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Risk-based process safety assessment and control measures design for offshore process facilities

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Abstract

Process operation is the most hazardous activity next to the transportation and drilling operation on an offshore oil and gas (OOG) platform. Past experiences of onshore and offshore oil and gas activities have revealed that a small mis-happening in the process operation might escalate to a catastrophe. This is of especial concern in the OOG platform due to the limited space and compact geometry of the process area, less ventilation, and difficult escape routes. On an OOG platform, each extra control measure, which is implemented, not only occupies space on the platform and increases congestion but also adds extra load to the platform.

Eventualities in the OOG platform process operation can be avoided through incorporating the appropriate control measures at the early design stage. In this paper, the authors describe a methodology for risk-based process safety decision making for OOG activities. The methodology is applied to various offshore process units, that is, the compressor, separators, flash drum and driers of an OOG platform. Based on the risk potential, appropriate safety measures are designed for each unit. This paper also illustrates that implementation of the designed safety measures reduces the high Fatal accident rate (FAR) values to an acceptable level.

Keywords: Offshore safety; Offshore risk assessment; Accidents; Risk-based design; Safety measures design

1. Introduction

An offshore production facility involves drilling rig, structure, transportation, process plant, worker's accommodation and utility facilities. The process plant of a fully manned production facility typically involves a number of stages of oil, gas and water separation, gas compression, and dehydration. The risk present on a typical offshore installation may be

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Nomenclature

AP	atmospheric pressure (kPa)
$F1$–$F3$	core energy factors used in damage index estimation
G	core toxic load factor used in toxic damage index estimation
H_c	heat of combustion (kJ/kg)
K	constant (3148)
M	mass of chemical (kg) or mass release rate (kg/s)
NF, NR, NH	NFPA ranking for flammability, reactivity and human health
pn	penalties for damage index estimation
pnr	penalties for toxic damage index estimation
PP	processing pressure (kPa)
SP	specific heat ratio
T	temperature (°C)
TP	transportation pressure (kPa)
V	volume of chemical (m^3)
VP	vapor pressure (kPa)

categorized as: process risk, dropped object risk, structural failure risk, helicopter accident risk, and ship collision risk. Among these, process risk (risk due to fire and explosion in the process facility) contributes more than 50% of the total risk of the installation [1].

With all of the available options, the numbers of design permutations are considerable. An offshore development can never be completely safe but the degree of inherent safety can be increased by selecting the optimum design in terms of the installation/field configuration and the layout, which reduces the risk to a level that is as low as reasonably practicable (ALARP) without resorting to costly protective systems. This requires the identification of major risk contributors and their assessment by using quantitative risk assessment (QRA) techniques early in the project life cycle [2]. If the structured approach of identification and assessment is not carried out early in the project, it is possible that the engineering judgment approach will fail to identify all of the major risks and loss prevention expenditure will be targeted in areas where there is little benefit. This would resulted in expensive remedial actions later during the life of the project.

Given the number of potential design options, it would not be possible, due to time and resource constraints, to develop all options to the point where a detailed QRA study could be carried out. At an early phase of the project, design often changes as a result of economic drivers or other external influences.

Crawley and Grant [3] have proposed a screening tool for offshore risk assessment. This tool permits the risk assessment of many design options in a methodical, consistent and auditable manner. It is aimed at reducing front-end design costs and targeting design efforts in a cost-effective and safety-oriented manner.

The time and effort required to complete a full QRA of an offshore installation is a function of the complexity and size of the installation which in the extreme case could require many months efforts spread over a prolonged period [3,4]. This time scale precludes the support of the rapidly changing design, which is a feature of the concept development phase. Vinnem

[5] presents a good overview of QRA use in offshore industries and emphasizes that QRA is an important tool in regulation development in various jurisdictions (e.g. UK, Norway, US and Canada). Recently, Falck et al. [6] have discussed the use of QRA in the design of an oil production system. They have detailed the use of QRA in safety and emergency preparedness analysis during the engineering and construction phase of the project. Though they have emphasized the use of QRA in the conceptual design stage, no such guidelines or methodology have been discussed.

The United Kingdom Offshore Operators Association (UKOOA) has developed guidelines for an instrument-based protective system for application to offshore oil and gas (OOG) installations [7]. Safety integrity level (SIL) determination is the key element of these guidelines. In its simple form, the allocation of a SIL for a safety system is a way of specifying the appropriate level of reliability to match both the hazard and the tolerable risk. Therefore, to determine a SIL, one needs to consider both the severity and the likelihood of an incident. A SIL can be qualitative and/or quantitative. In a qualitative SIL, each unit consequences are selected out of four levels ranging from catastrophic to negligible. Similarly, the probability of occurrence ranges from frequent to implausible in six levels. Finally, the consequences and probability of occurrence are combined to determine the SIL level. The quantitative SIL, on the other hand, involves the quantification of consequences by using appropriate models, and probability estimation using event/fault tree analysis (FTA). These results are combined to give a quantitative SIL rank. Though the qualitative SIL is easy to use, the quantitative SIL is more effective [1].

Recently, Khan et al. proposed a quantitative methodology for safety measure design based on a feedback system of fault tree and credible accident. The methodology, named SCAP, has been applied to many onshore process industries [8,9]. It is effective in deciding what safety measures would reduce the risk to an acceptable level.

These authors have revised the SCAP methodology for its application to offshore process facilities. The revised methodology endorses all the characteristics of the original SCAP methodology. Further, the revised methodology is applicable at any stage of the design, and is particularly useful at the early design stage when the designer is free to adopt the suggested safety measures or modifications. Application of this methodology at the early design stage is possible as it requires data that is readily available at this stage (Table 1). The reliability of a study conducted with such early stage data (involving uncertainties) is debatable. We believe that it can be counter argued on the basis of the following two points.

1. The objective of the present study is the design and evaluation of safety measures based on the risk potential of the units. Therefore, the risk potential here is considered in relative

Table 1
Set of parameters required to implement SCAP methodology

Parameter class	Details
Process details	Brief process description, units with capacities and process involved, tentative operating conditions, plot plan
Chemicals	Physical properties, chemical properties
Pipe and instrumentation	Tentative piping, instruments and control details
Reliability data	Reliability data of unit components, instruments, accessories

terms. If there are uncertainties, they are present in all units, and in relative terms will not have much effect. Risk potential based on precise data may have a lesser degree of uncertainty. Improvement in the degree of uncertainty would not change the overall situation of risk potential among the different units from a design perspective.

2. The techniques used in SCAP, such as analytical simulations with fuzzy set theory and maximum credible accident analysis (MCAA), are robust and less susceptible to input data uncertainty [8,9]. Therefore, early stage data (involving uncertainties) will not significantly affect the final outcome of the study.

This methodology tries to make the concept of a risk-based safer design a reality. This paper recapitulates this methodology and demonstrates its application to a typical offshore platform.

2. Methodology for risk-based safety assessment and control measures design

The proposed SCAP methodology involves risk assessment steps which are interactively linked with the implementation of safety measures. The resultant system reveals the extent of risk reduction by each successive safety measure. It also tells, based on sophisticated MCAA and probabilistic FTA (PFTA), how a given unit can ever be made ‘safe’. This methodology has been applied to many onshore process industries and proved to be efficient and easy to use, and required limited data [8,9].

In this paper, the authors apply this methodology with some modifications to an OOG process facility. The major steps of the revised SCAP methodology remain the same with modifications in their sub-steps. This paper presents a brief account of the revised SCAP procedure and a detailed description of its application to an OOG facility. The details of SCAP and other tools used in this paper are discussed in Khan et al. [8,9].

2.1. Hazard identification step

The immediate objective is to identify all possible hazards in different process units and/or activities. Techniques available for hazard identification include hazard and operability (HAZOP) studies, what–if analysis, and quantitative hazard index, with the later being the preferred one. From time to time hazard indices have been proposed: the Dow fire and explosion index [10,11], Dow chemical exposure index [10], the Mond fire explosion and toxicity index [12], the IFAL index [13], and hazard indexing and ranking analysis (HIRA) [14,15]. Most of these indices are for onshore process operations, but are also applicable to offshore process facilities as offshore process activities are no different than those onshore, except that offshore units are more vulnerable. This step utilizes the revised HIRA system, as it is flexible and able to consider the vulnerability of the offshore operation [16]. The revised HIRA comprises of two indices: fire and explosion damage index (FEDI; $B1$) and toxic damage index (TDI; $B2$).

2.1.1. Fire and explosion damage index (FEDI)

FEDI is a representation of lethal heat and overpressure load over an area. It is measured in terms of the radius of the area (in m) affected lethally by overpressure and heat load

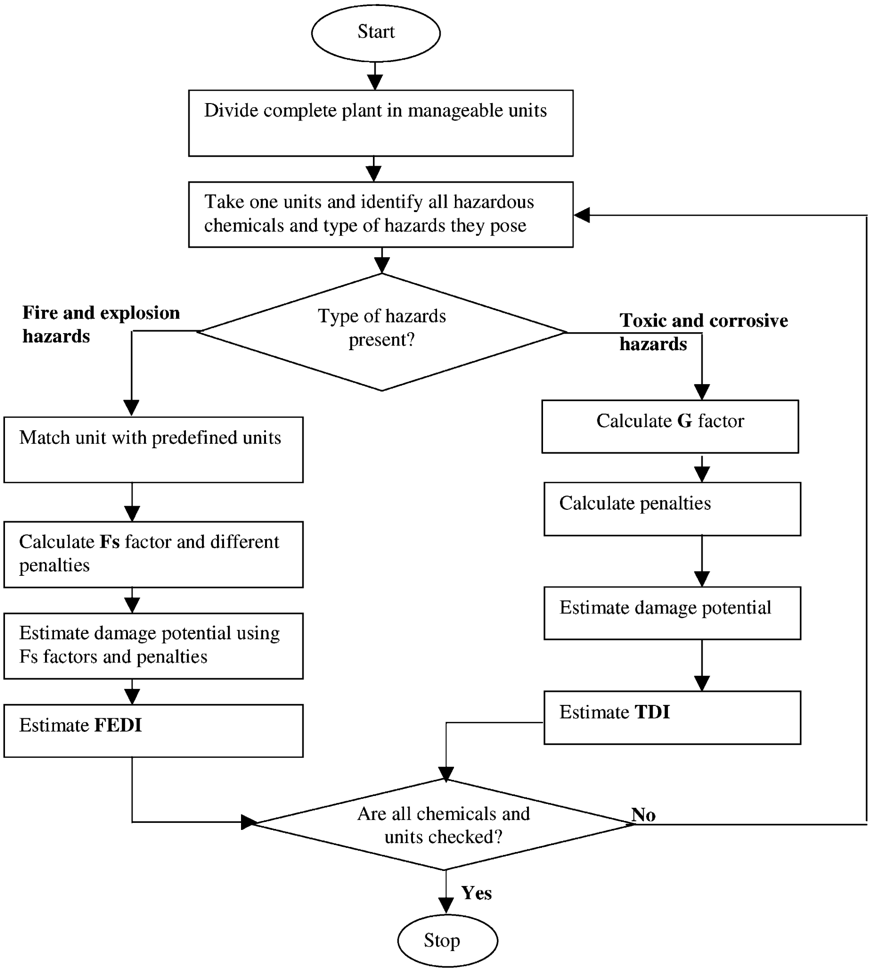

Fig. 1. Methodology for FEDI and TDI computation.

(50% probability of causing fatality). For the purpose of computing FEDI, process facility units are classified as: (i) storage units, (ii) units involving physical operations, (iii) units involving chemical reactions, (iv) transportation units, and (v) other hazardous units such as furnaces, boilers, direct-fired heat exchangers, etc. A stepwise procedure, as shown in Fig. 1, is used to compute FEDI. A summary of the FEDI computing procedure for storage units is presented in the subsequent sections.

2.1.2. Storage units

Storage units involve the storage and intermediate-process inventories of chemicals. To estimate FEDI, three energy factors ($F1$–$F3$), which account for physical and chemical energy, are defined.

$$F1 = 0.1M\frac{H_c}{K}$$

$$F2 = 1.304 \times 10^{-3}\mathrm{PP} \times V$$

$$F3 = 1.0 \times 10^{-3}\frac{1}{(T + 273)(\mathrm{PP} - \mathrm{VP})^2 V}$$

These equations are based on complex thermodynamic expressions for the isentropic expansion of pressurized gases and liquids [17]. Penalties have also been assigned to account for the impact of various parameters on the total damage potential which is subsequently transformed to FEDI.

pn1: ftemp1 (flash fire, auto ignition, and working temperature).
pn2: fpres1 (AP, VP, PP).
pn3: floc (distance).
pn4: fquan (quantity in tonnes).
pn5: maximum [1, 0.30(NR + NF)].
pn6: 1 + %space occupied by the unit in an area of 30 m radius from the unit/100.

The effect of external factors such as earthquakes and hurricanes is accounted for by considering the frequency of their occurrence. A penalty (pn7) of 2 is assigned if it occurs every year, and a penalty of 1.5–1.1 if it occurs once in 5–20 years. If an area is highly vulnerable to riots, such as those caused by ethnic or communal clashes, there is a greater likelihood of damage to the facility. Studying the area’s history helps in identifying of the vulnerability; this is also reflected in a penalty (pn8). A maximum value of 2 is assigned to an area that is highly prone to accidents and 1.1 to an area that is not prone to any accident.

The estimated energy factors and penalties are combined to determine the hazard potential, which is further transformed into FEDI. For details of functions and methods of FEDI calculations for other units, see Khan et al. [16].

$$\text{Hazard\_potential} = (F1\times\mathrm{pn1}+F2\times\mathrm{pn2})\times\mathrm{pn3}\times\mathrm{pn4} \times \mathrm{pn5} \times \mathrm{pn6} \times \mathrm{pn7} \times \mathrm{pn8}$$

$$\mathrm{FEDI} = 4.76(\text{Hazard\_potential})^{1/3}$$

2.1.3. Toxic damage index (TDI)

TDI quantifies the toxic load over an area in terms of the radius (in m) affected by a toxic load of 50% probability of causing a fatality. It is derived by using transport phenomena and empirical models based on the quantity of chemical(s) involved in the unit, the physical state of the chemical(s), the toxicity of the chemical(s), the operating conditions, and the site characteristics [14,15,18,19]. The dispersion is assumed to occur under slightly stable atmospheric conditions. We have opted for ‘slightly stable atmospheric conditions’ as these represent a median of high instability and high stability. We believe that this assumption of dispersion may also hold good in an offshore process facility as it is partially confined in a rig and there is a low likelihood of dilution.

TDI estimation uses the ‘G factor’ and several penalties.

pnr1: $f1$(ambient, operating, auto ignition, flash, and fire temperature).
pnr2: $h1$(PP) or $-h2$(PP), where $h1$(PP) and $h2$(PP) are pressure functions.
pnr3: 1.2 × vapor density/air density.
pnr4: maximum (1, 0.6NH).
pnr5: fpop (population density).
$B2$: $a(G \times \text{pnr1} \times \text{pnr2} \times \text{pnr3} \times \text{pnr4} \times \text{pnr5} \times \text{pn6} \times \text{pn7})^b$.

where $a = 25.35$ and $b = 0.425$ (a and b are constant) and are estimated empirically by studying the release and dispersion of a range of chemicals (super-heated liquids, liquefied gases, gases, etc.). See Khan and Abbasi [14,15] and Khan et al. [16] for details of G factor and penalties quantification.

2.1.4. *Why is revised HIRA appropriate here?*

Revised HIRA is appropriate for the present application due to following reasons.

1. It considers the impact of various process operations and associated parameters for hazard identification.
2. It accounts for vulnerability due to the degree of unit congestion, characteristics of the surrounding unit, and site characteristics.
3. It considers several operating conditions generally encountered in an offshore process operation.
4. It provides quantitative results of good reliability.
5. It does not require a case-to-case calibration as its magnitude directly signifies the hazard level.

2.2. *Quantitative hazard assessment step*

This step aims to quantify hazards, and MCAA is the preferred approach. MCAA is comprised of two steps [20,21]: (i) forecasting of the accident scenario and (ii) damage estimation for the envisaged accident scenario.

2.2.1. *Forecasting of accident scenarios*

Forecasting likely accident scenarios is the most important step in this exercise. A number of accident scenarios can be envisaged in a unit; however, it may not be possible to analyze all these scenarios particularly at an early design stage. A system which short-lists the important scenarios is needed. The screening or short-listing of accident scenarios has been debated since it was originally proposed by CCPS [22]. Subsequently, a modified “worst-case accident scenario” approach has been practiced [23]. Although the CCPS and worst-case approaches are effective and easy to use, they focus only on one accident parameter, “consequence.” Recently, Khan [24] proposed a “maximum credible accident scenario” (MCAS) approach which considers both consequences and the likelihood of accident occurrence. Khan [24] demonstrates that although accidents may not be the worst in consequence, their high probability of occurrence is a major concern. These accidents often escalate and cause a catastrophe which is not even modeled by a worst-case accident scenario [24].

The MCAS approach centers on the theme of credibility, which is defined as a combination of impact area and the probability of occurrence, and is estimated as

$$C = (L1^2 + L2^2)^{1/2}$$

where $L1$ and $L2$ represent the credibility factors estimated for fire and explosion hazard, and toxic hazard, respectively.

2.2.2. Estimation of damage

Many computer-automated tools are available for a detailed consequence assessment for offshore facilities. COMEX, VENTEX, CLICHÉ, SCOPE2, ARAMAS, OHART, and PLATO are the most frequently used. Gardner et al. [25] reviewed these hazard assessment tools. Complex computer models are also available for fire and explosion characteristics estimation, e.g. FLACS, μFLACS, REAGAS, EXSIM, and EXPSIM [26–28].

These models are frequently used for a detailed QRA. However, their application at the early design stage is not an easy task, due to the large data requirement and lengthy processing time. Though these models yield reliable detailed results, they may not be helpful at the early design stage. A computer-automated tool MAXCRED [29] and its latest version MAXCRED-III [30] perform MCAA. This tool enables the simulation of accidents and an estimation of their damage potential. MAXCRED-III, which incorporates the domino/cascading effect, is developed on advanced concepts of software engineering [30].

MAXCRED-III has five main modules (options): scenario generation, consequence analysis, domino, documentation, and graphics. In the scenario generation module, accident scenarios are generated for the unit under study. This step, based on the MCAS approach, is an important input for subsequent steps. The more realistic the accident scenario, the more accurate is the forecast of the type of accident, its consequences, and associated risks; and, consequently, the more appropriate and effective is the strategy for averting and managing a crisis.

The consequence analysis module involves the assessment of likely consequences if an accident scenario materializes. The consequences are quantified in terms of damage radii (DR) of different propensities. The assessment of consequences involves source models to predict the rate of release of hazardous materials, the degree of flashing, and the rate of evaporation. The explosion and fire models are used to predict the characteristics of explosions and fires. The impact intensity models are used to predict damage zones due to fires, explosions, and toxic loads. A special feature of MAXCRED-III its ability to handle the dispersion of heavy (heavier-than-air) gases as well as light-as-air and lighter-than-air gases.

The domino module analyzes the damage potential of the primary event at the point of location of the secondary unit, and checks for the likelihood of occurrence of the secondary accident. If the probability of the secondary accident is sufficiently high, then appropriate accident scenarios are developed and analyzed for consequences.

The graphics module enables the visualization of risk contours in the context of accident sites. This option has two facilities: (i) site drawing, and (ii) contour drawing. The documentation module of MAXCRED-III deals mainly with the handling of different files: data file, scenario file, output file, and flow of information. This object works as an ‘information manager’.

2.3. Probabilistic fault tree analysis step

The objective of this step is to quantify the probability of occurrence of the earlier envisaged accident scenario. FTA, the most appropriate technique for this application, uses deductive reasoning to determine the occurrence of an undesired event. FTA along with component failure and human reliability data can help in determining the frequency of occurrence of an accidental event.

Methods for FTA include the analytical method [31], the Monte Carlo simulation method [32,33], and the Markov simulation method [34,35]. Recently, Khan and Abbasi [36] have proposed a new methodology for PFTA: analytical simulation methodology (ASM). ASM combines analytical methods with fuzzy mathematics, Monte Carlo simulations, and structure modeling. The ASM is easier, faster and involves less uncertainty in its predictions [36]. A computer-automated tool, probabilistic fault tree analysis (PROFAT) was developed to perform ASM. Fig. 2 illustrates the ASM algorithm and the steps involved.

Step1 (*fault tree development*): Based on a detailed study of the process, control arrangement, and behavior of components of the unit/plant, the top event (most undesirable situation) is identified. A logical dependency between the causes leading to the top event is developed and represented in terms of a fault tree.

Step 2 (*Boolean matrix creation*): The developed fault tree is transformed to a Boolean matrix. If the dimension of the Boolean matrix exceeds the processing ability of the user's computer, a structural modeling technique may be applied [31,37]. This technique proposes modeling of the fault tree into a number of smaller sub-modules with a dependency relation among them. This reduces the memory allocation problem and increases the computation [38].

Step 3 (*finding of minimum cutsets and optimization*): The Boolean matrix is then solved using an analytical method for finding minimum cutsets [39]. If the problem has been structurally moduled, then each module is solved independently, and the results combined. These may be subsequently optimized using any appropriate technique.

Step 4 (*probability analysis*): The already optimized minimum cutsets are processed for probability estimation. We recommend the Monte Carlo simulation method. To increase the accuracy of the computations and to reduce the margin of error due to inaccuracy involved in the reliability data of the basic events (initiating events), we recommend a fuzzy set [40–43].

Step 5 (*improvement index estimation*): The contribution of each cause is estimated by repeating step 4 while keeping the particular cause absent. Subsequently, the contribution of each cause is transformed into an 'improvement index' which signifies the percent contribution of each cause in leading to the top event. The higher the improvement index for a cause, the more vulnerable it is in leading the event.

2.3.1. PROFAT

The methodology summarized above was resolved into the computer software PROFAT. PROFAT is written in C++ and consists of five main modules: DATA, minimum cutsets analysis, probability analysis, improvement factor analysis, and general purpose modules, each of which performs a specific task, and is linked with the other modules.

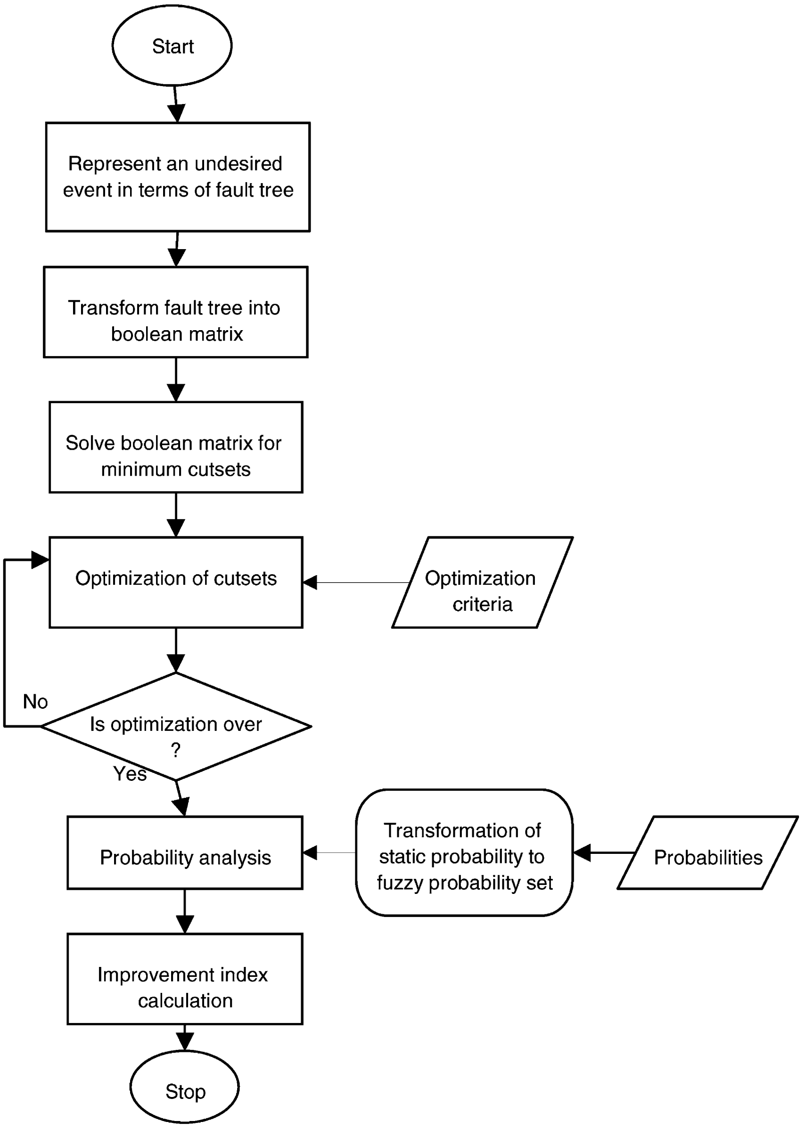

Fig. 2. Algorithm of ASM.

2.4. *Risk quantification and design of safety measures step*

Using the results of hazard assessment and probabilistic hazard assessment (PHA) steps, the individual risk and/or fatality accident rate (FAR) is computed and then compared with the regulatory standards. If they exceed the acceptance criteria, extra safety measures need to be implemented on the unit. After deciding the necessary safety options to be implemented, the PHA and hazard quantification steps are repeated and the latest individual risk and/or FAR is again computed and compared with the regulatory standards. This is repeated until the risk and/or FAR fall within the acceptable range.

3. Risk-based safety measures design for an offshore process unit

The above methodology has been applied to decide on the safety measures for various process units on an offshore platform. The purpose of the offshore production platform is to operate the wells, and to separate the fluid from the wells into oil, gas-condensate, gas, and water. It subsequently pumps oil, gas-condensate and gas to the onshore facility. The process plant on an offshore platform generally has three main parts: (i) the wellhead, (ii) separators, and (iii) gas compression. The layout of the process plant of a typical platform is depicted in Fig. 3, and it indicates the compact placements of the units.

Production lines from individual wells terminate at the wellhead, with each line being topped by a 'Christmas tree.' The well fluid passes through a manifold and is withdrawn at a production separator through a wing valve. The main hazard from the well is blowout which is liable to occur during work-over of the well. The present study does not include wellhead hazards but focuses on the other major parts of the process plant (separation and compression).

3.1. Process description

The well fluid passes through separators where it is separated into the four major components mentioned above. Oil is pumped through the main oil line to the onshore facility. Part of the condensate is pumped along with the oil. Gas is compressed using centrifugal compressors; it is subsequently passed through the flash drum where the temperature is reduced, condensate formed and separated out. The gas, is subsequently dried and purified. It is then further compressed to high-pressure through reciprocating compressors. Part of the gas is used at the wells and for power generation on the platform; the remaining gas is pumped to the onshore facility with a small amount being flared. A simplified process flow diagram is presented in Fig. 4.

3.2. Hazard identification

The complete process facility (separators, compressors, and pipelines) is subjected to a detailed study. Safety measures are designed and implemented on each and every process unit; however, in order to prioritize by importance, a hazard identification study is first conducted. The results of the study are plotted in Fig. 5. It is evident from this figure that the separators, compressors, drier, and flash drum are highly hazardous, whereas the oil and gas pipeline and pumps are moderately hazardous. To illustrate the methodology in the subsequent section, a detailed study is presented on only the highly hazardous units.

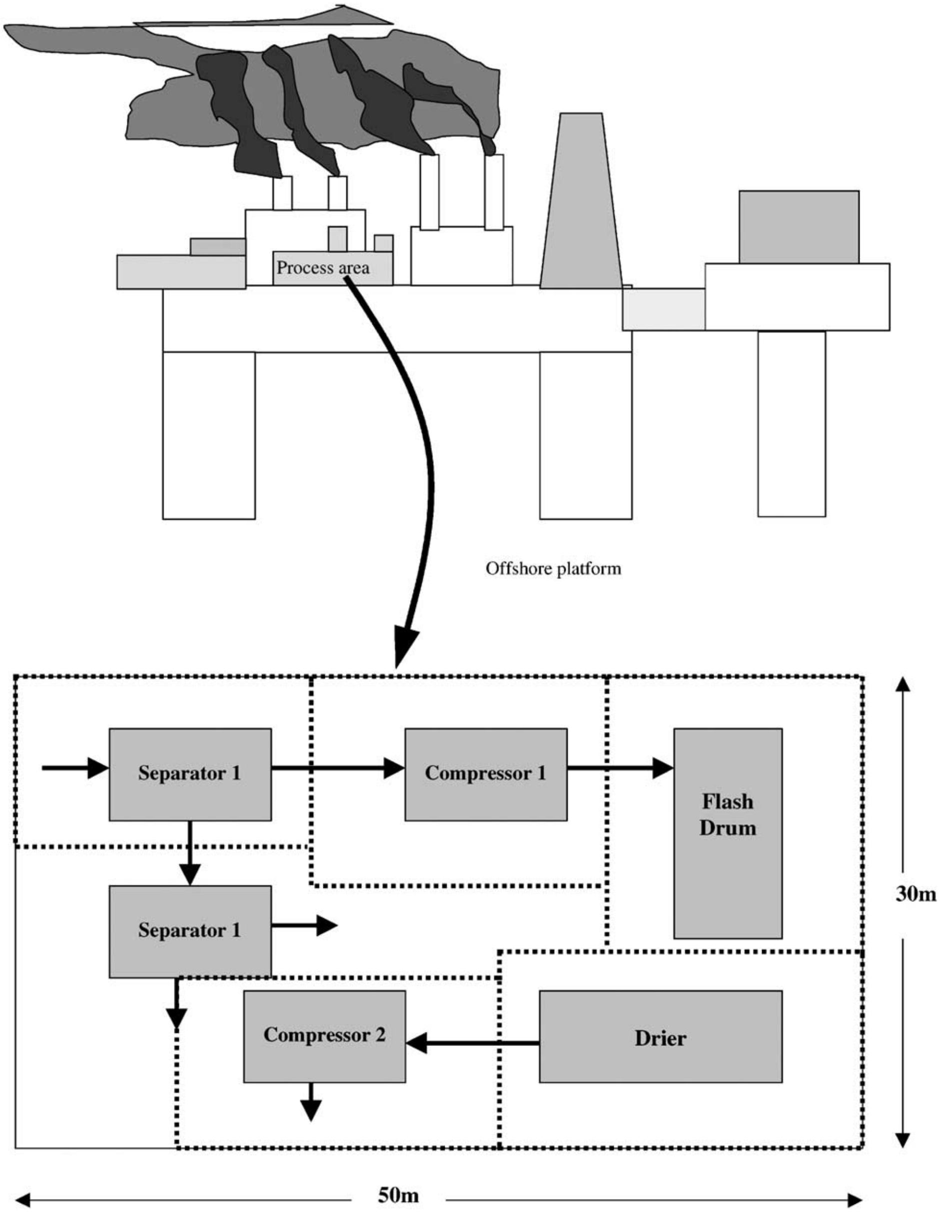

Fig. 3. Layout of process plant on offshore platform.

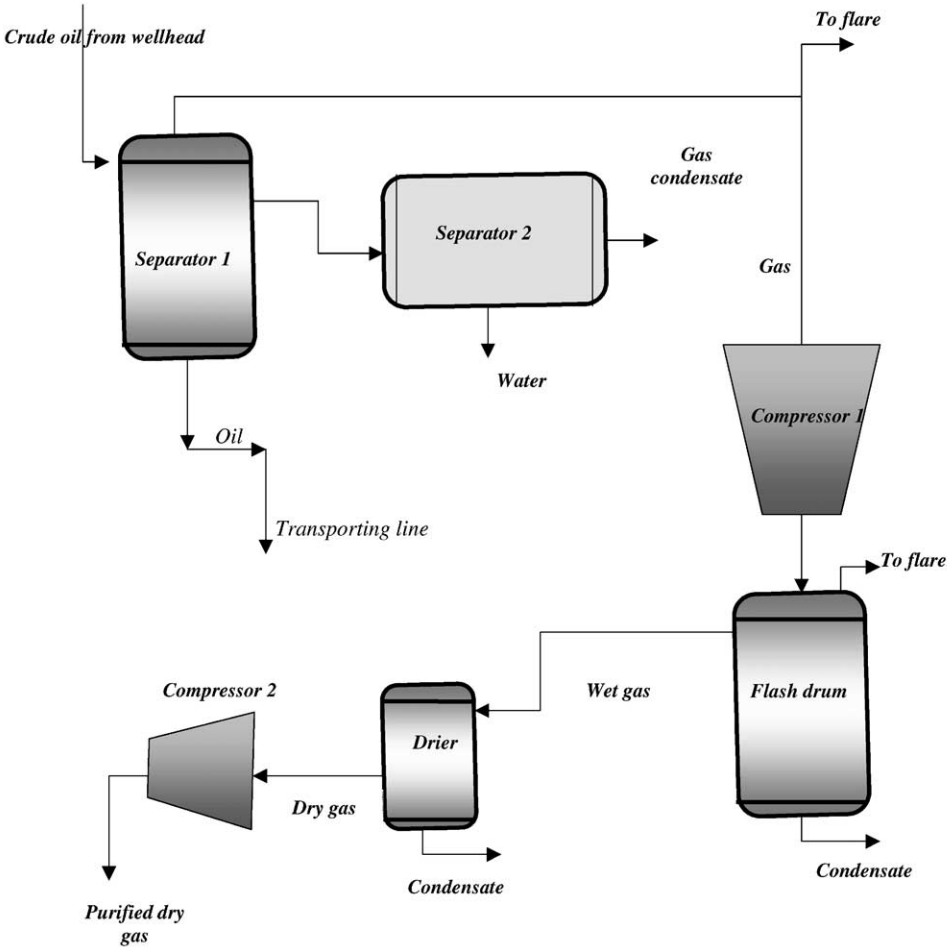

Fig. 4. Process flow diagram of separation and compression operation on offshore production platform.

3.3. Quantitative hazard assessment

3.3.1. Maximum credible accident scenario development

A number of accident scenarios has been envisaged for each unit. The most credible scenario for each unit is presented here. The credibility of an accident scenario is assessed considering the damage potential and the likelihood of occurrence.

Oil separator (*boiling liquid expanding vapor explosion* (*BLEVE*) *followed by fire* (*scenario 1*)): High-pressure development in the separator causes the unit to fail as BLEVE. The vapor cloud formed due to BLEVE on ignition would cause a fireball. The cumulative effect of overpressure and heat load may cause the release of a chemical from other units, which on ignition would cause a fire.

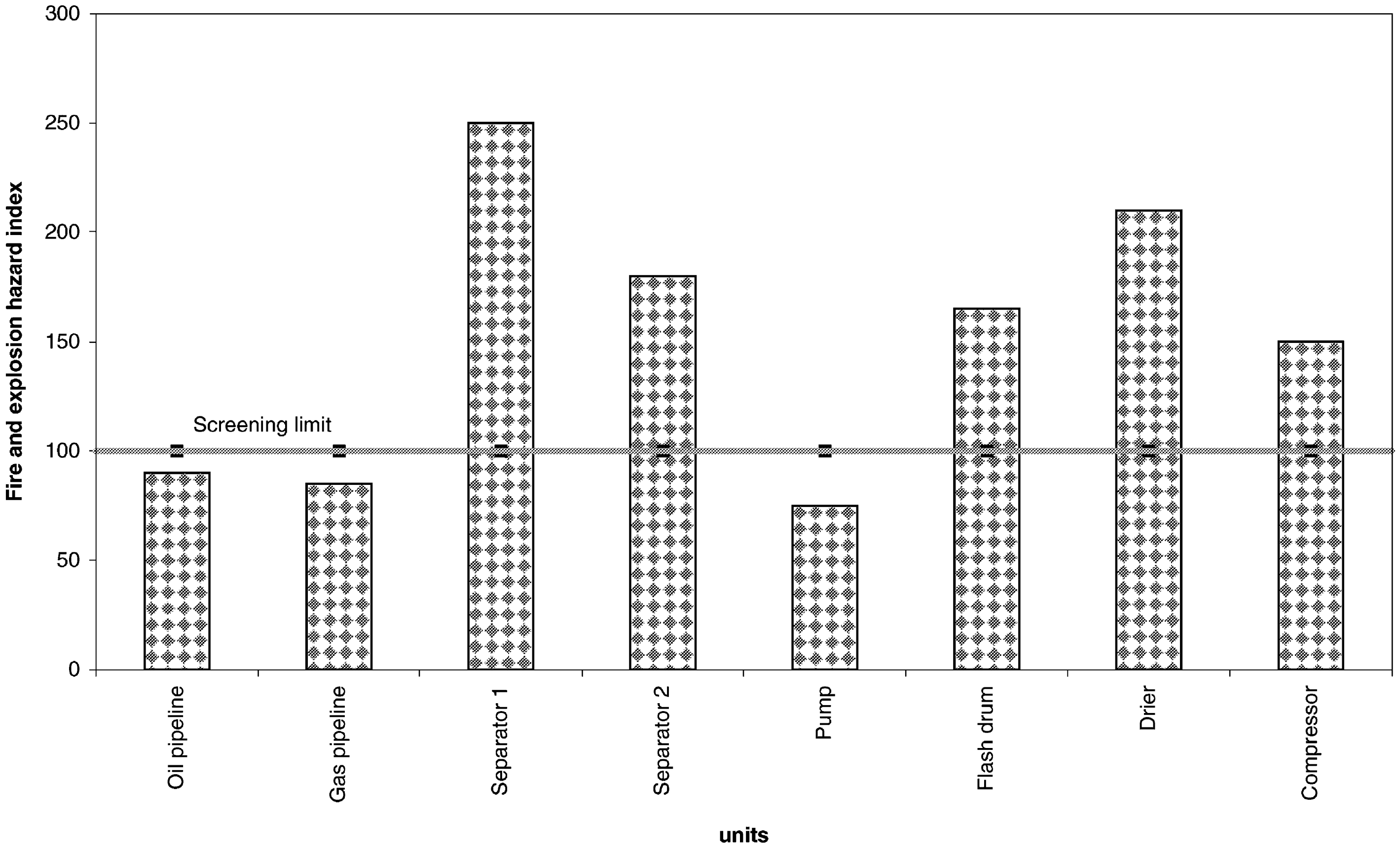

Fig. 5. Results of hazard identification step.

Condensate separator (*vapor cloud explosion* (*VCE*) *followed by fire* (*scenario 2*)): The instantaneous or continuous release of a chemical from the condensate separator would form a vapor cloud. On ignition the vapor cloud would cause VCE. Unreleased liquid in the unit would burn as a pool fire.

Table 2
Results of consequence analysis for scenario 1; accident in separator 1

Parameters	Values
Unit: separator 1	
Scenario: BLEVE followed by fireball and pool fire	
Explosion: BLEVE	
Total energy released (kJ)	2.2E+08
Peak overpressure (kPa)	600
Variation of overpressure in air (kPa/s)	482
Shock velocity of air (m/s)	753
Duration of shock wave (ms)	64
Missile characteristics	
Initial velocity (m/s)	137
Kinetic energy of fragment (kJ)	4.65E+04
Fragment velocity at study point (m/s)	134
Penetration ability at study point (based on empirical models)	
Concrete structure (m)	0.0529
Brick structure (m)	0.0676
Steel structure (m)	0.0136
DR for various degrees of damage due to overpressure	
DR for 100% complete damage (m)	61
DR for 100% fatality or 50% complete damage (m)	93
DR for 50% fatality or 25% complete damage (m)	138
Fire: fireball	
Radius of fireball (m)	92
Duration of fireball (s)	38
Energy released by fireball (kJ)	5.87E+08
Radiation heat flux (kJ/m^2)	22449
DR due to thermal load	
DR for 100% fatality/damage (m)	144
DR for 50% fatality/damage (m)	181
DR for 100% third degree of burn (m)	209
DR for 50% third degree of burn (m)	268
Fire: pool fire	
Radius of pool fire (m)	5
Burning area (m^2)	79
Burning rate (kg/s)	8
Heat flux (kJ/m^2)	57283
DR due to thermal load	
DR for 100% fatality/damage (m)	230
DR for 50% fatality/damage (m)	288
DR for 100% third degree of burn (m)	333
DR for 50% third degree of burn (m)	428

Table 3
Results of consequence analysis for scenario 2; accident in separator 2

Parameters	Values
Unit: separator 2	
Scenario: VCE followed by pool fire	
Explosion: VCE	
Total energy released by explosion (kJ)	1.23E+07
Peak overpressure (kPa)	320
Variation of overpressure in air (kPa/s)	345
Shock velocity of air (m/s)	353
Duration of shock wave (ms)	8
DR for various degrees of damage due to overpressure	
DR for 100% complete damage (m)	53
DR for 100% fatality or 50% complete damage (m)	74
DR for 50% fatality or 25% complete damage (m)	86
Fire: pool fire	
Burning area (m^2)	265
Burning rate (kg/s)	10
Heat flux (kJ/m^2)	2654
DR due to thermal load	
DR for 100% fatality/damage (m)	34
DR for 50% fatality/damage (m)	55
DR for 100% third degree of burn (m)	69
DR for 50% third degree of burn (m)	78

Compressor 1 (*jet fire* (*scenario 3*)): The continuous release of flammable gas from compressor 1 on ignition would cause a jet fire.

Compressor 2 (*jet fire* (*scenario 4*)): The continuous release of flammable gas from compressor 2 on ignition would cause a jet fire.

Table 4
Results of consequence analysis for scenarios 3 and 4; accident in compressor units

Parameters	Values
Unit: compressor units	
Scenario: jet fire	
Fire: jet fire	
Flame length (m)	5.45
Burning area (m^2)	792
Burning rate (kg/s)	10
Heat flux (kJ/m^2)	1493
DR due to thermal load	
DR for 100% fatality/damage (m)	24
DR for 50% fatality/damage (m)	35
DR for 100% third degree of burn (m)	44
DR for 50% third degree of burn (m)	57

Flash drum (*VCE followed by fire* (*scenario 5*)): Flammable gas released from the flash drum would form a highly flammable vapor cloud which on ignition would burn instantly causing high overpressure. Unreleased condensate in the unit would burn as a pool fire.

Drier (*BLEVE followed by fire* (*scenario 6*)): The high-pressure instantaneous release of gas from the drier may cause BLEVE. The released gas on ignition would cause a fireball. The cumulative effect of overpressure and heat may cause other units to fail and result in pool and/or jet fires.

3.3.2. Damage potential estimation

The results for scenario 1 (BLEVE followed by fire) are presented in Table 2. BLEVE would generate fatal overpressure over an area of ∼90 m radius. The vapor cloud generated by the released chemical on ignition causes a fireball, which would generate a heat radiation

Table 5
Results of consequence analysis for scenario 5; accident in flash drum

Parameters	Values
Unit: separator 2	
Scenario: VCE followed by pool fire	
Explosion: VCE	
Total energy released by explosion (kJ)	7.97E+06
Peak overpressure (kPa)	226
Variation of overpressure in air (kPa/s)	225
Shock velocity of air (m/s)	359
Duration of shock wave (ms)	11
DR for various degrees of damage due to overpressure	
DR for 100% complete damage (m)	23
DR for 100% fatality or 50% complete damage (m)	35
DR for 50% fatality or 25% complete damage (m)	47
Fire: flash fire	
Volume of vapor cloud (m^3)	104
Effective time of fire (s)	738624
Effective thermal load (kJ/m^2)	1214
DR due to thermal load	
DR for 100% fatality/damage (m)	17
DR for 50% fatality/damage (m)	21
DR for 100% third degree of burn (m)	25
DR for 50% third degree of burn (m)	32
Fire: pool fire	
Burning area (m^2)	358
Burning rate (kg/s)	15
Heat flux (kJ/m^2)	1579
DR due to thermal load	
DR for 100% fatality/damage (m)	25
DR for 50% fatality/damage (m)	42
DR for 100% third degree of burn (m)	56
DR for 50% third degree of burn (m)	77

Table 6
Results of consequence analysis for scenario 6; accident in drier unit

Parameters	Values
Unit: drier	
Scenario: BLEVE followed by fireball and pool fire	
Explosion: BLEVE	
Total energy released (kJ)	4.4E+07
Peak overpressure (kPa)	600
Variation of overpressure in air (kPa/s)	363
Shock velocity of air (m/s)	753
Duration of shock wave (ms)	28
Missile characteristics	
Initial velocity (m/s)	61
Kinetic energy of fragment (kJ)	9.30E+03
Fragment velocity at study point (m/s)	61
Penetration ability at study point (based on empirical models)	
Concrete structure (m)	0.0161
Brick structure (m)	0.0205
Steel structure (m)	0.0062
DR for various degrees of damage due to overpressure	
DR for 100% complete damage (m)	36
DR for 100% fatality or 50% complete damage (m)	55
DR for 50% fatality or 25% complete damage (m)	81
Fire: fireball	
Radius of fireball (m)	44
Duration of fireball (s)	18
Energy released by fireball (kJ)	7.33E+07
Radiation heat flux (kJ/m^2)	11205
DR due to thermal load	
DR for 100% fatality/damage (m)	51
DR for 50% fatality/damage (m)	64
DR for 100% third degree of burn (m)	74
DR for 50% third degree of burn (m)	95
Fire: pool fire	
Radius of pool fire (m)	5
Burning area (m^2)	79
Burning rate (kg/s)	8
Heat flux (kJ/m^2)	22912
DR due to thermal load	
DR for 100% fatality/damage (m)	73
DR for 50% fatality/damage (m)	92
DR for 100% third degree of burn (m)	106
DR for 50% third degree of burn (m)	136

effect. It is clear from Table 2 that an area of ∼180 m radius faces a 50% probability of fatality due to heat load. The overpressure and heat radiation effect may cause a fatality as well as second-order accidents by seriously damaging other units such as separator 2, the oil transportation pipeline, and the main pumping station; these consequences would extend far beyond a 250 m radius.

The forecasts based on detailed calculations for scenario 2 are presented in Table 3. VCE followed by fire would cause considerable damage. It is evident from Table 3 that damage of a high degree of severity due to overpressure and shockwave would be operative over an area of ∼50 m radius, while moderate damage (50% probability of lethality) would occur over an area of ∼75 m radius. The unburned chemical in the unit would burn as a pool fire. The heat load generated due to the pool fire would be lethal over an area of 55 m radius. The heat load and shockwave generated by this unit may initiate secondary and a higher order of accidents in the units within close proximity such as condensate and gas pipeline.

The forecasts of scenarios 3 and 4 are presented in Table 4. It is evident from the results that this scenario would cause moderate damage. There is no likelihood of overpressure development; however, a fire jet of ∼5 m in length would be operative. The lethal heat load of 50% probability of causing fatality and damage would be operative over an area of 35 m radius. It is likely that the jet flame would cause damage in the neighboring unit either through direct impingement or by external heat load. The units that would become frayed by this accident are the flash drum and the drier.

Table 7
Elements of the fault tree developed for a probable accident in separator 1

Number in Fig. 6	Elements	Failure frequency (per year)
1	Flow control valve failed	0.0250
2	Level indicator failed	0.0200
3	Excess flow at upstream	0.0800
4	Impurities causing exothermic reaction	0.0030
5	Sudden change in pressure	0.0170
6	Temperature controller failed	0.0200
7	High-pressure upstream line	0.0700
8	Upstream pressure controller failed	0.0250
9	Condensate line choked	0.0021
10	Oil pipeline choked	0.0075
11	Gas pipeline or valve choked	0.0015
12	Safety valve undersize	0.0500
13	Safety/pressure release valve choked or could not function on demand	0.0015
14	External heating	0.0150
15	Exothermic reaction in vessel	0.0030
16	Temperature controller failed	0.0200
17	Pressure controller system of separator failed	0.0200
18	Pressure or safety release inadequate	0.0015
19	Ignition due to explosion energy	0.1500
20	Ignition due to heat from surroundings	0.2000
21	Electric spark as source of ignition	0.2500

Unlike the separators, the flash drum poses fewer hazards. The results of the damage calculation for the most credible accident scenario (scenario 5) in the flash drum are presented in Table 5. It is evident from the results that damage causing shockwaves would be effective only to a limited area (∼35 m radius). The burning of a vapor cloud as well as a liquid pool would generate a lethal heat load which would encompass an area of ∼40 m radius. As

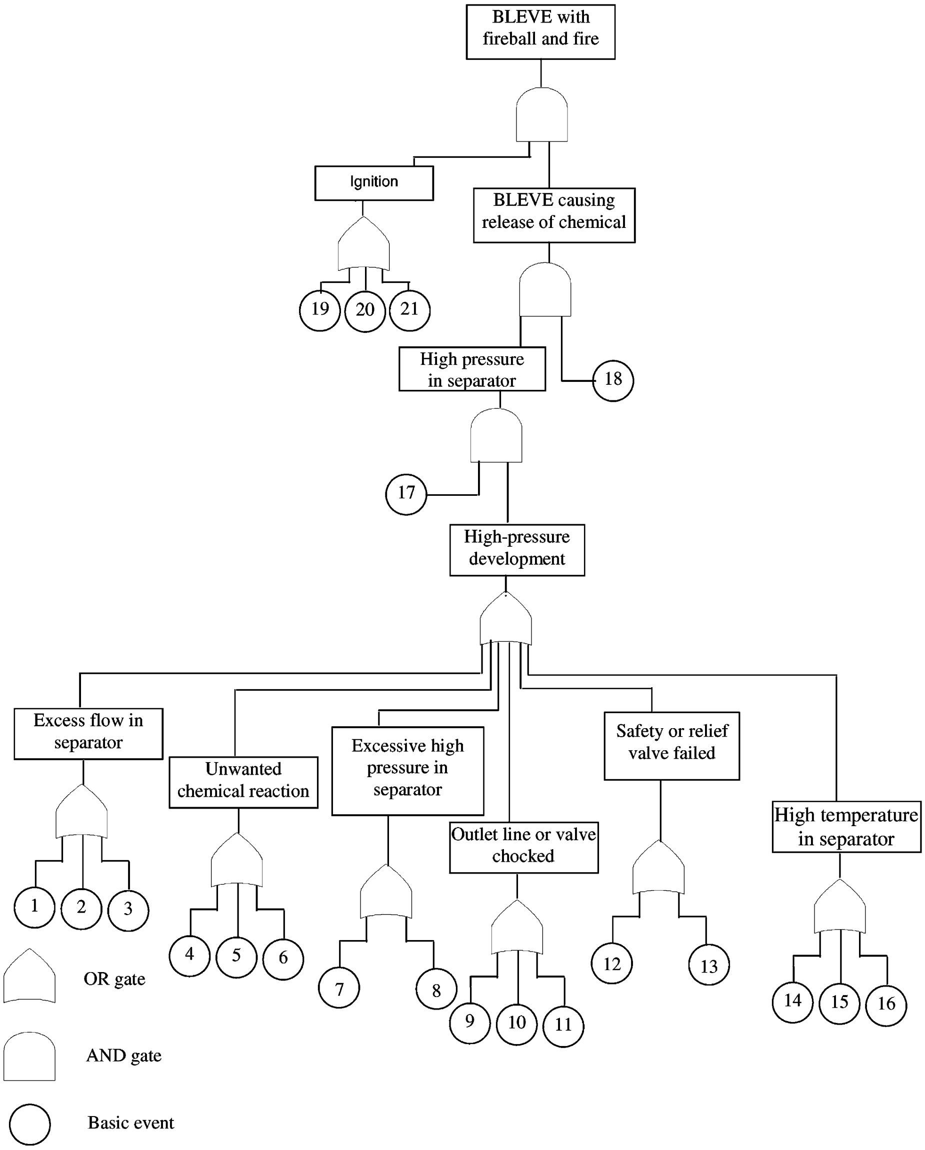

Fig. 6. Fault tree diagram for separator 1; detail of basic events is presented in Table 7.

Table 8
FTA results (output of PROFAT) for separator 1 (scenario 1)

Event not occurring	Probability	Improvement	Improvement index
0	1.066923E−05	0.000000E+00	0.000000
1	9.462237E−06	4.827976E−06	2.514747
2	9.670852E−06	3.993516E−06	2.080101
3	7.554889E−06	1.245737E−05	6.488667
4	1.023710E−05	1.728537E−06	0.900342
5	9.819864E−06	3.397467E−06	1.769638
6	9.670852E−06	3.993516E−06	2.080101
7	7.882713E−06	1.114607E−05	5.805650
8	9.462237E−06	4.827976E−06	2.514747
9	1.029670E−05	1.490117E−06	0.776157
10	1.010299E−05	2.264976E−06	1.179757
11	1.032650E−05	1.370906E−06	0.714063
12	1.014769E−05	2.086166E−06	1.086620
13	1.032650E−05	1.370906E−06	0.714063
14	9.849667E−06	3.278258E−06	1.707545
15	1.023710E−05	1.728537E−06	0.900342
16	1.029670E−05	1.490117E−06	0.776157
17	0.000000E+00	4.267693E−05	22.22911
18	0.000000E+00	4.267693E−05	22.22911
19	7.793307E−06	1.150369E−05	5.991926
20	6.973744E−06	1.478195E−05	7.699469
21	5.945563E−06	1.889467E−05	9.841661

Table 9
Elements of the fault tree developed for a probable accident in separator 2

Number in Fig. 7	Elements	Failure frequency (per year)
1	Leak from joints	0.045
2	Leak from main pipeline	0.003
3	Leak from joints	0.045
4	Leak from main pipeline	0.003
5	Leak from vessel	0.0015
6	Leak from fracture, joints or crack	0.0004
7	Leak from the pipe connections	0.0065
8	Leak from safety valve	0.0055
9	Leak from pressure release valve	0.015
10	Leak from control valves	0.025
11	Outlet pipe choked	0.0035
12	High-pressure upstream line	0.17
13	Sudden phase change	0.017
14	External heat absorption causing increase in pressure	0.016
15	Ignition due to explosion energy	0.15
16	Ignition due to external heat from surroundings	0.20
17	Ignition due to electric spark	0.25
18	Release from pipe after explosion	0.10
19	Release from vessel aftermath of explosion	0.05
20	Ignition due to external explosion energy	0.20
21	Ignition due to fire heat load	0.25

evident from the detailed results, this unit does not pose a serious threat and there is less likelihood of a secondary accident.

The drier is another important unit in the process facility as it handles a large quantity of flammable gas at high-pressure. The detailed results of the most credible accident scenario (scenario 6) in the unit is presented in Table 6. It is evident from this table that this scenario would cause considerable damage. Lethal overpressure load is enough to cause fatality, and damage would be operative over an area of 55 m radius. The released chemical on ignition would cause a fireball and a pool fire (leftover chemical in the unit), which would generate an excessive heat load. The lethal heat load of 50% probability of causing fatality and damage would engulf an area of ∼90 m radius. It is likely that overpressure and heat radiation load may cause other units to fail as secondary accidents. The units which are likely to become frayed are compressors, gas transportation line, and drier.

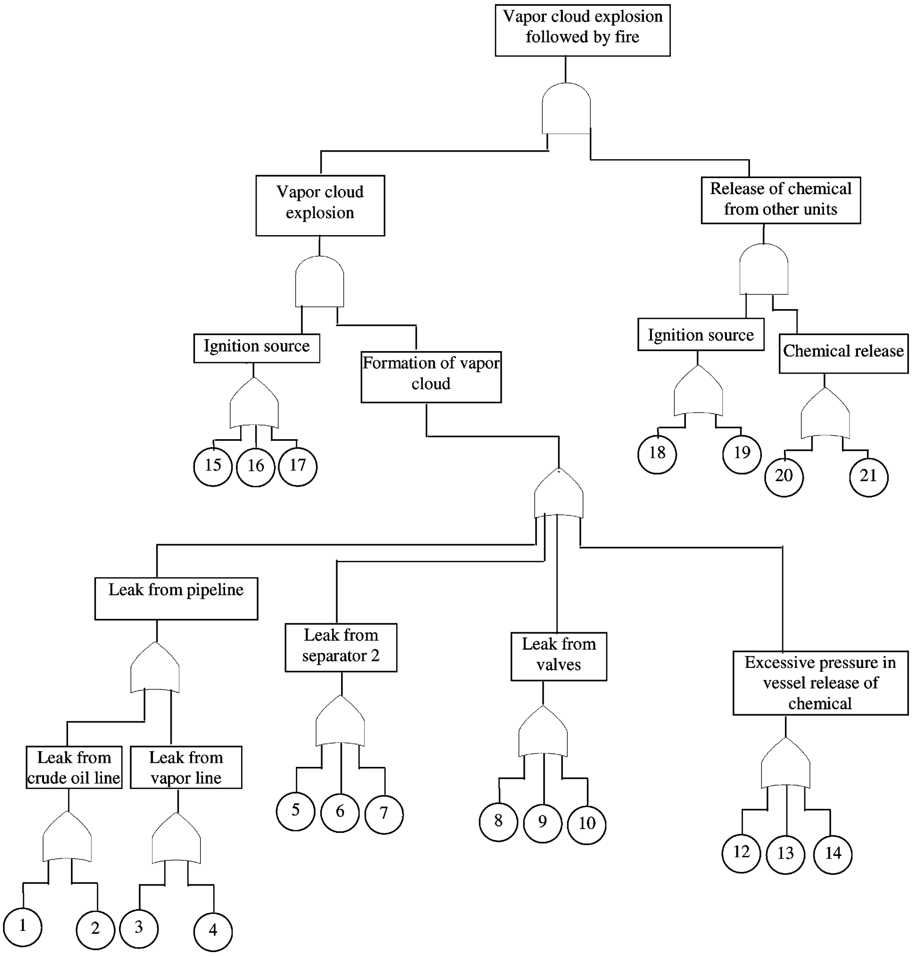

Fig. 7. Fault tree diagram for separator 2; detail of basic events is presented in Table 9.

3.4. Probabilistic hazard assessment (PHA)

PHA has been conducted for all six accidents scenarios identified in the six different units. Most of the failure frequency data is presented in Tables 7, 9, 11, 13 and 14. This data is derived from World-wide Offshore Accident Databases [44], HSE reports [45,46], and offshore data from E&P forum [47]. Using the data presented in Tables 7, 9, 11, 13 and 14, a FTA has been conducted to estimate the failure probability of each accident scenario.

3.4.1. Separator 1

The fault tree has been constructed for the most credible accident scenario in this unit (Fig. 6). There are 21 basic events which contribute directly and indirectly to the happening of the accident scenario. These events and their frequencies of failure are given in Table 7. The developed fault tree is subsequently analyzed using the ASM algorithm.

The result of a FTA (output of PROFAT) is presented in Table 8. The total probability of occurrence of the undesired event, when all initiating events occur, is estimated as 1.07E−05 per year. The improvement factor analysis (fifth step in ASM) suggests that events 17 and 18 have the largest contribution (about 22% each) to the probability of the eventual accident. It is further evident from Table 8 that events 4, 9, 11, 13, 15 and 16 do not contribute significantly to the occurrence of the accident. This analysis concludes that particular attention must be paid to events 17,18, 21, 20, 3, 7, and 19, as these are the most likely to cause this accident.

Table 10
FTA results (output of PROFAT) for separator 2 (scenario 2)

Event not occurring	Probability	Improvement	Improvement index
0	9.474457E−04	0.000000E+00	0.000000
1	8.279830E−04	4.778510E−04	3.155792
2	9.397716E−04	3.069656E−05	0.202724
3	8.279830E−04	4.778510E−04	3.155792
4	9.397716E−04	3.069656E−05	0.202724
5	9.436756E−04	1.508045E−05	0.099593
6	9.465664E−04	3.517309E−06	0.023229
7	9.302496E−04	6.878450E−05	0.454262
8	9.329916E−04	5.781649E−05	0.381828
9	9.077042E−04	1.589659E−04	1.049832
10	8.810459E−04	2.655993E−04	1.754053
11	9.383557E−04	3.635992E−05	0.240126
12	4.958510E−04	1.806379E−03	11.92956
13	9.023399E−04	1.804231E−04	1.191538
14	9.050069E−04	1.697551E−04	1.121085
15	7.109045E−04	9.461649E−04	6.248599
16	6.318837E−04	1.262248E−03	8.336055
17	5.529077E−04	1.578152E−03	10.42232
18	3.161132E−04	2.525330E−03	16.67761
19	6.318094E−04	1.262546E−03	8.338019
20	3.161281E−04	2.525270E−03	16.67722
21	6.318094E−04	1.262546E−03	8.338019

3.4.2. Separator 2

The most credible accident scenario for this unit is envisaged as VCE followed by a fire. There are 21 basic events that contribute directly and indirectly to the occurrence of this accident (Table 9). The likely sequences of events in this accident are depicted in Fig. 7.

The developed fault tree (Fig. 7) was analyzed using PROFAT, and the results are presented in Table 10. The overall probability of the occurrence of this accident scenario is computed as 9.474E−04 per year. Table 10 indicates that events 18, 20, 12, and 17 contribute 17, 17, 12, and 10%, respectively to causing this accident. Controlling these events would reduce considerably the overall probability of their occurrence.

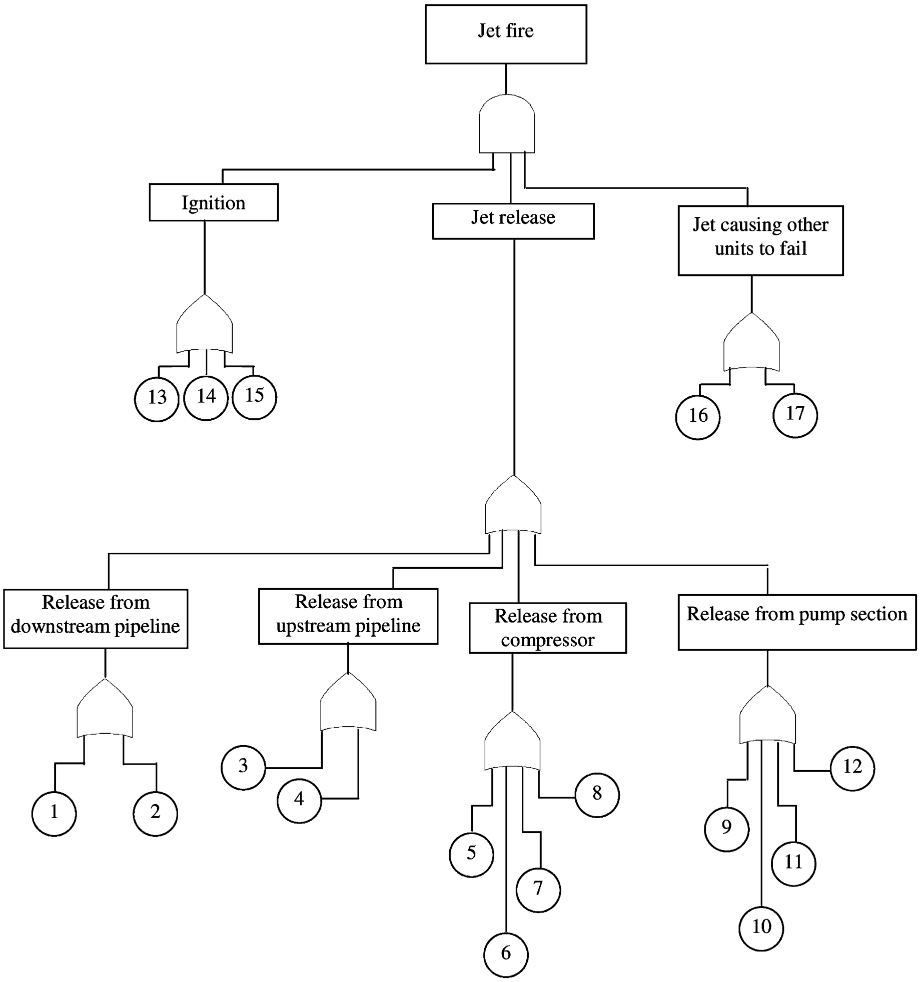

Fig. 8. Fault tree diagram for compressor unit; details of basic events is presented in Table 11.

Table 11
Elements of the fault tree developed for a probable accident in compressor units

Number in Fig. 8	Elements	Failure frequency (per year)
1	Leak from compressor downstream pipeline	0.0065
2	Leak from compressor downstream pipeline joints	0.090
3	Leak from compressor upstream pipeline	0.003
4	Leak from joints of compressor upstream pipeline	0.045
5	Release from casing of compressor	0.050
6	Leaking of seal	0.120
7	Release from impeller	0.100
8	Compressor completely failed causing release of chemical	0.070
9	Leak from junction of pump and pipeline	0.010
10	Leak from rotor	0.060
11	Pump failed to operate and caused release of chemical	0.150
12	Leak from casing	0.200
13	Ignition due to explosion energy	0.150
14	Ignition due to external heat from surrounding	0.200
15	Ignition due to electric spark	0.250
16	Fire caused failure of pipeline leading to chemical release	0.010
17	Fire caused vessel to fail and release of chemical from vessel	0.005

3.4.3. *Compressors 1 and 2*

The fault tree comprising of 17 basic events has been developed for the most credible accident scenario in the compressor units (Fig. 8). The probabilities of the occurrence of these basic events are presented in Table 11.

Table 12
FTA results (output of PROFAT) for compressors (scenarios 3 and 4)

Event not occurring	Probability	Improvement	Improvement index
0	1.364250E−02	0.000000E+00	0.000000
1	1.355903E−02	3.339117E−04	0.205645
2	1.248035E−02	4.648631E−03	2.862933
3	1.360403E−02	1.539034E−04	0.094784
4	1.306202E−02	2.321958E−03	1.430014
5	1.299739E−02	2.580464E−03	1.589220
6	1.209246E−02	6.200195E−03	3.818488
7	1.235117E−02	5.165338E−03	3.181155
8	1.273893E−02	3.614304E−03	2.225926
9	1.286812E−02	3.097529E−03	1.907662
10	1.170394E−02	7.754267E−03	4.775589
11	1.170394E−02	7.754267E−03	4.775589
12	1.105588E−02	1.034648E−02	6.372044
13	7.998807E−03	2.257479E−02	13.90304
14	9.132371E−03	1.804053E−02	11.11054
15	1.026367E−02	1.351535E−02	8.323643
16	9.132714E−03	1.803916E−02	11.10970
17	4.584522E−03	3.623193E−02	22.31400

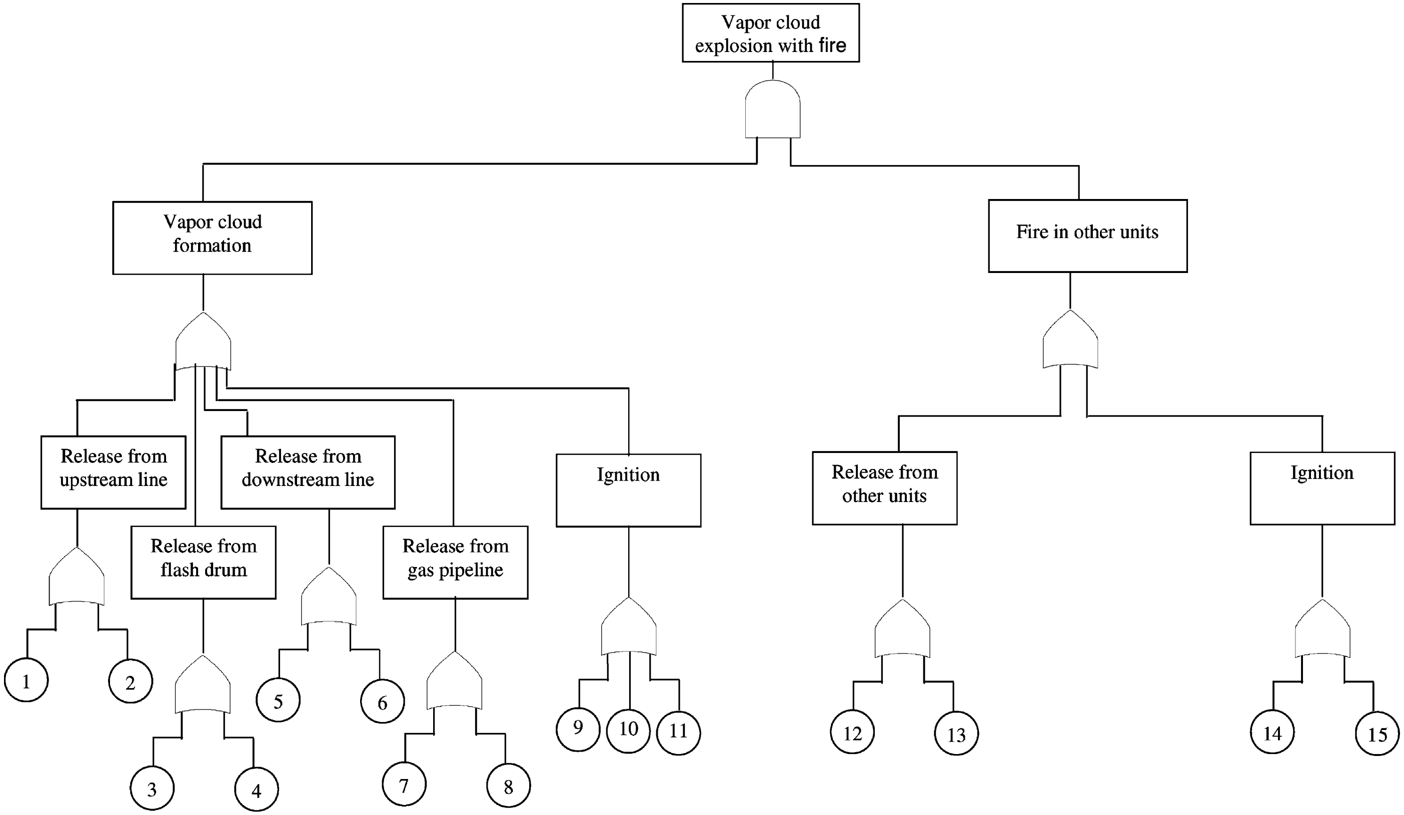

Fig. 9. Fault tree diagram for flash drum; detail of basic events is presented in Table 13.

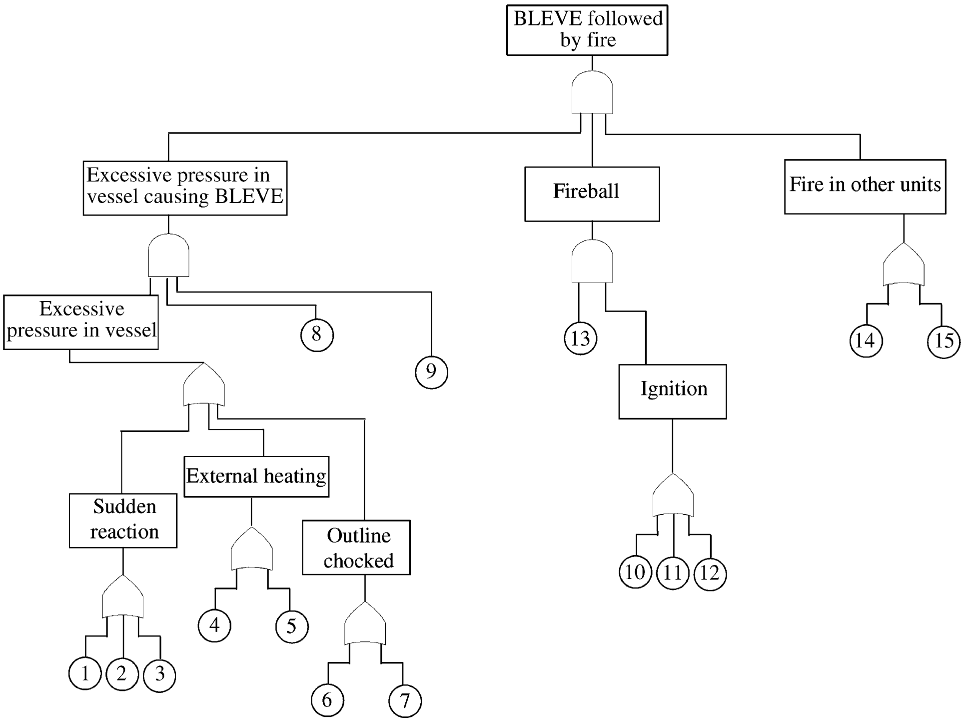

Fig. 10. Fault tree diagram for drier; detail of basic events is presented in Table 14.

Table 13
Elements of the fault tree developed for a probable accident in flash drum unit

Number in Fig. 9	Elements	Failure frequency (per year)
1	Leak from upstream pipeline	0.003
2	Leak from upstream pipeline joints	0.045
3	High-pressure in vessel causing rupture of vessel and release of gas	0.003
4	Leak from joints or flange	0.0075
5	Leak from downstream pipeline	0.00003
6	Leak from joints of downstream pipeline	0.0450
7	Leak from joint of gas pipeline	0.0650
8	Leak from gas pipeline	0.0045
9	Ignition due to explosion energy	0.150
10	Ignition due to external heat from surroundings	0.200
11	Ignition due to electric spark	0.250
12	Ignition due to explosion energy	0.150
13	Ignition due to external heat from surroundings	0.200
14	VCE causes pipeline to fail and release chemical	0.150
15	VCE causes vessel to fail and release chemical	0.050

Table 14
Elements of the fault tree developed for a probable accident in the drier

Number in Fig. 10	Elements	Failure frequency (per year)
1	Impurities in feed line	0.002
2	Control system failed	0.020
3	Sudden phase change	0.025
4	Temperature controller failed	0.020
5	Heating due to external heat source	0.150
6	Drier outlet line choked	0.004
7	Outlet valve choked	0.008
8	Safety valve failed to operate on demand	0.0075
9	Pressure relief valve failed to operate on demand	0.010
10	Ignition due to external heat from surroundings	0.200
11	Ignition due to electric spark	0.250
12	Ignition due to explosion energy	0.150
13	Ignition due to external heat from surroundings	0.200
14	BLEVE causes vessel to fail and release chemical	0.050
15	BLEVE causes pipeline to fail and release chemical	0.100

The developed fault tree was analyzed using the ASM algorithm, which computes the total probability of the occurrence of the top event as 1.364E−02 per year. Results reveal that events 17, 13 and 14 are the most crucial and contribute about 47% in initiating the accident. Controlling these basic events would drastically reduce the probability of their occurrence (Table 12).

Table 15
FTA results (output of PROFAT) for flash drum (scenario 5)

Event not occurring	Probability	Improvement	Improvement index
0	9.062887E−04	0.000000E+00	0.000000
1	8.906126E−04	6.270446E−05	0.432300
2	6.735921E−04	9.307862E−04	6.417066
3	8.802116E−04	1.043084E−04	0.719127
4	8.672774E−04	1.560454E−04	1.075815
5	9.045153E−04	7.093447E−06	0.048904
6	6.735921E−04	9.307862E−04	6.417066
7	5.701929E−04	1.344383E−03	9.268506
8	8.827745E−04	9.405663E−05	0.648449
9	4.531294E−04	1.812637E−03	12.49676
10	7.250159E−04	7.250910E−04	4.998954
11	6.344170E−04	1.087487E−03	7.497399
12	5.180090E−04	1.553119E−03	10.70758
13	3.883690E−04	2.071679E−03	14.28266
14	3.022254E−04	2.416254E−03	16.65823
15	6.041825E−04	1.208425E−03	8.331176

Table 16
FTA results (output of PROFAT) for drier (scenario 6)

Event not occurring	Probability	Improvement	Improvement Index
0	2.831220E−06	0.000000E+00	0.0000000
1	2.875924E−06	1.788148E−07	0.2695430
2	2.607703E−06	8.940692E−07	1.3477080
3	2.533197E−06	1.192093E−06	1.7969460
4	2.607703E−06	8.940692E−07	1.3477080
5	9.685755E−07	7.450580E−06	11.230907
6	2.875924E−06	−1.788148E−07	−0.269543
7	2.786517E−06	1.788130E−07	0.2695400
8	0.000000E+00	1.132488E−05	17.070980
9	0.000000E+00	1.132488E−05	17.070980
10	1.907349E−06	3.695487E−06	5.5705290
11	1.713634E−06	4.470347E−06	6.7385440
12	2.130866E−06	2.801416E−06	4.2228190
13	0.000000E+00	1.132488E−05	17.070980
14	1.981854E−06	3.397464E−06	5.1212930
15	8.940698E−07	7.748602E−06	11.680142

3.4.4. *Flash drum and drier*

The fault tree of the flash drum and the drier as illustrated in Figs. 9 and 10 are comprised of 15 basic events. Although the number of basic events in both cases is the same, their details are different (summarized in Tables 13 and 14).

These fault trees were analyzed using PROFAT. The results for the flash drum as presented in Table 15 indicate that the likelihood of this accident occurring is 9.06E−04 per year. Among the 15 basic events, events 14, 13, 9, 7 and 15 contribute almost 50% to the total probability of occurrence. Control of these events would ensure a better design and a safer operation. The FTA for the drier (Table 16) estimates the probability of occurrence of this accident scenario as 2.831E−06 per year. Among the various basic events 9, 13, 5, and 15 control the total probability of occurrence. A check on these basic events would ensure a safer design and operation.

3.5. *Risk quantification*

Using the results of the previous steps, risks are computed for all six units under study. Interesting results are observed. Though the compressor units are moderate in damage causing capabilities, they were found to be the most risky. This is because of their high probability of failure. The unit observed to be the most disastrous in damage calculation—separator 1—was found to be comparatively less risky, due to its low probability of failure. Fig. 11 presents a summary of the average individual risk factors caused by different units along with ALARP criteria. Analysis of these results reveals that the compressor units followed by separator 2, flash drum and separator 1 pose a high individual risk. Their risk and FAR values exceed the ALARP acceptance criteria. These units need attention in order to bring these high risks to an acceptable level.

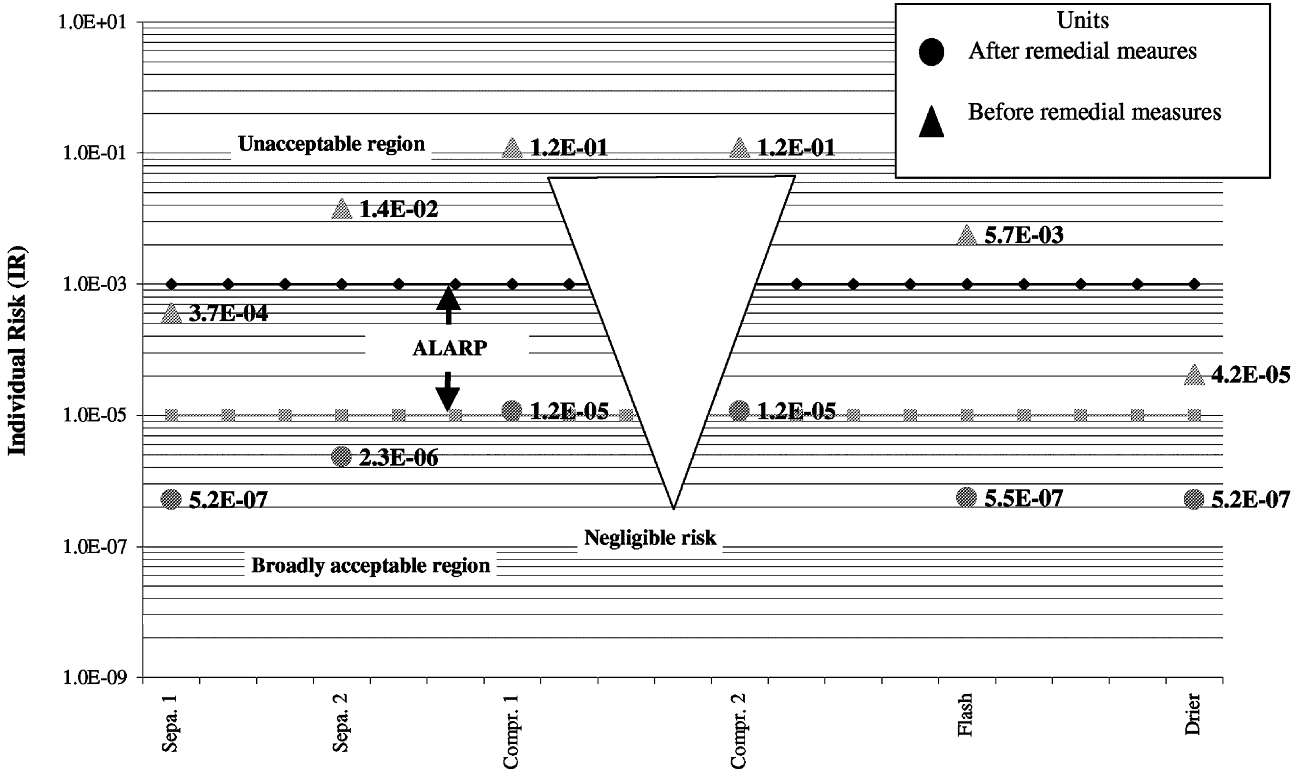

Fig. 11. Comparison of individual risk factors with ALARP criteria.

Table 17
Control measures implemented over different units to reduce the risk

Control measures	Frequency of failure (per year)
Flame arrester	0.040
Water sprinkling system	0.045
Flammable gas detector	0.065
Advanced control mechanism, i.e. feed forward, cascade control, neural network based control, DDC	0.005
Advanced final control element (digital controller)	0.002
Installation of emergency relief system against overpressurization of separators, flash drum, and drier	0.050
Check valve with relief provision to flare	0.030
Installation of bypass line	0.004
Preventive maintenance of pumps	0.100
Preventive maintenance of compressors	0.150
Preventive maintenance of pipeline	0.070
Leak detector in compressor and pumping section	0.057
Installation of safe venting system on pipeline	0.010
Installation of blast barriers	0.030
Installation of external cooling system for separators, and drier	0.045
Installation of inert gas purging system to prevent flammable gas cloud formation	0.065

3.5.1. Risk reduction through safety measures—MCCA–PFTA controller system

A risk reduction exercise was conducted by incorporating various safety measures and add-on control measures. Possible control options to reduce the risk are given in Table 17 [17,48], and from these, various combinations of control measures were selected to reduce the risk potential of a unit. When these measures are taken into account, the unit fault tree is modified, as shown in Fig. 12 (compressor unit). On analyzing the new fault tree (Fig. 12), the frequency of occurrence of the top event (envisaged accident) is reduced to 1.311E−06, which is about 10,373 times lower than the previous value. The individual risk and FAR value after the implementation of control measures for this unit come well within the acceptable range (Fig. 11). The FAR value was reduced from 11127 to 1.

After deciding the safety measures (Table 17), the fault tree for separator 2 is modified, as shown in Fig. 13, and processed through PROFAT for probability estimation. The results reveal that after implementing the safety measures, the probability of occurrence decreases to 1.555E−08. Using the revised value of the probability of occurrence, the average individual risk decreases to 1.55E−07 and FAR reduces from an original value of 1291–0.01. These values lie within the acceptable zone of ALARP criteria.

The incorporation of safety measures on separator 1, the flash drum and the drier reduces the probability of occurrence to 1.79E−08, 7.86E−08, and 3.47E−08, respectively. The average individual risk and FAR values for these units after implementing the safety measures fall well within the ALARP acceptable region (Fig. 11).

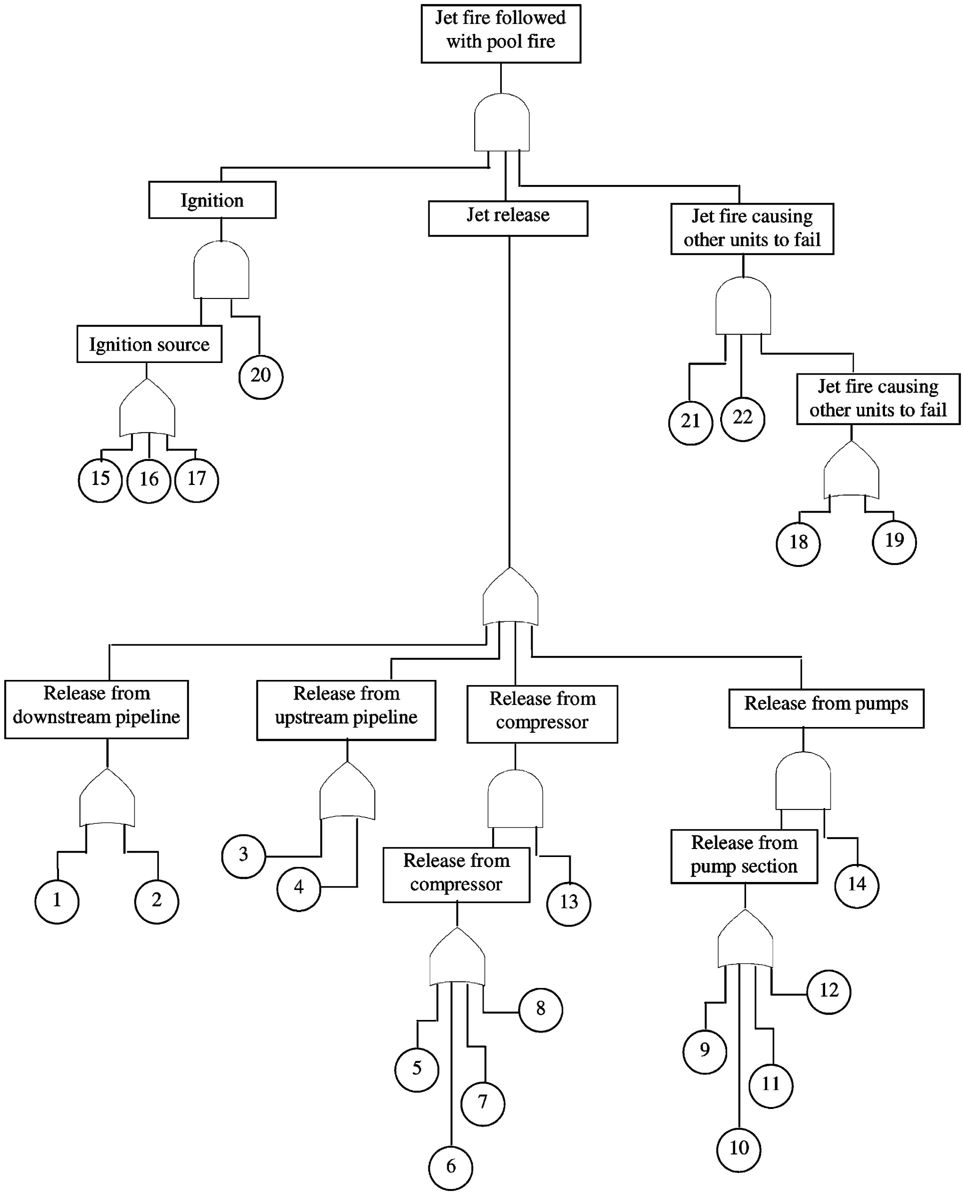

Fig. 12. Modified fault tree diagram for compressor unit after implementing safety measures.

4. Summary and conclusion

This paper discusses a revised version of the recently proposed SCAP methodology for risk-based safety management for offshore process activities through a quantitative feed-

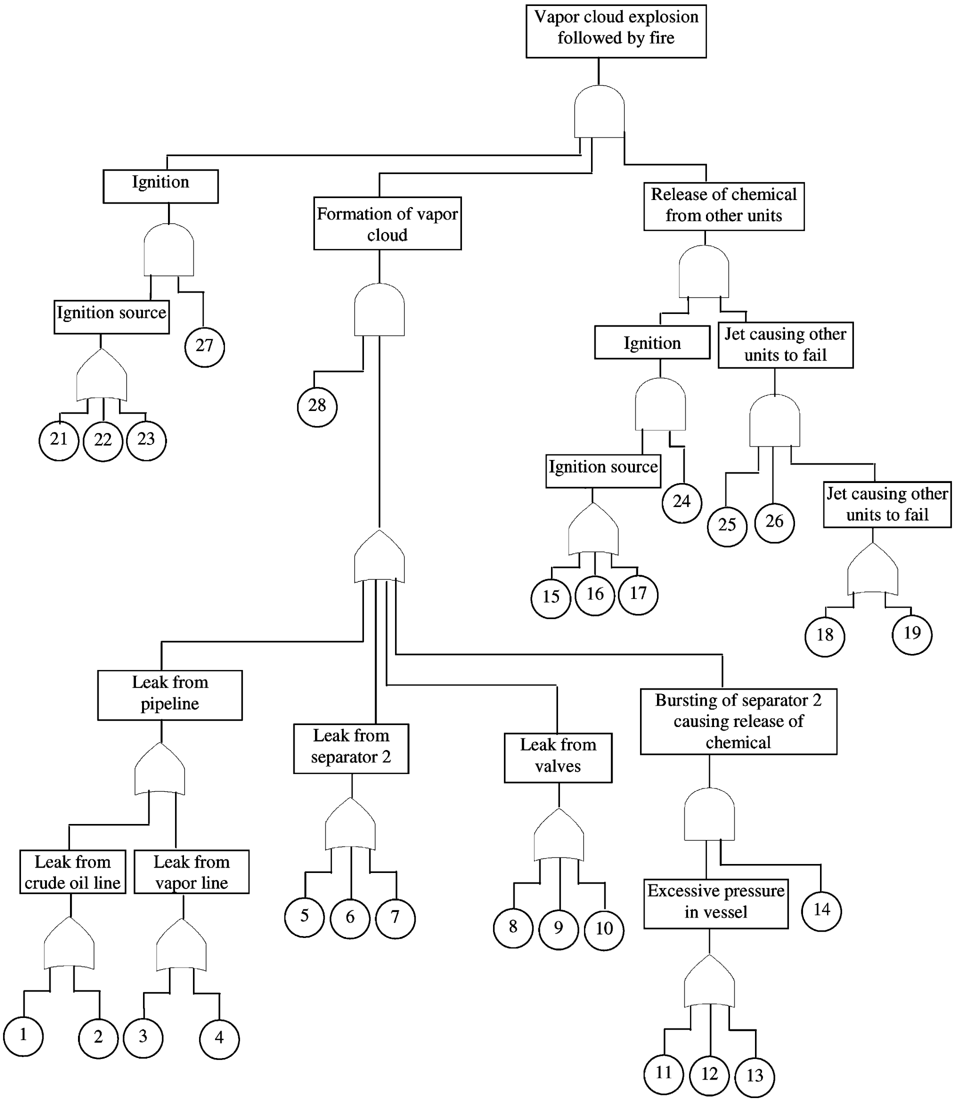

Fig. 13. Modified fault tree diagram for separator 2 after implementing safety measures.

back system of probabilistic risk assessment. It illustrates the application of the discussed methodology to a typical offshore process plant. The methodology is a combination of five quantitative steps; each requires an independent technique and computer-aided tools. The first step is to identify and screen the hazards in a process area, and the HIRA technique is recommended for this purpose. The next step is quantitative hazard assessment that depends upon MCAA with MCAS; MAXCRED-III is the recommended tool for this step. The third step is PHA, which estimates, the probability of an envisaged accident scenario and uses the FTA; PROFAT is used for this purpose. In the fourth step, the results of the previous two steps are combined to compute the risk. The estimated risk is subsequently compared with the acceptance criteria; if it exceeds the acceptable level, step 5 is executed as a feed back loop. It carries out steps 3 and 4 once the necessary safety measures to control the risk have been decided.

The advantage of using this methodology has been demonstrated by applying it to a typical offshore process facility. From the initial phase of the case study, it was observed that compressor units inherit maximum risk due to their higher probability of failure. However, after implementing safety measures, the probability of occurrence was reduced drastically, causing a substantial risk reduction. Finally, these authors feel that this methodology is useful due to following reasons.

1. It is a step-by-step straightforward approach with structured techniques and computer-automated tools available at each step.
2. It does not require much data like other detailed QRA methodologies. This makes its application easy at the early design stage of the process units.
3. It recommends the latest reliable techniques and models for each step, such as revised HIRA, MCAA with MCAS, and ASM.
4. The outcome of each step is self-explanatory and does not require any interpretation; for example, the results of revised HIRA—the radius of the area under threat; MCAS—the most credible accident scenario; MCAA—damage radii of various propensities; and risk computation—individual risk factor and FAR values.

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