended a plan for preparing and responding to emergencies and classifying areas and individuals based on location to prioritize the implementation of the programs of the organizations involved [63]. Therefore, in the range of ERPG3 and above (which in this study is about 220 m in the wind direction), emergency evacuation of people from this area should be done in the shortest possible time. At level 2, where the concentration of acetone is in the range of ERPG2 (which in this study is equal to 312 m), people should be educated about the dangers of these substances and the use of personal protective equipment. For ERPG1 (which in this study is equal to 500 m) it is necessary to educate people, establish a database of people (phone number, location, etc.).

In general, the number of losses and damages resulting from the release and spread of toxic substances depends on the concentration of the toxic substance and the time of contact with it. One of the limitations of this software is the inability to predict the exact amount of substance concentration, especially in the early times after leakage. Since the storage of these materials can be potential sources of danger, it is recommended that: The volume of storage and storage tanks of these materials be reduced, to periodic inspection of these tanks to be aware of any leakage and corrosion The body should take action, avoid storing the storage tanks of these materials in direct sunlight and in contact with other flammable materials, educate and educate people about the dangers of these materials, consider any operations at dangerous distances. It should be done by considering it as an emergency.

The limitations of this study can be independently considering the basic events of the X37, X38 and X39, which can be explored using Dynamic Bayesian Networks to accurately examine these events and their effect on each other in future studies.

Also, the lack of a tangible and quantitative criterion to evaluate the reduction of uncertainty was one of the other limitations of the present study, but according to the characteristics and nature of the appropriate approaches used in this study, it can be concluded that the uncertainty has been reduced.

5. Conclusion

In this study, a method for dynamic risk assessment of storage using modeling with ALOHA and Bayesian network software was presented. In order to identify the basic events affecting the occurrence of the main event, the BT bow tie diagram was drawn by a team consisting of safety experts and the tank unit. Databases were used to determine the failure rate of the probability of root events identified in the Fault tree qualitative analysis. The BT diagram was drawn in the form of a Bayesian network and deductive reasoning and induction were performed based on the BN model.

The results showed that using outcome modeling, hazard privacy and release of chemicals from acetone and methyl acetate tank leakage can be well predicted and emergency levels can be determined. It is also possible to prevent human or environmental damage in these areas by using appropriate strategies. According to the results of outcome modeling, it can be used as a suitable tool in emergency response programs.

Author contribution statement

Heidar Mohammadi: Conceived and designed the experiments, Analyzed and interpreted the data.
Fereydoon Laal: Conceived and designed the experiments, Performed the experiments.
Farough Mohammadian: Analyzed and interpreted the data, Performed the experiments.
Peyman Yari: Conceived and designed the experiments, Analyzed and interpreted the data.
Mehdi Kangavari: Performed the experiments, Analyzed and interpreted the data.
Saber Moradi Hanifi: Contributed reagents, materials, analysis tools or data, Wrote the paper.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Glossary			
ALOHA	Areal Locations of Hazardous Atmospheres	PA	Pressure alarm
BN	Bayesian network	PI	Pressure indicator
BT	Bow Tie	TI	Temperature indicator
P&ID	piping and instrumentation diagram	PSV	Pressure safety valve
LA	Level Alarm	MH	Manhole
LI	Level indicator	SV	Safety valve
LIT	Level indicating transmitter	PIT	Pressure indicating transmitter
TIT	Temperature indicating transmitter		

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