Fault Tree Analysis to Compute the Probability of an Event: A Case Study in Oil and Gas Industry

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ABSTRACT

The aim of this study is establishing Fault Tree Analysis (FTA) with using experts' opinions to compute the probability of an event (as a main factor of risk value). Thus, in order to find the probability of top event, all of the basic event's probability should be available when FTA is drawn for an event. In this case, several experts will be employed to express their opinions in qualitative terms for all basic events instead of using probabilities from handbooks. In real life, participated experts have subjective weights based on their background and experiences. Therefore, they should be weighted by a standard method like as AHP. Then the experts' opinions will be collected. In this case, fuzzy set theory will be employed. All experts' opinion which is expressed in qualitative terms (crisp value) is transferred to fuzzy set number (triangular or trapezoidal). Accordingly, in fuzzy environment their opinions will be aggregated in a set of fuzzy number form. So, the fuzzy number requires to be defuzzified to crisp value. Finally probability of basic events will be computed, and subsequently the probability of top event will be calculated using Boolean algebra.

Keywords: Fault tree analysis, Fuzzy logic, Chemical complex plant, Expert judgment

ÖZ

Bu çalışmanın amacı bir olayın olasılığını (risk değerinin ana faktörü olarak) hesaplamak için uzmanların görüşlerini kullanarak Arıza Ağacı Analizi (AAA) kurmaktır. Böylece, en önemli olay olasılığını bulmak için, bir olay için AAA çekildiğinde temel olay olasılığının tümünün mevcut olması gerekir. Bu durumda, el kitaplarındaki olasılıkları kullanmak yerine, tüm temel olaylar için görüşlerini nitel olarak ifade etmek üzere birkaç uzman görüşüne başvurulmuştur. Gerçek hayatta katılan uzmanların geçmiş deneyimlerine dayalı öznel ağırlıkları bulunmaktadır. Bu nedenle, Analitik Hiyerarşi Süreci gibi standart bir yöntemle ağırlıklandırılmalıdır. Bu aşamada uzmanların görüşleri toplanıp, bulanık küme teorisi kullanılacaktır. Niteliksel terimlerle (net değer) ifade edilen tüm uzmanların görüşleri bulanık kümeye (üçgen veya trapez şeklinde) aktarılacaktır.Buna göre, bulanık ortamda görüşleri bulanık sayı formunda toplanacaktır. Böylece, bulanık sayı, berrak bir değere çekilmeyi gerektirecektir. Sonunda temel olayların olasılığı hesaplanacak ve daha sonra en üstteki olay olasılığı Boolean cebri kullanılarak hesaplanacaktır.

Anahtar Kelimeler: Hasar ağacı analizi, Bulanık mantık, Kimyasal kompleks tesis, Uzman yargısı

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INTRODUCTION

1.1 Significance of the Research

In recent years, complex chemical plants have been rapidly developed to meet the increasing demand of process industries. As these plants are usually used to process hazardous materials, their failure has the potential to cause serious harm, both to people and the environment. For this reason, it is necessary to recognize potential risks sat by these specified systems and then take measures to minimize the likelihood of these risks. To deal with a large amount of accidents, incidents, near misses, and mishaps in process industries, different risk assessment approaches have been developed and widely used to perform hazard analysis, thus enabling the prevention of inadvertent incidents and also to plan mitigative actions.

A fault tree (FT) can be analyzed both qualitatively and quantitatively. Qualitative analysis minimizes a fault tree to a set of basic events, which are the smallest combinations of events that are necessary and sufficient to cause the top event (TE), i.e., a hazardous event. Quantitative analysis mathematically calculates the occurrence probability of the top event and other relevant numerical indexes, given the failure rate/probability of individual element of a system. For this reason applicability of FTA for quantitative analysis mostly depends on the availability of failure data. However, for many large and complex systems, it is usually very difficult to obtain exact failure data due to lack of information, shortage of statistical data, ambiguous basic events behavior, and operating environment of the system.

To deal with ambiguities and shortages of data in conventional FTA, fuzzy logic is used by considering the triangular and trapezoidal fuzzy numbers to compute the failure probability (FP) of top event (TE) with respect to expert judgment in specified chemical industries.

1.2 Motivation of Research

Nowadays, all approaches in all aspects of science have become comprehensive. In other word, goal of development, is not just economic growth, but also satisfying public opinion with a sustainable development. Paying attention to health, safety and environment issues in a comprehensive approach would follow such a goal.

Occurrence of accidents related to industry, annually costs a country a lot. In the recent century, with rapid development of industries and as a result, more accidents, methods and solutions were investigated to lower accidents consequences and likelihood. With growth of process industries such as oil, gas and petrochemical, work related accidents become more comprehensive than industrial safety classifications such as falls from height, and equipment collision with humans; therefore process safety was established. Process safety investigates process industries accidents in terms of fire, explosion and toxic release.

Since Iran is well known for its vast resources of oil and gas, process industries are common. Therefore new methods should be introduced to enhance safety and efficiency of these industries. That was a motivation, great enough, to propose a new method of evaluating process safety based on fault tree analysis concept by using fuzzy logic.

1.3 Objective of this research

The overall objective of this study is to risk assessment in a chemical complex plant. The objectives are specified below:

1- Safety risk assessment by employing fault tree analysis (FTA).

2- Employing a heterogeneous group of experts which are specialist in their fields.

3- Using systematic improved fuzzy analytical hierarchy process (FAHP) to evaluate the weights of each expert.

4- Quantitative assessment of hazards by employing Fuzzy FTA in chemical complex plants.

5- Considering common cause failure in specified risk assessment procedure.

6- Increasing plant safety by identifying basic events with low safety rules or in other words by identifying critical basic events.

7- Identifying the critical components in system and providing appropriate solution.

8- Identifying the critical paths to occurring top event compared to critical basic events.

9- Comparing contribution of each basic event with the critically of them.

1.4 Research Questions

1. What is probability of occurrence specified top event in chemical complex plant?

2. Which basic events are more critical and has more contribution to occurring top event?

3. Which of the critical and contribution of basic events are more reliable for consideration further actions?

4. How fuzzy logic can cope with any ambiguities in a risk assessment.

Chapter 2

LITERATURE REVIEW

2.1 Risk Assessment

Over recent years major accident such Flixborough, Bhopal, Chernobyl, and Piper Alpha have taken a sad toll of lives and increased public perception of the risks associated with operation large process plant. After such accidents the reaction is always to say “This must never happen again”; however, sadly, it is clearly impossible to eliminate all risks. Therefore, in a modern society there is a need for resolving apparent paradox of obtaining the benefits of modern technology without increasing the problems that such technology can bring for the public and government regulations.

The safety of industrial plants has become a subject of public concern because of several notable accidents; some of important ones between 2011 and 2016 are listed in Table 2.1.

Table 2.1. Lists of notable industrial disasters (Khakzad & Reniers, 2015; "Massive explosion at Cyprus naval base," 2011; Mesiar, 2007; Noroozi, Khakzad, Khan, Mackinnon, & Abbassi, 2013; Trucco, Cagno, Ruggeri, & Grande, 2008; Vasheghani Farahani, 2014; Yan, Xu, Yao, & Li, 2016; Zarei, Azadeh, Khakzad, Aliabadi, & Mohammadfam, 2017; D. Zhang, Yan, Yang, & Wang, 2014)

Date	Location	Description
2015, August	Tianjin, China	173 people died because of two explosions happening in storage tank station at loading port.
2014, May	Manisa, Turkey	301 workers died due to breathing carbon monoxide as a result of an explosion in a coal mine when 783 workers were working approximately 2 kilometer below the surface.
2013, July	Quebec, Canada	During drilling task on oil ship, gas leakage release into atmosphere and reach to near ignition source, then big explosion occurred. As a result of this accident, 47 employees were died. This event is called the worse accident that happened in the whole history of Canadian industries.
2013, April	Dhaka, Bangladesh	1129 people were killed because of domino series fire extend in 8 building were located near to each other. The Most important reason of these numbers of dies mentioned that there were not any escapes gates in aforementioned buildings.
2013, April	West Texas, US	As a result of a terrible explosion in one of the storage facility in a big company in west Texas, 150 buildings totally ruined, at least 160 people were injured and 14 workers of that company were killed. A weakness safety system as a cause of the accident was published by Chemical Safety Board (CSB).
2012, September	Karachi, Pakistan	Extending fire in garment factory caused 289 workers killed because of severe burns on their body and breathing carbon monoxide.
2012, August	Amuay, Venezuela	Gas leakage in one of the high risk pipelines in oil refinery caused that a catastrophic explosion occurred. As a result of this crisis, 39 and 80 workers were passed away respectively.
2011, July	Evangelos Florakis Naval Base, Cyprus	An explosion on 98 boxes and containers as domino series caused a big crisis happened. As a result of this event totally 13 people were died and 62 ones injured.
2011, March	Fukushima, Japan	Since after Chernobyl accident, Fukushima nuclear crisis is called the worse accident that happened in nuclear history until now. Fortunately, no one injured or died because of this accident. But unsafe conditions were implemented for a long time.

Hazards should be eliminated as far as possible and reduce the risks from the plant. The term of risk covers two parameters; the first one is scale of event (in expression: loss and fatality) and the second one is the probability of common event. Additionally the value of risk defined as probability of an event (likelihood) multiplied by severity of the occurrence.

Thus, the remaining hazards can be seen to make only a small addition in to the inherent background risks of everyday life. This can never be achieved by the age old method of learning from past experience. Each new plant is different from any previous one and therefore it needs to be assessed to identify, evaluate and control the particular hazards associate with it. Risk assessment techniques are the methods advocated by many regulatory bodies to assess the safety of modern, complex process plant and their protective systems. The term quantified risk assessment (which includes both analysis and management) is now incorporated into the requirement for safety cases in nuclear, chemical/petrochemical, and offshore industries. The methods have been adopted in the defense, marine, and automotive industries.

Risk assessment methods have developed over a number of years from a variety of different initiatives. The pioneer work in Germany on missile systems during the Second World War, the development of risk assessment methods for defense equipment by the US Department of defense, and in the UK the contributions on hazards analysis by Trever Kletz of ICI Ltd and on safety analysis by Green and Bourge of UKAEA are all worthy of note, Milesones also exist such as the reports of public enquiries following the accident at Windscale, Flixborough, Piper Alpha, the well-known WASH 1400 report on nuclear safety, the Canvey Island risk assessment report and many others. All of these initiatives have contributed to the increased awareness of general public of potential hazards and highlighted the need for better methods for ensuring the safety design of our plants and improving the safety of hazardous plants (Kletz, 2001, 2009).

Hazard and operability study (HAZOP) is a proper method in order to investigate how complex plant may deviate from its design procedure. In this case if a deviation accrued, problem will be found out and accordingly the solutions as corrective actions will be recommended. In addition, the other output of HAZOP is that assessor will be able to recognize which component is more hazardous and which types of accident such as fire, explosion, leakage may occur (Banerjee, 2003).

Main (2004) reviewed the fundamentals and principles of risk assessments methods which contains four keys including identified hazards, assess risks, reduce risks and document results. Besides, he explained the value of risk assessment because of several reasons. As an example the following factors like as time, cost, competition and customer requirements can be considered the importance of risk assessment implementation.

Rausand (2011) provided much valuable information about common used risk assessment methods. The procedure of risk assessment technique with respect to specified example in related industries are explained and solved respectively. In addition, common problems of risk assessment methods which may assessors face them in complex systems are pointed and suggested some techniques to overcome them.

Berni, (2012) introduced a quantitative fault tree analysis in order to estimate the dependent events. The complexity of measuring is found out through the study. Then, the framework is purposed to increase the quality of the measures and the simulation of approach is applied in a health system. Evaluation of error components and comparing the result with independent case can be named as a novelty of the study.

Rajakarunakaran et al. (2015) presented a new method for reliability analysis of complex engineering systems. Authors used a fault tree analysis for assessing the risk and by employing expert elicitation tried to reduce the uncertainties and ambiguities of qualitative and quantitative analysis. Using fuzzy set theory, they aggregated the experts' opinions in fuzzy environment and by diffuzification procedure the results seem to be more realistic. The novel criteria of their study are applying the purposed approach on LPG refueling station which has not done any safety studies yet.

Villa et al. (2016) analyzed the progress of Quantitative Risk Assessment (QRA) during the last decades. The limitations of QRA are considered and the newly advancements of QRA are presented. They used the network model to transfer conventional risk assessment in to dynamic ones; for example bow-tie model to Bayesian network. Additionally, some recommendations as further directions are offered.

2.2 Fault Tree Analysis (FTA)

A hazardous event or failure in a component at any part of industry may occur as a result of domino series incidents. FTA method is a systematic procedure which is usually used not only to analyze of event or failure causes but also to determine possibility of expected event or failure. In general speaking, FTA method presents high important casual information from potential events and their probability of occurrence. This method is usually utilized when other types of risk assessment methods to purpose of evaluate the accident needs more details and also specified methods do not able to determine accurate probability. In order to identify the cause of a failure, other risk assessment methods including FMEA, HAZOP,etc. could be employed.

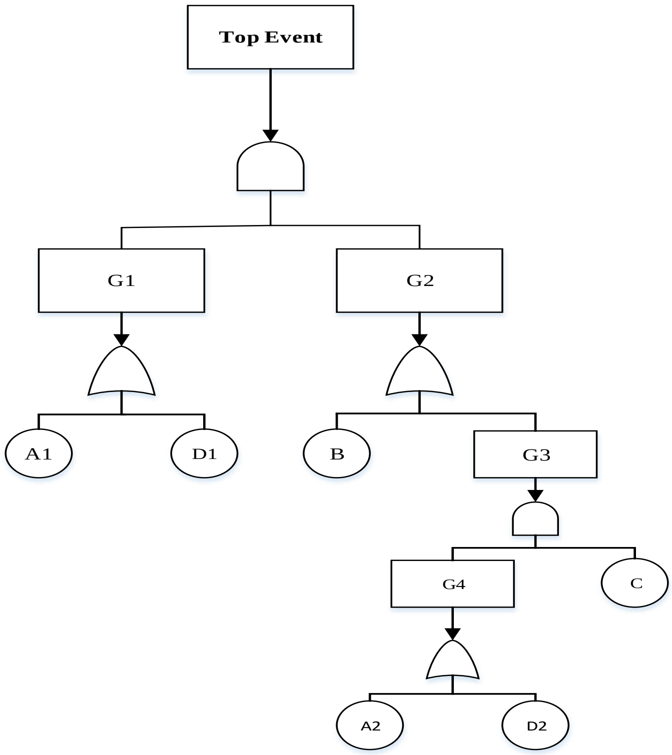
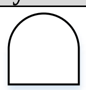
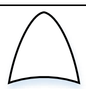


Figure. 2.1 A simplified fault tree (Andrews, 1993)

FTA is a graphical representation of event which leading to unforeseen event or Top Event (TE). The symbols for basic events, conditions, transfers and gates are defined in Table 2.2 Moreover in Table 2.3 the symbol and rules of mathematic gate are explained (Rausand & Høyland, 2004).

Table 2.2 symbols for basic events, conditions, transfers and gates

Symbol	Type	Description
	AND Gate	When all input faults take place then output fault will happen
	OR Gate	At least one input fault should be happened in order to output fault occur

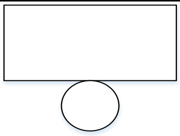
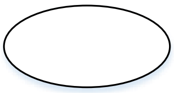
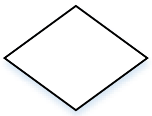
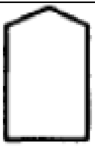
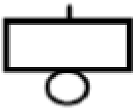
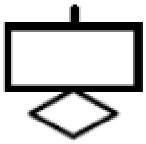
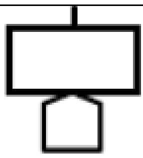
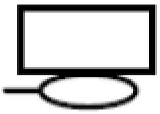
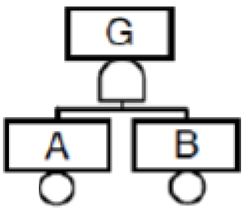
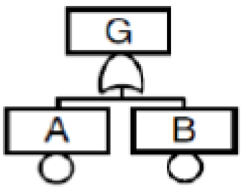
	Basic Event	A basic fault event needs no more extension and development
	Conditioning Event	Individual conditions or limitation which use for AND/OR gates
	Undeveloped Event	It is used when event cannot extend due to the lack of information
	External Event	It is expected event in normal situation happening
	Primary Failure (BE)	Arbitrary failure event on basic component failure
	Secondary Failure (SF)	Arbitrary externally failure event on basic component failure, it needs more details for development
	Normal event (NE)	It is expected that an event happen in a normal situation of system
	Condition event (CE)	Controlled by limitation or probability

Table 2.3 The symbol and mathematic rules of gates

Gate Symbols		
	AND	$P(\mathrm{G}) = P(A) \cdot P(B)$ (2 *input gate*) $P(\mathrm{G}) = P(A) \cdot P(B) \cdot P(C)$ (3 *input gate*)
	OR	$P(\mathrm{G}) = P(A) + P(B) - P(A) \cdot P(B)$ (2 *input gate*) $P(\mathrm{G}) = P(A) + P(B) + P(C) - P(AB) + P(AC) + P(BC)$ $+ P(ABC)$ (3 *input gate*) And for mutually exclusive events: $P(\mathrm{G}) = P(A) + P(B)$ (2 *input gate*)

For intersection of AND gates, it is necessary to note that if A and B was independent it could be calculated by $P(G) = P(A) \cdot P(B)$ otherwise, for dependent situation: $P(G) = P(A) \cdot P(B/A)$.

Mahmood et al. (2013) reviewed a concept and application of fuzzy fault tree analysis. They discussed the strengths, weaknesses and applications of fuzzy set theory for fault tree analysis. They illustrated that fuzzy set theory has high importance in handling the uncertainties that may happen in conventional methods. Also, they categorized the publications in four concepts related to fuzzy fault tree analysis including: fuzzy FTA Diagnosis, fuzzy FTA application, expert knowledge with fuzzy FTA and uncertainty possibility of fuzzy FTA.

Wu et al. (2014) constructed a fire risk analysis in a city of China. Authors used fault tree analysis to find root causes of fire and to improve the guarantee and facilitate of city in face of fire accident. By employing fuzzy important degree, they sorted any founded root causes to rank corrective actions for specified events in near future. In addition, the outlook of their study is implemented for city fire safety management of China.

Omidvari et al. (2014) utilized the fuzzy triangular set to aggregate the expert opinions for a specified event on distillation tower in a refinery, discussed that there are many available scales for transferring quantified opinions to fuzzy numbers. Also, they showed that one of the useful ways to defuzzified is the center of gravity method. The probability of the event based on Boolean algebra is computed for further actions.

Investigation of marine accidents/incidents in Turkey from 1993 to 2011 were done by Kum and Sahin (2015). They used fault tree analysis to find out root causes of the accidents/incidents in order to improve the safety performance of marine industry and to prevent the future incidents that may happen. Therefore, they recognized collision and grounding were more common accident/incident in mentioned field. Fuzzy fault tree analysis was applied for further recommendations to reduce the failure probability collision and grounding for the Arctic Region (Kum & Sahin, 2015).

Sarkar et al. (2015) carried out a risk assessment on gas turbine power plant systems with employing conventional fault tree analysis. Author discussed that the mentioned system has high complexity in order to achieve a proper assessment. Therefore, they utilized Fish bone method to find out all causes and consider them as basic events in terms of basic events and human errors. The outputs of their study can be useful for designers and operators of gas turbine power plant (Sarkar et al., 2015).

Komal, (2015) studied a research based on safety risk modeling in order to reduce the frequently of medical error in healthcare system as an important aspects for everyone. The author presented the number of tools with their features to assess the risk in specified fields. Fault tree analysis is selected for this purpose. Because of human error, conventional fault tree analysis cannot be more reliable; therefore, an extension of fault tree analysis is introduced to cope with the uncertainties. An integration of trapezoidal fuzzy numbers and Alfa cut set are used in the purposed approach. Furthermore, the results of this approach are compared with the other existing technique in healthcare system.

Lavasani et al. (2015a) purposed a framework in order to assess the risk in natural-gas wells. Fuzzy fault tree analysis is utilized to compute the probability of specified disastrous event in their study.

Three engineers expressed their opinions in quantified form for the probability of each event. Then, the triangular fuzzy set is used for transferring the qualitative terms to fuzzy numbers. Additionally, the purposed approach is increased the safety performance of maritime industry and environmental aspects.

According to Lavasani et al. (2015b), an extension of fuzzy fault tree analysis is applied on a petrochemical complex. They used fuzzy set theory in order to overcome the shortages of data and the ambiguities that may happen during the assessment. Three experts expressed their opinions based on their background and their individual knowledge and with employing triangular fuzzy set in fuzzy environment; they aggregate the expert opinions by similarity method. The sensitivity analysis is done to show that the efficiency of their purposed approach.

Kabir et al. (2016) presented an extension of temporal fault tree analysis. In their study they used fuzzy set theory for aggregating the expert opinions by overlapping two pair opinions. Six experts participated in this study and express their opinion in quantified way on a fault tolerant fuel distribution system of a ship and the probability of mentioned failure are found out subsequently. Additionally the result of this paper is compared to the other available assessment techniques.

Abdo and Flaus (2016) introduced widely applications of fault tree analysis for complex systems. Moreover, they compared both static and dynamic fault tree and represented the usage of dynamic one in different areas. Additionally, they employed triangular fuzzy set for logic gates which are used in fault tree analysis and engaged Monte Carlo simulation in dynamic model in order to predict the availability of system and also also to propagate uncertainty in risk analysis. As direction for further study, they suggested that the comparison between ongoing approach and using fuzzy time of failure can help engineers which approach be more trustable.

Zhang et al. (2016) introduced a new approach in order to cope with the limitations of subjective opinions from experts that participated during the study. Therefore, they prepared the framework and applied it on an oil and gas production plant to improve the safety importance procedure. Conventional fault tree analysis is chosen as a risk assessment method and beside this the fuzzy comprehensive evaluation is engaged to compute the overall safety level of production plant.

Yazdi et al. (2017) purposed a framework in order to calculate the probability of specified event in granule storage tank in a petrochemical industry. Fuzzy set theory is used for aggregation of experts when the lack of data or incompleteness of information was available. They showed that fuzzy set theory has high reliability in mentioned circumstances in order to cope with ambiguities which exist during the risk assessment. Additionally, common cause failure as a rare situation of fault tree analysis was considered in their study to achieve more realistic result. Also, the corrective actions were recommended for each event that has high probability to be occurred in failure of granule storage tank.

Kabir, (2017) reviewed the applications of fault tree analysis over the past two decades and provided an overview of extensions of fault tree analysis in different kinds of industries. Additionally, various numbers of models which are based on dependability analysis are reviewed. Subsequently, as a direction for future study, the outlook like as data mining for dependability analysis is outlined.

According to Zarei et al. (2017) a dynamic fault tree analysis is done on a natural gas station. Failure mode and effect analysis is used for hazard identification and the worst case is found out by using Bow-tie diagram and also with employing Bayesian networks the dependency of each basic event in fault tree analysis is considered. Accordingly, human errors are recognized as a most critical factor for specified system failure and regulator was the worst case accident.

2.3 Analytic Hierarchy Process (AHP)

Analytic hierarchy process (AHP) is proposed by Thomas L. Saaty in early 1970s in order to handle and analyze complex decision. It has populated as a common application of group decision making which is widely used in different kinds of decision situation fields including government, business, healthcare education and industry. Also, AHP provides a structure of decision problem to illustrate quantify of elements for representing which elements have related to each other to get overall goals.

Figure 3 ilustrates an example where the goal is selecting a leader among three candidates with respect to their four criteria. After constructing hierarchy, series of *pairwise comparisons* based on numeral scales are done for each node. Therefore, the comparisons according to the goal for importance are derived mathematically and subsequently ranking are obtained for each node.

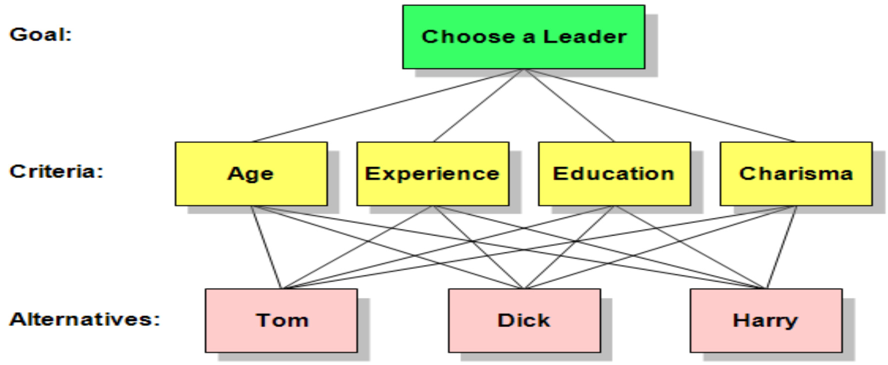


Figure 2.2. AHP for selecting a leader (Saaty & Peniwati, 2008)

Buckley (1985) introduced the first extension AHP in fuzzy environment. He used the set of triangular fuzzy numbers to pairwise comparison. Accordingly, the geometric mean is utilized to determine the weight of fuzzy matrix decision and there is combined for final weight of fuzzy alternatives. Final rank is ordered from highest to lowest one based on fuzzy weights of alternatives

Chang (1996) introduced an extension of AHP model with respect to fuzzy set numbers. He used fuzzy triangular set to compare pairwise scale which based in intersection theory. An example is examined for this purposed approach and result showed that efficiency of the approach is high.

Maggie and VMR (2000) applied the analytic hierarchy process (AHP) in order to select a vendor of a telecommunications system due to mentioned system is a long-term investment for company and selecting the best one will effect through whole of company decisions. Therefore, AHP can be helpful to consider both different conflicting opinions and numerous decision- makers. Real case is studied in order to examine the selection of a vendor for a telecommunications system. Accordingly, AHP model helped reduce the time for selecting the vendor with high reliability.

Wei et al. (2005) introduced a in order to select the best option of Enterprise Resource Planning (ERP) system. Besides, the authors reviewed the applications of AHP through the past two decades. Additionally, the real-world example illustrate that AHP can help decision makers to take the best decision for an ERP system.

Caputo et al. (2013) discussed that the safety of machineries is vital to implement the safety of personnel on the workplace. Therefore, they assessed all available devices with respect to AHP approach which presented the specific rating criteria to select the best safety devices in industrial machinery. This approach help decision makers to rank the risks fastly. This purposed approach not only avoids any possible subjective opinions, but it provides a systematic decision process which can be utilized by spreadsheet software.

Aminbakhsh et al. (2013) introduced a new model to help in risk assessment procedure and to prevent the possible incidents in budgeting process. New model reduces the uncertainties of decision makers with integration of AHP and cost of safety theory. A real case study in construction project is selected to show that how the purposed model can guide the decision makers during risk assessment procedure. However, much pairwise comparison in new model should be considered in large and complex projects.

Shi et al. (2014) assessed the probability of fire and explosion accident as a common incident in steel storage tanks. Fuzzy fault tree is applied for mentioned accident and in order to expert elicitation, where an improvement to AHP has been done. Also, the researchers compared statistical data and computed data which were found out from fuzzy environment. The output of the study provided important information to manage the mitigation procedure.

Hadidi and Khater (2015) studied loss prevention in turnaround maintenance projects as an important issue for selecting contractors. Due to this fact, AHP model was applied based on safety criteria for contractors' selection. Safety criteria will increase the safety performance of project during the implementation of period. A case study was done to show that the process plant for contractors' selection in Saudi Arabia. Additionally, they recommended that planning and scheduling should be considered based on safety criteria in order to prepare all required resources.

Raviv et al. (2017) applied the AHP technique to assess the safety of cranes in the construction industry. Besides, experts' opinions were considered to find out the cost against the reputation of company. In addition, potential risk was measured using by database. The quantitative evaluations illustrated that such types of incident reports has high necessity to increase the safety performance of the company.

2.4 Fuzzy logic

The theory of Fuzzy set is formulized in 1965, and also has been widely employed in different fields. This application in system and safety and reliability analysis could prove to be useful since such an analysis often requires the use of objective judgment and uncertain data.

The use of linguistic variables provides flexible modeling of imprecise data and information. The significance of Fuzzy variables is to assist gradual transition between conditions.

Classical set contains expressions which satisfy exact characteristics of membership. In other area, Fuzzy set contains expressions that satisfy ambiguous characteristics of membership. It means that the characteristics of Fuzzy set expressions could be partial. A comparison between a classical set (Boolean) and a fuzzy set could be emphasized in Figure 2.3. For classical sets, in a universe U element D could be or not as a member of some crisp set S. This binary characteristic of membership could be shown in mathematic model as follows:

$$U_S = \begin{cases} 1 \;\;, & \text{when } \; D \in S \;\; (\text{D is a member of S}) \\ 0, & \text{when } \; D \notin S \; (\text{D is not a member of S}) \end{cases}$$

Figure 2.3. Diagrams for a classical set (Boolean) and a fuzzy set (Hong, Pasman, Sachdeva, Markowski, & Mannan, 2016).

The characteristic of binary membership is extended by (Zadeh, 1965) in order to assist the different rate of membership on the real continuous distance zero to one [0,1]. In other words the beginning of distance zero means that there is no membership whereas the endpoint one illustrates that the completed membership are existed. The set of universe U which could assist the rates of membership were named as a Fuzzy sets. Thus, by using mathematical tools as $\mu_{\tilde{S}}$ (D) $\in [0,1]$, a Fuzzy set could be presented. Where $\mu_{\tilde{S}}$ (D) is rate of membership of element D in Fuzzy set $\tilde{S}$ or clearly membership of $\tilde{S}$. The value of $\mu_{\tilde{S}}$ (D) is on the unique distance [0,1] that computes the rate to which element D is a member of Fuzzy set $\tilde{S}$. As a same way, it could be illustrated $\mu_{\tilde{S}}$ (D) = the rate to which D $\in$ S. The biggest value of $\mu_{\tilde{S}}$ (D) is the more powerful rate of member for D in $\tilde{S}$.

Trapezoidal fuzzy numbers is a common set of all fuzzy set numbers like as triangular. Following definitions is provided for related fuzzy operations.

Let $\widetilde{D}$ = (d1, d2, d3, d4) and $\tilde{F}$ = (f1, f2, f3, f4) be two trapezoidal fuzzy numbers. The calculate operation on the mentioned fuzzy numbers could be defined as follows:

Fuzzy Change of sign : - (d1, d2, d3, d4) = (-d1, -d2, -d3, -d4) ,

Fuzzy Addition $\oplus$: (d1, d2, d3, d4) $\oplus$ (f1, f2, f3, f4) = (d1 + f1, d2 + f2, d3 + f3, d4 + f4) ,

Fuzzy Subtraction – : (d1, d2, d3, d4) $-$ (f1, f2, f3, f4) = (d1 - f1, d2 - f2, d3 - f3, d4 - f4) ,

Fuzzy Multiplication $\otimes$: (d1, d2, d3, d4) $\otimes$ (f1, f2, f3, f4) = (d1 · f1, d2 · f2, d3 · f3, d4 · f4)

,

Fuzzy Division÷ : (d1, d2, d3, d4) ÷ (f1, f2, f3, f4) = $(\frac{d1}{f4}, \frac{d2}{f3}, \frac{d3}{f2}, \frac{d4}{f1})$,

Fuzzy Inverse: (d1, d2, d3, d4)-1 = $(\frac{1}{d_4}, \frac{1}{d_3}, \frac{1}{d_2}, \frac{1}{d_1})$.

Fuzzy logic is introduced by Zadeh, (1965) in order to cope on uncertainties and ambiguities of circumstances. Many developments of fuzzy are purposed in recent decades by several authors as follows.

Atanassov (1986) introduced a new extension of fuzzy sets theory as it is called “intuitionistic fuzzy sets”. This new sets include membership and non-membership function whereas the conventional fuzzy which proposed by Zadeh, (1965) based on membership function. Therefore, the new sets can more deal with uncertainties may happen from biased results. However, the main features that should consider in Atanassov’s model, are complexity and time-consuming.

Chen and Hwang (1992) developed fuzzy reasoning using algebraic properties of fuzzy sets in order to provide a solution to deal with complex problem including bounded-sum, unbounded-sum, union, intersection and algebraic product.

Atanassov (2012) introduced an extension of previous intuitionistic fuzzy sets. In this case, both membership and non-membership function are included and besides the hesitation margin groups is also added to cope with complexity of conventional intuitionistic fuzzy sets. However, time is a significant limitation in Atanassov's model.

2.5 Integration of AHP and Fuzzy logic

Zheng et al. (2012) used a Fuzzy AHP method to evaluate the safety performance of workplace in hot and humid circumstances. Trapezoidal fuzzy set numbers are considered to cope with imprecise of information during the decision making process. A novelty of the paper is attending to compute the safety grade and warning grade in order to show that how results can be practicable and efficient in this model.

Kepaptsoglou et al. (2013) introduced an application of Fuzzy AHP for assessing the quality, attractiveness and performance of metro stations in Athens, Greece metro system. In order to cope with uncertainties from group decision making in AHP, authors transfer their qualitative opinion in to fuzzy environment and purposed fuzzy AHP. Accordingly, results were compared to conventional AHP and represented the differences between both methods with using statistical analysis.

Deng et al. (2014) studied a new approach in order to cope with subjective uncertainties of AHP. They used an extension of fuzzy set theorem which is called D numbers and is purposed as a D-AHP method. D numbers represent the pairwise of decision matrix with respect to experts' opinions. They applied this approach for selecting supplier as an important parts of supply chain management. Example proved the effectiveness of the proposed method.

Fattahi et al. (2015) discussed a proper selection technique for excavation assessment zone seems to be vital in safety and economic fields.

An extension of fuzzy theory is integrated with AHP in order to select the best zone technique for the assessment. Real example Aba Saleh Almahdi tunnel is considered for this issue. Results represented that geophysics method with respect criteria is the best technique for excavation assessment zone.

Beskese et al. (2015) stated that there is no proof to show that which multi-attribute decision making has high superiority to other ones. Therefore, they purposed a new approach by utilizing fuzzy logic to overcome any subjective situations. An extension of fuzzy AHP is introduced to aggregate the experts' opinions and for ranking the criteria to select landfill site in Istanbul, fuzzy TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is considered. Additionally, the purposed model is based on environmental and industrial engineering domain.

Hsu et al. (2016) introduced a risk matrix based fuzzy AHP in order to rank the identified hazardous goods in airfreights as an important issue in operational safety. The purposed approach is studied on hazardous goods in Taiwan. The results showed that the new approach improved the conventional risk matrix. Using and interview instead of sending email is better to be considered for future study in order to get more reliable result.

Krejčí et al. (2016) highlighted the importance of using constrained fuzzy arithmetic instead of standard fuzzy arithmetic in AHP model. Authors used geometric mean method in order to derive and create fuzzy pairwise comparison matrix. The purposed model can eliminate the uncertainty of fuzzy weight. A numerical example is studied to show the validity of their purposed approach. As a direction for future studies, authors suggested that the fuzzy AHP approach can solve nonlinear constrained mathematical programming problems.

2.6 Computation of event probability using AHP and Fuzzy logic

Yevkin (2016) represented an efficient approximation to contribute fault tree analysis by employing Markov chain. He considered that there are some situations that component may fail and accordingly be repaired for future process. Therefore, the base concepts of fault tree analysis are not trustable. An extension of Markov chain in that case is introduced to solve these kinds of situations. A few limitations are defined to simplified fault tree structure to use Markov chain including limit number of events. Some applicable examples are solved to show that the efficiency of purposed model.

Nadjafi et al. (2016) discussed that the limitations of traditional fault tree analysis like as time-consuming or unknown information for components are difficult to compute the probability of the events in multi-state systems. Therefore, they used Monte Carlo simulation for this purposed in the fuzzy environment in order cope with any ambiguities that may happen during the study. Authors applied the purposed approach on Launch Emergency Detection System as multi-state system. Besides, this purposed approach is further developed for the most generic case where the components have multi-states.

Guan et al. (2016) applied a risk assessment with employing traditional fault tree analysis on ship diesel room for fire and explosion accident. They tried to find out the critical component which has a high probability to occur an accident. Therefore, minimal cut set as a measurement tool is used through the analysis. Accordingly, safety performance of specified field is improved with respect to measurement results in Chinese inland dual fuel ships.

Ramzali et al. (2015) engaged fuzzy triangular and fuzzy trapezoidal set to cope on uncertainties during the safety barrier analysis of offshore drilling system. Reliability Block Diagram and Fault Tree Analysis are employed to improve the safety barrier performance. Using both fuzzy sets shows that the purposed approach was trustable to reduce the uncertainties of expert opinions for computing each event. Additionally, they used the same way for event tree analysis for consequence assessment.

Chapter 3

METHODOLOGY

3.1 Collecting Expert Opinion

3.1.1 Information required

Hazard and operability study (HAZOP) is a common method in oil and gas plants to show that the hazardous conditions and components. This method is usually completed by plant's specialists including different expert fields or company asked high qualify contractor to do this assessment for them. In this study, a hazardous component of a process industry which is found out as result of HAZOP is selected.

In order to understand the conditions and function of component for further actions for the processes of the company, fault tree drawing and questionnaire are required.

A fault tree diagram is to be drawn to show the processes of the company. This figure will show the basic events and their logic relations to how reach top event. The main essential information about process of industry is the flow diagram which can be schematic or prepared as a process flow diagram (PFD).

3.1.2 Data collection

One of the hazardous oil and gas industries which are confronting many accidents in recent years is selected in this study. Iranian Offshore Oil Company (IOOC) which is a complex chemical plant is considered as a case study within the context of this research. Therefore, the information process of company and employing related specialists' is required. Electronic communication has been employed to send questionnaires and to collect information about the processes.

3.1.3 Selection of experts

In order to find out the probability of each basic event, expert's judgment is employed. Expert's opinions are biased by their backgrounds and knowledge. Here the significant point is selecting the both heterogeneous and homogenous groups of experts (Ford & Sterman, 1998). Heterogeneous group may be included by workers and specialists whereas homogenous is formed as an example by only workers. Therefore, the selection of expert group has high necessity and also is difficult process. In decision making circumstances, using a heterogeneous group of experts seems be more realistic in comparison with homogenous one (Helvacioglu & Ozen, 2014). Thus, in this study a heterogeneous group of experts who has related knowledge and background for oil and gas process is employed. In order to organize a heterogeneous group, four experts including worker, technician, engineer, and academic professor are employed to express their opinions for sended questionnaire.

3.1.4 Establishing FTA

Likelihood as a main parts of risk assessment procedure can be computed based on FTA. A top event with respect to process information and his background is selected for establishing FTA. Subsequently, in order to find out the basic events the root cause analysis is recognized and their logic relation using AND/OR gates is done.

3.1.5 Expert opinion analysis

Questionnaire includes brief information of process industry so that the fault tree can be drawn accordingly. Then, experts are asked to express their opinions in available quantified terms for each basic event. Also, because of their background in oil and gas industry and safety systems, it is asked to put any comments to improve the fault tree.

3.2 Application of AHP

3.2.1 Selection of factors

In order to recognize the best weight for each expert, several criteria should be considered. That is because of avoiding any cognitive biases may appear by a single expert opinion. Therefore four experts are invited in this study to express their opinion for each basic event in quantify terms. From literature, three factors including job tenure, age, and level of education which common criteria are considered to compute their respective capability. However, personal experience as the fourth factor is added to these criteria which is has not been included yet. The main reason of selecting personal experience as the fourth factor is that an employing expert may have high job tenure or level of education but in other side have low personal experience in specified fields.

The pairwise comparison to weight factors is done in order to further computations. Figure 3.1 shows the criteria in order to expert evaluation.

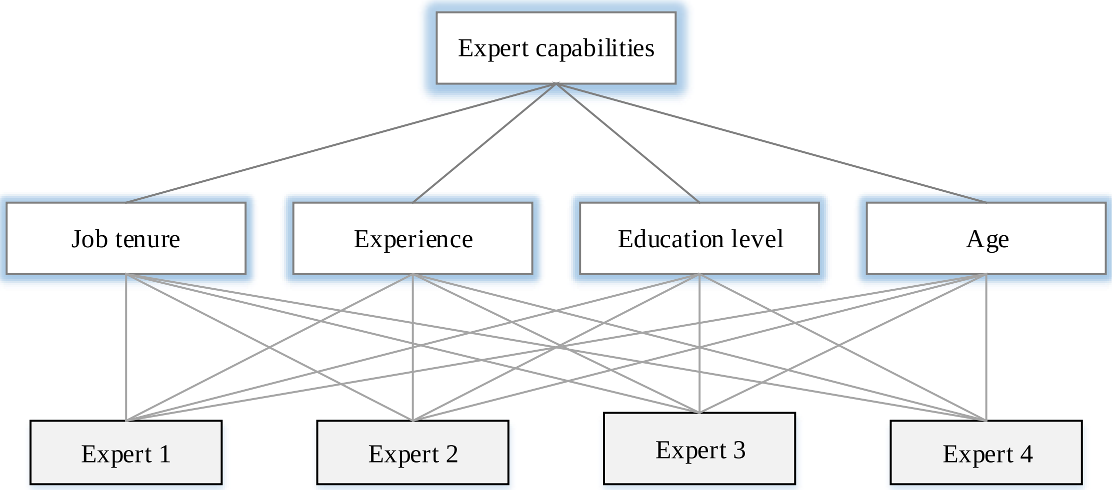


Figure 3.1. AHP system for experts' evaluation

3.2.2 Assignment of the weight

Pairwise comparison for each criterion is based on fuzzy triangular set. A triangular fuzzy set is defined as $\mu_{\tilde{S}} = (l, m, u)$ where $l, m, and\ u$ is denoted as lower, middle and upper boundary and satisfy $l < m < u$. The membership function of fuzzy triangular set is as follows.

$$\mu_{\tilde{S}}(x) = \begin{cases} 0, & x < 1 \\ \frac{x-l}{m-l}, & l \leq x \leq m \\ \frac{u-x}{u-m}, & m \leq x \leq u \\ 0, & x > u \end{cases} \qquad \text{Eq 3.1}$$

In this part, the relative importance of evaluation criteria in the same level is done by author in a matrix comparison. For this purpose, the pairwise terms which are provided in fuzzy triangular set is used. Table 3.1 shows the modified quantified terms and related fuzzy triangular set to pairwise comparison after Kabir, G and Hasin, (2012). The quantified terms with respect to fuzzy numbers represent the importance of criteria i and j with each other. $\tilde{9}^{-1}$, $\tilde{1}$ and $\tilde{9}$ are the least, middle and most impotence in pairwise comparison. This conversion is based on human think which is provided more description in literature.

Table 3.1. Fuzzy numbers and related fuzzy triangular set, modified after Kabir, G and Hasin, (2012)

Fuzzy number	Fuzzy triangular set (l, m, u)
$\tilde{5}$	(3,5,5)
$\tilde{3}$	(1,3,5)
$\tilde{1}$	(1,1,1)
$\tilde{3}^{-1}$	(1/5,1/3,1)
$\tilde{5}^{-1}$	(1/5,1/5,1/3)

In order to combine the pairwise comparison matrices, the geometric mean formulas is applied for aggregate a group decisions:

Stage 1: Pair wise comparison matrices are made in the dimensions of the hierarchy procedure throughout all defined criteria. Experts' opinions in quantifiable terms are allocated by considering the importance of pairwise comparison. An example is the high superiority in each of the two criteria.

$$\tilde{M} = \begin{bmatrix} 1 & \tilde{b}_{12} & \cdots & \tilde{b}_{1n} \\ \tilde{b}_{21} & 1 & \cdots & \tilde{b}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{b}_{n1} & \tilde{b}_{n2} & \cdots & 1 \end{bmatrix} = \begin{bmatrix} 1 & 1/\tilde{b}_{12} & \cdots & 1/\tilde{b}_{1n} \\ 1/\tilde{b}_{21} & 1 & \cdots & 1/\tilde{b}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{b}_{n1} & 1/\tilde{b}_{n2} & \cdots & 1 \end{bmatrix}$$

when criterion i is of relative importance to criterion j, $\tilde{b}_{ij} = \tilde{1}, \tilde{3}, \tilde{5}$. In contrast when criterion j is of relative importance to criterion i, $\tilde{b}_{ij} = \tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}$. In a situation i=j, $\tilde{b}_{ij} = 1$.

Stage 2: Using geometric mean method, the fuzzy weights of dimensions are calculated by Eq. (3.2) as follows.

$$\tilde{r}_i = \left(\tilde{b}_{i1} \otimes \tilde{b}_{i2} \otimes \cdots \otimes \tilde{b}_{in}\right)^{1/n} \qquad \text{Eq. 3.2}$$

Stage 3: For each criterion, fuzzy weights are defined as follows.

$$\tilde{w}_i = \tilde{r}_i \otimes \left(\tilde{r}_1 \oplus \tilde{r}_2 \oplus \cdots \oplus \tilde{r}_n\right)^{-1} \qquad \text{Eq. 3.3}$$

$\tilde{w}_i$ is defined as a fuzzy weight of criterion i and $\tilde{w}_i = (lw_i, mw_i, uw_i)$ where lw_i, mw_i, uw_i justify lower, middle and upper value of the fuzzy weights of criterion i respectively.

Stage 4: Center of area (CoA) is used to compute the best non-fuzzy performance (BNP) value of the fuzzy weights of each dimension.

$$w_i = \left[(uw_i - lw_i) + (mw_i - lw_i)\right] / 3 + lw_i \qquad \text{Eq. 3.4}$$

So far, the weight of each expert is computed in more reliable way based on their knowledge and experience. Therefore, the computed weights are vital in order to represent the relative superiority of the employed experts.

3.3 Employment of fuzzy set theory

Lin and Wang (1997) discussed that qualitative opinion can be used to compute the possibility of each basic event in fault tree analysis. They introduced both triangular and trapezoidal fuzzy set according to Eq 3.5 and Eq 3.6 respectively. The related values are provided in Table 3.2 which is used in this study.

Consider $\tilde{B}_1 = (b_{11}, b_{12}, b_{13})$ and $\tilde{B}_2 = (b_{11}, b_{12}, b_{13}, b_{14})$ were the triangular and trapezoidal fuzzy number respectively and purposed by expert one. The membership function is defined as follows:

In triangular case:

$$f_{\tilde{B}_1}(x) = \begin{cases} \frac{(x-b_{11})}{(b_{12}-b_{11})}, & b_{11} \le x \le b_{12} \\ \frac{(a_{13}-x)}{(a_{13}-a_{12})}, & b_{12} \le x \le b_{13} \\ 0, & otherwise \end{cases} \quad \text{Eq 3.5}$$

In trapezoidal case:

$$f_{\tilde{B}_1}(x) = \begin{cases} \frac{(x-a_{11})}{(a_{12}-a_{11})}, & a_{11} \le x \le a_{12} \\ 1, & a_{12} \le x \le a_{13} \\ \frac{(a_{14}-x)}{(a_{14}-a_{13})}, & a_{13} \le x \le a_{14} \\ 0, & otherwise \end{cases} \quad \text{Eq 3.6}$$

Table 3.2. Level value qualitative opinion

Judgment for probability	Value
Happening	1
Certain high	0.9
Very high	0.8
High	0.7
Moderately high	0.6
Medium	0.5
Moderately low	0.4
Low	0.3
Very low	0.2
Certain low	0.1
Not happening	0

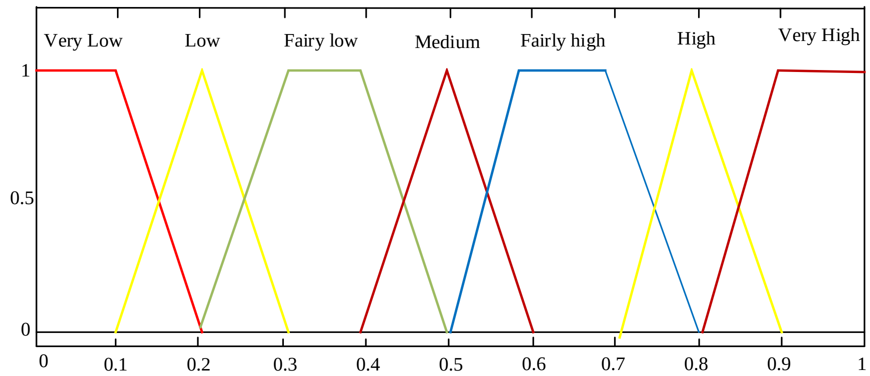


Figure 3.2. Corresponding fuzzy set (Shi, Shuai, & Xu, 2014)

Table 3.3. Fuzzy corresponding number (Shi et al., 2014)

Qualitative terms	**Fuzzy sets**
Very Low (VL)	(0,0.1,01,0.2)
Low (L)	(0.1,0.2,0.2,0.3)
Fairly Low (FL)	(0.2,0.3,0.4,0.5)
Medium (M)	(0.4,0.5,0.5,0.6)
Fairly High (FH)	(0.5,0.6,0.7,0.8)
High (H)	(0.7,0.8,0.8,0.9)
Very High (VH)	(0.8,0.9,0.9,1)

3.3.1 Transferring (Qualitative) expert opinion in to fuzzy set numbers

Since in section 3.2.2 the weight of each expert is computed; therefore, in order to aggregated the experts opinions, Eq 3.11 is utilized (Hsi-Mei Hsu & Chen-Tung Chen, 1996).

$\tilde{B}_{aggregated} = \sum_{u=1}^{M} W_m \otimes \tilde{B}_m$ Eq 3.7

Where m is the number of expert and $\tilde{B}_{aggregated}$ represented the aggregation of fuzzy numbers where m experts express their opinions respect to fuzzy numbers. In addition, $W_m$is defined the weighting of experts which is computed in section 3.2.2.

With respect to Eqs 3.11 and 3.12, computation of $W_m \otimes \tilde{B}_u$ is provided as below.

Triangular case:

$$W_m \otimes \tilde{B}_u = (W_m \times b_{m_1}, W_m \times b_{m_2}, W_m \times b_{m_3}) \quad \text{Eq 3.8}$$

Trapezoidal case:

$$W_m \otimes \tilde{B}_u = (W_m \times b_{m_1}, W_m \times b_{m_2}, W_m \times b_{m_3}, W_m \times b_{m_4}) \quad \text{Eq 3.9}$$

To aggregate the two experts' opinion:

Triangular case:

$$\tilde{B}_1 \oplus \tilde{B}_2 = (b_{11} + b_{21}, b_{12} + b_{22}, b_{13} + b_{23}) \quad \text{Eq 3.10}$$

Trapezoidal case:

$$\tilde{B}_1 \oplus \tilde{B}_2 = (b_{11} + b_{21}, b_{12} + b_{22}, b_{13} + b_{23}, b_{14} + b_{24}) \quad \text{Eq 3.11}$$

If the number of experts is more than two, mentioned procedure can be used.

However, the experts may express their opinion as a combination of both triangular and trapezoidal set. So, the aggregation procedure is changed according to follows:

Consider Eqs 3.11 and 3.12 as triangular and trapezoidal fuzzy set respectively. In order to aggregate these sets, α-cut method is used (Lin & Wang, 1997).

$\tilde{B}_{w_\alpha} = \sum_{m=1}^{n} W_m \otimes \tilde{B}_{m_\alpha}$ Eq 3.12

Where $\tilde{B}_{w_\alpha}$ represents α-cut for aggregated fuzzy sets $\tilde{B}_w$. In addition, W_m expressed the expert weighting and $\tilde{B}_{m_\alpha}$indicated α-cut for membership function of $\tilde{B}_m$. n denoted the number of fuzzy numbers,

Therefore, α-cut for membership function of $\tilde{B}_1$and $\tilde{B}_2$ are defined:

$$\begin{cases} \tilde{B}_{1_\alpha} = [x_1, x_2] \\ \tilde{B}_{2_\alpha} = [y_1, y_2] \end{cases}$$

The set $= \frac{(x - b_{11})}{(b_{12} - b_{11})}$, and x can be substitute by $x_1 \; and \; x_2$. Therefore, $x_1 = (b_{12} - b_{11})\alpha + b_{11}$. Besides, according to mentioned rules, the α-cut for $\tilde{B}_1$ and $\tilde{B}_1$ is computed as:

$$\begin{cases} x_1 = (b_{12} - b_{11})\alpha + b_{11} \\ x_2 = b_{13} - (b_{13} - b_{12})\alpha \\ y_1 = (b_{22} - b_{21})\alpha + b_{21} \\ y_2 = b_{24} - (b_{24} - b_{23})\alpha \end{cases}$$

$\tilde{B}_{w_\alpha}$is obtained Eq 3.14 thought 3.18;

$\tilde{B}_{w_\alpha} = W_1 \otimes \tilde{B}_{1_\alpha} \oplus W_2 \otimes \tilde{B}_{2_\alpha} = W_1 \otimes [x_1, x_2] \oplus W_2 \otimes [y_1, y_2] = W_1 \otimes [(b_{12} - b_{11})\alpha + b_{11}, b_{13} - (b_{13} - b_{12})\alpha] \oplus W_2 \otimes [(b_{22} - b_{21})\alpha + b_{21}, b_{24} - (b_{24} - b_{23})\alpha] = \big[(W_1(b_{12} - b_{11}) + W_2(b_{22} - b_{11})\big)\alpha + W_1 a_{11} + W_2 a_{21}, W_1 b_{13} +$

$W_2b_{24} - (W_1(b_{13} - b_{12}) + W_2(b_{24} - b_{23}))\alpha]$ Set $\tilde{B}_{w_\alpha} = [z_1, z_2]$, then α can be found out as:

$$\begin{cases} \alpha = \dfrac{z_1 - (W_1b_{11} + W_2b_{21})}{W_1(b_{12} - b_{11}) + W_2(b_{22} - b_{21})} \\ \alpha = \dfrac{W_1b_{13} + W_2b_{24} - z_2}{W_1(b_{13} - b_{12}) + W_2(b_{24} - b_{23})} \end{cases}$$

Thus, the membership function of aggregated fuzzy number can be computed as follows:

$$f_{\tilde{B}_W(z)} = \begin{cases} \dfrac{z_1 - (W_1b_{11} + W_2b_{21})}{W_1(b_{12} - b_{11}) + W_2(b_{22} - b_{21})}, & W_1b_{11} + W_2b_{21} \leq z \leq W_1b_{12} + W_2b_{22} \\ 1, & W_1b_{12} + W_2b_{22} \leq z \leq W_1b_{12} + W_2b_{23} \\ \dfrac{W_1b_{13} + W_2b_{24} - z_2}{W_1(b_{13} - b_{12}) + W_2(b_{24} - b_{23})}, & W_1b_{12} + W_2b_{23} \leq z \leq W_1b_{13} + W_2b_{24} \\ 0, & otherwise \end{cases}$$

Next, the aggregation fuzzy set number $\tilde{B}_W$ for both $B_1$and B_2 in trapezoidal case is computed as follows:

$$\tilde{B}_W = (\ W_1b_{11} + W_2b_{12}, W_1b_{12} + \ W_2b_{22}, W_1b_{12} + W_2b_{23}, W_1b_{13} + W_2b_{24})$$

3.4 Defuzzing fuzzy numbers into crisp value

Center of area (CoA) is utilized to transfer from fuzzy set theory to crisp value. Using Eq 3.13 the possibility of each basic event with respect to aggregation opinion is obtained.

$$X = \frac{\int g(x)xdx}{\int g(x)dx} \qquad \text{Eq. 3.13}$$

Where x is denoted as Defuzzified output $g(x)$ is called as aggregated membership function, and x is the variable of output.

Eq. 3.13 may be utilized in trapezoidal and triangular cases and both are obtained as follows:

In triangular case:

$$\tilde{B}_1 = (b_1, b_2, b_3);$$

$$X = \frac{\int_{b_1}^{b_2} \frac{x-b_2}{b_2-b_1} xdx + \int_{b_2}^{b_3} \frac{b_3-x}{b_3-b_2} xdx}{\int_{b_1}^{b_2} \frac{x-b_2}{b_2-b_1} dx + \int_{b_2}^{b_3} \frac{b_3-x}{b_3-b_2} dx} = \frac{1}{3}(b_1+b_2+b_3) \qquad \text{Eq.3.14}$$

In trapezoidal case:

$$\tilde{B}_2 = (b_1, b_2, b_3, b_4);$$

$$X = \frac{\int_{b_1}^{b_2} \frac{x-b_1}{b_2-b_1} xdx + \int_{b_2}^{b_3} xdx + \int_{b_3}^{b_4} \frac{b_4-x}{b_4-b_3} xdx}{\int_{b_1}^{b_2} \frac{x-b_1}{b_2-b_1} dx + \int_{b_2}^{b_3} dx + \int_{b_3}^{b_4} \frac{b_4-x}{b_4-b_3} dx}$$

$$= \frac{1}{3} \frac{(b_4+b_3)^2 - b_4 b_3 - (b_1+b_2)^2 + b_1 b_2}{(b_4+b_3-b_1-b_2)} \qquad \text{Eq.3.15}$$

Onisawa (1988) discussed that the output of CoA in this case is based on possibility and there is a difference between possibility and probability. Therefore, Eq 3.16 is introduced in order to convert the possibility into probability.

$$Probability = \begin{cases} \frac{1}{10^{K}} & , crip\ possiblity\ \neq 0 \\ 0 & , crip\ possiblity\ = 0 \end{cases} \quad , \quad K = \left[\left(\frac{1}{crip\ possiblity} - 1\right)\right]^{1/3} \times 2.301 \qquad \text{Eq 3.16}$$

Thus, the probability of each basic event with respect experts' opinion is computed. The computation of basic events using Boolean algebra is explained in next section.

3.5 Computation of basic events probability

As it mentioned before the using of mathematics in FTA is based on Boolean algebra and probability theory. In the following, the main rules which are used continuously in FTA are explained.

3.5.1 Rules of Boolean algebra

The Boolean algebra technique directly is used in FTA employing mathematical elegance in order to finalize the assessment. This technique provides some rules during the evaluation process by reduction of algebraic (Andrews, 1993)

a•b = b•a a+b = b+a	Commutative rule
a•(b•c) = (a•b)•c a•(b•c) = (a•b)•c a+(b+c) = (a+b)+c	Associative rule
a•(b+c) = a•b+a•c a•(b+c) = a•b+a•c a+b•c = (a+b)•(a+c)	Distributive rule
a•a = a a+a = a	Idempotent rule
a•(a+b) = a a+a•b = a	Absorption rule

3.5.2 Probability theory

***AND** gate probability expansion*: AND gate expansion is defined:

$$P = P_A P_B P_C P_D P_E, \ldots, P_N \qquad \text{Eq 3.23}$$

which N is the number of input gates.

***OR** gate probability expansion*: OR gate expansion is defined:

$$P = (\sum 1st\ terms) - (\sum 2nd\ terms) + (\sum 3rd\ terms) - (\sum 4th\ terms) + (\sum 5th\ terms), \qquad \text{Eq 3.24}$$

3.6 Finding the probability of Top Event (At FTA)

As regards all mentioned earlier, Boolean algebra with respect to AND/OR gates are used to compute the probability of TE.

Figure 3.3 illustrated the simplest fault tree diagram in order to compute probability of TE using Boolean algebra.

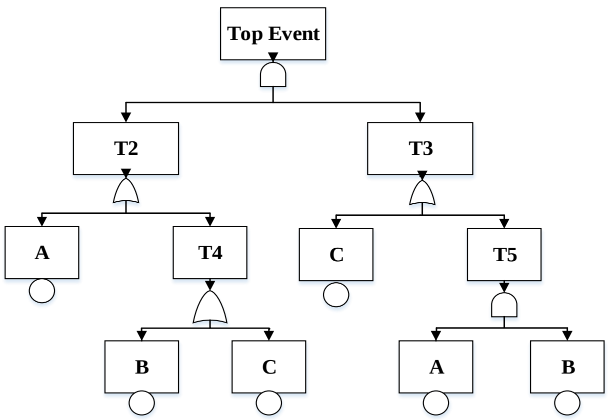


Figure 3.3. Example Fault Tree

Boolean algorithm is begun from up to down:

$$TE = T2 \cdot T3$$

Since:

$$T4 = B + C$$

$$T5 = A \cdot B$$

$$TE = (A + T4) \cdot (C + T5)$$

Finally substituting:

$$TE = (A + (B + C)) \cdot (C + (A \cdot B))$$

If the probability of A, B and C be available then the probability of TE can be computed.

3.7 Brief Introduction of the Iranian Offshore Oil Company (IOOC), Khark Island

IOOC is known as one of the biggest companies employed on exploring, producing, and exporting crude oil in Persian Gulf area over the last decades. The significant mission of IOOC is producing crude oil located in Persian Gulf where in other side four countries including Iraq, Saudi Arabia, Qatar, and United Arab Emirates are working in same oil reserves. Therefore, the competition should be more important for IOOC. But over last decades, before and after the Iranian revolution (1979), IOOC emphasized on this motto as a main rule of the company “Cooperation instead of Competition”. That is because, Persian Gulf area is a well-known area contains enormous reserves of hydrocarbon and considered as a huge part of world's energy.

Figure 3.4 shows the general information of Persian Gulf area and oils areas.

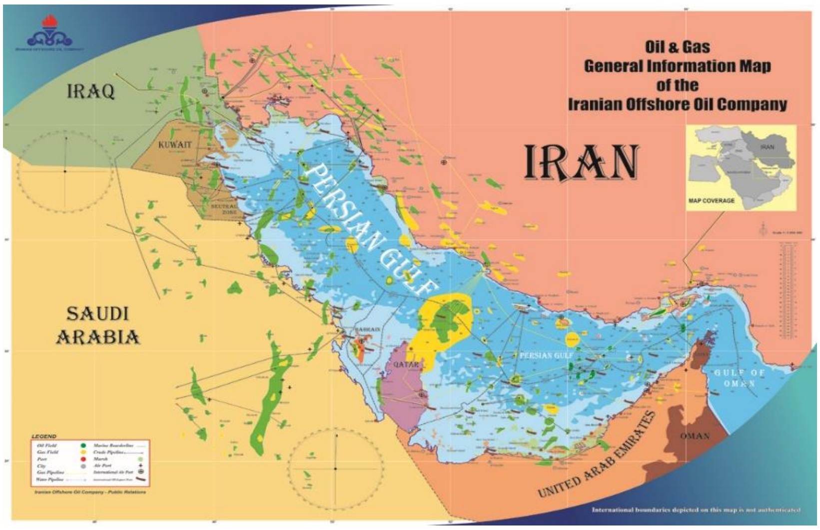


Figure 3.4. General information of Persian Gulf area and oils areas.

The operation of IOOC is divided into 5 islands and one peninsula in Persian Gulf area as follows.

Islands:

1. **Khark:** This area is known as important area of IOOC because of more than 90 percent of oil exporting is done through this island. It includes several complex plants, rigs, wells, and storage tanks.
2. **Siri:** This area has several common reserves with Qatar and included a complex plant in order to produce crude oil and transfer to land for inside purposes.

3. **Lavan:** This Island is the largest area of IOOC. Accordingly it contains several complex plants, wells, and a refinery.
4. **Kish:** This area is selected as an economic zone because of Kish is a well-known island for tourist destination for inside and outside.
5. **Qeshm:** This area is invested last decade because of some common reserves with United Arab Emirates explored. During last decades several complex plants have been built.

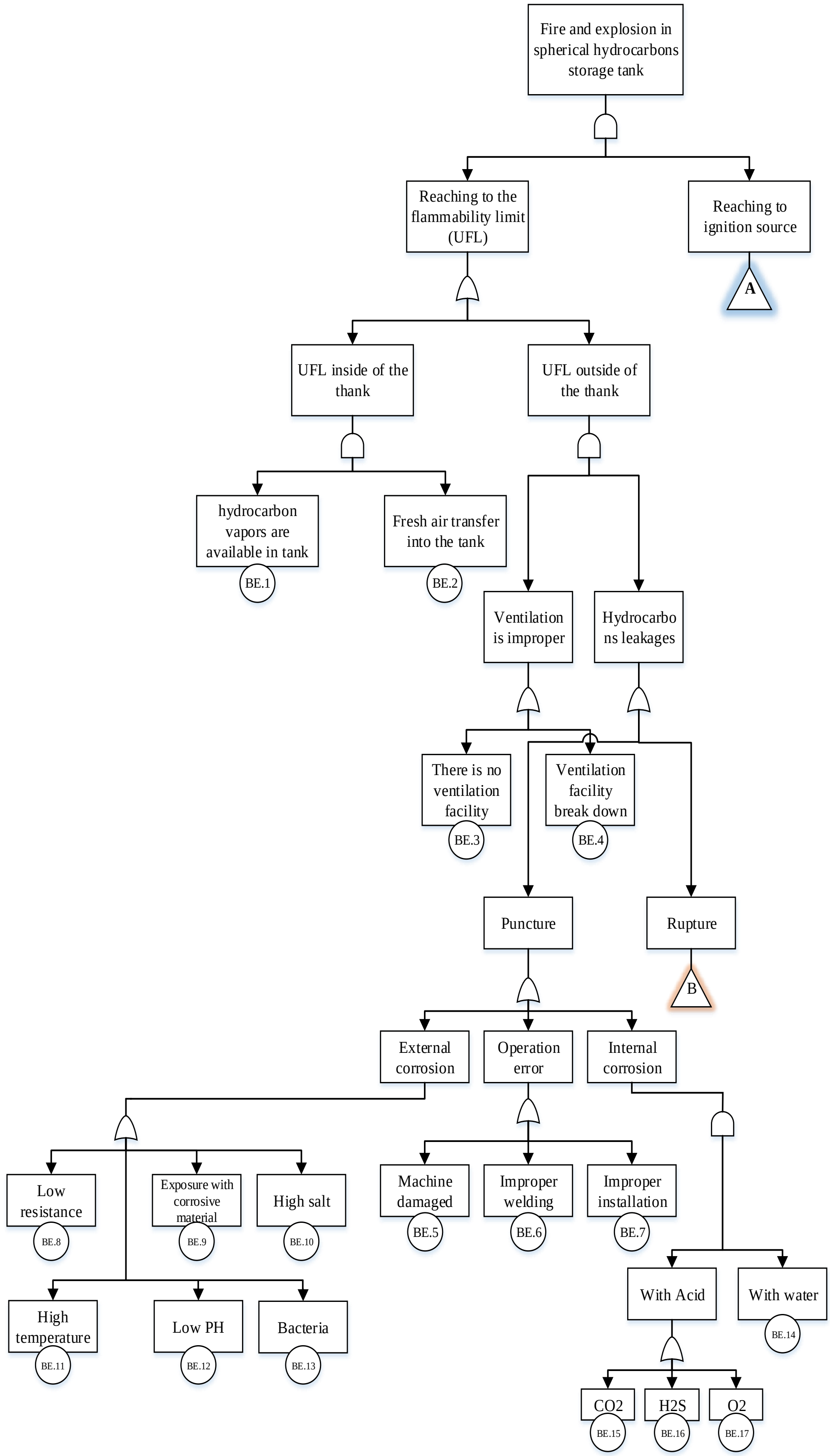
Peninsula:

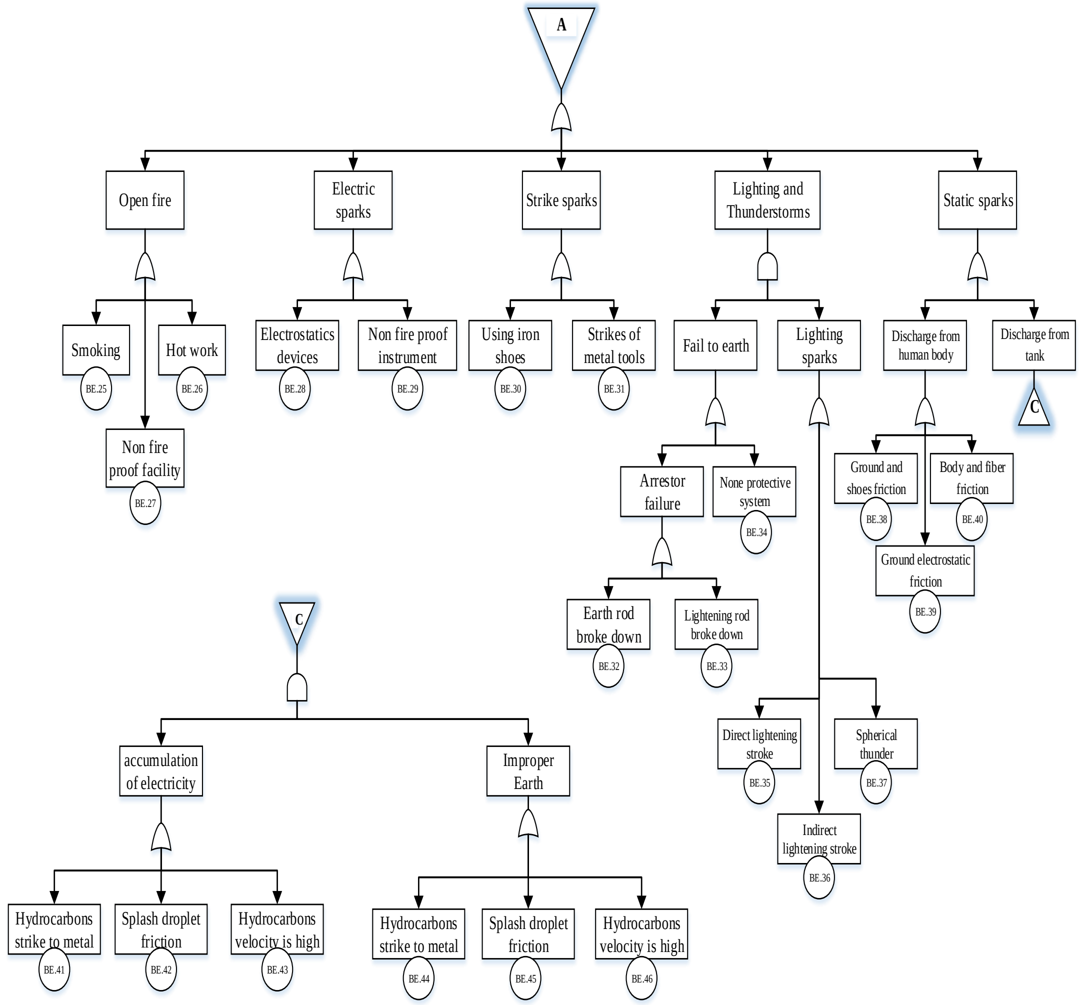
- **Bahregan:** The main mission of this area is based on logistic issues and also includes some rigs and a complex plant.

Figure 3.5. The illustration of six IOOC areas.

Figure 3.5 illustrates the six areas which IOOC is working on.

In this study, Khark Island because of its strategic location is selected for area of study and a spherical storage tank (Fire/explosion) is considered for our study. The fault tree diagram for fire and explosion in spherical storage tank is drawn as follows.


Fire and explosion in spherical hydrocarbons storage tank
Reaching to the flammability limit (UFL)
Reaching to ignition source
A
UFL inside of the thank
UFL outside of the thank
hydrocarbon vapors are available in tank
BE.1
Fresh air transfer into the tank
BE.2
Ventilation is improper
Hydrocarbons leakages
There is no ventilation facility
BE.3
Ventilation facility break down
BE.4
Puncture
Rupture
B
External corrosion
Operation error
Internal corrosion
Low resistance
BE.8
Exposure with corrosive material
BE.9
High salt
BE.10
Machine damaged
BE.5
Improper welding
BE.6
Improper installation
BE.7
High temperature
BE.11
Low PH
BE.12
Bacteria
BE.13
With Acid
With water
BE.14
CO2
BE.15
H2S
BE.16
O2
BE.17


A
Open fire
Electric sparks
Strike sparks
Lighting and Thunderstorms
Static sparks
Smoking
BE.25
Hot work
BE.26
Non fire proof facility
BE.27
Electrostatics devices
BE.28
Non fire proof instrument
BE.29
Using iron shoes
BE.30
Strikes of metal tools
BE.31
Fail to earth
Lighting sparks
Discharge from human body
Discharge from tank
C
Arrestor failure
None protective system
BE.34
Earth rod broke down
BE.32
Lightening rod broke down
BE.33
Ground and shoes friction
BE.38
Body and fiber friction
BE.40
Ground electrostatic friction
BE.39
Direct lightening stroke
BE.35
Spherical thunder
BE.37
Indirect lightening stroke
BE.36
C
accumulation of electricity
Improper Earth
Hydrocarbons strike to metal
BE.41
Splash droplet friction
BE.42
Hydrocarbons velocity is high
BE.43
Hydrocarbons strike to metal
BE.44
Splash droplet friction
BE.45
Hydrocarbons velocity is high
BE.46

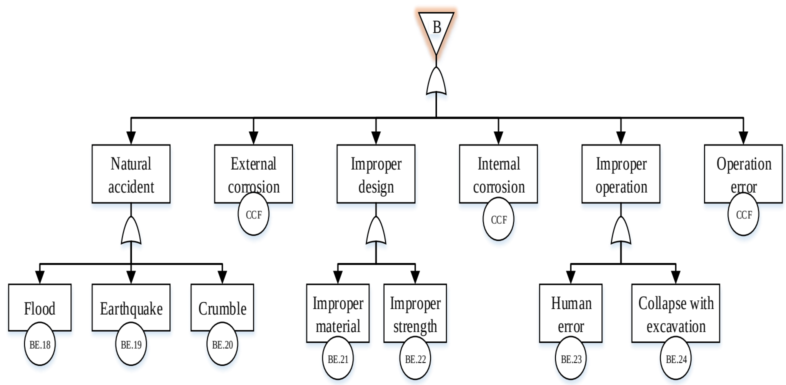

B
Natural accident
External corrosion
CCF
Improper design
Internal corrosion
CCF
Improper operation
Operation error
CCF
Flood
BE.18
Earthquake
BE.19
Crumble
BE.20
Improper material
BE.21
Improper strength
BE.22
Human error
BE.23
Collapse with excavation
BE.24

Table 3.4. Basic events

TAG	Basic events
BE.1	Hydrocarbon vapors are available in tank
BE.2	Fresh air transfer into the tank
BE.3	There is no ventilation facility
BE.4	Ventilation facility break down
BE.5	Machine damaged
BE.6	Improper welding
BE.7	Improper installation
BE.8	Low resistance
BE.9	Exposure with corrosive material
BE.10	High salt
BE.11	High temperature
BE.12	Low PH
BE.13	Bacteria
BE.14	With water
BE.15	CO_2
BE.16	H_2S
BE.17	O_2
BE.18	Flood
BE.19	Earthquake
BE.20	Crumble
BE.21	Improper material
BE.22	Improper strength
BE.23	Human error
BE.24	Collapse with excavation
BE.25	Smoking
BE.26	Hot work
BE.27	Non fire proof facility
BE.28	Electrostatics devices
BE.29	Non fire proof instrument
BE.30	Using iron shoes
BE.31	Strikes of metal tools

BE.32	Earth rod broke down
BE.33	Lightening rod broke down
BE.34	None protective system
BE.35	Direct lightening stroke
BE.36	Indirect lightening stroke
BE.37	Spherical thunder
BE.38	Ground and shoes friction
BE.39	Ground electrostatic friction
BE.40	Body and fiber friction
BE.41	Hydrocarbons strike to metal
BE.42	Splash droplet friction
BE.43	Hydrocarbons velocity is high
BE.44	Hydrocarbons strike to metal
BE.45	Splash droplet friction
BE.46	Hydrocarbons velocity is high

Chapter 4

DATA ANALYSIS AND RESULTS

As afore mentioned in Chapter 3, in order to find out the probability of each basic event, experts express their opinions in qualitative terms. Therefore, through expert judgment, specialists express their opinions about each basic events (BEs) based on each intellectual characteristic. Expert elicitation is the combination of specialists' opinions about a subject when there is a lack of or limited resources due to physical limitations. Experts' elicitation is, in fact, a fundamental scientific solidarity methodology. Besides, expert elicitation usually quantifies uncertainty by allowing specialists to parameterizing as an *educated guess*.

Quantification of subjective probabilities can be applied in the following situations:

- Evidence is unfinished because it cannot be practically attained.
- Data can be found out just in analogous circumstances.
- There are contradictory models or data references.
- Scaling up from experimentations to physical objective procedures is not direct (rescaling the uncertainties is usually more difficult than scaling of mean values).
- When the uncertainties are substantially comparative to the demonstration of obedience (Kotra, Lee, Eisenberg, & DeWispelare, 1996).

Expert knowledge is affected by solo visions and purposes (Ford & Sterman, 1998); thus, it is very difficult to access them in order to complete the impartiality of expert knowledge. The main point here is the selection of both heterogeneous specialists (e.g. either workers or scientists) and homogenous specialists (in this case it just includes scientists).

Therefore, in our study the heterogeneous group of expert was employed and their background is provided in Table 4.1.

Table 4.1. Experts profile and their background

No of expert	Title	Age (year)	Job tenure (year)	Experience (year)	Education level
Expert 1	A Worker working as a skillful employee	27	2	4	BSc (Unrelated to the process)
Expert 2	An experience engineer	29	2	9	MSc (related to the process)
Expert 3	A technician working around 6 years in Iranian Offshore Oil Company IOOC company.	28	4	6	BSc (semi related the process)
Expert 4	A Professor which working as instructor for safety and chemical process courses	30	10	8	PhD (related to the process)

4.1 Determining the weight of Criteria

Four experts with different background are employed in this study. Questionnaires were distributed among the selected respondents (experts). Experts' survey responses were collected electronically within duration of three weeks. When data collection is completed, each of qualitative terms from the questionnaire was transferred to equivalent triangular fuzzy numbers. These equivalent triangular fuzzy numbers are provided in Table 3.1.

Collected data from questionnaires are inserted as inputs to the Microsoft EXCEL software and the related criteria are obtained according to corresponding qualitative terms. In order to find the weight of each criteria in this step, all respondents are considered to have equal weight. The corresponding fuzzy triangular numbers and geometric fuzzy mean with respect to each question are provided in tables 4.2-4.7.

Table 4.2 shows the experts' answer to the first question of the questionnaire related to the importance of the criterion of "age" compared to the criterion of "education level.

Table 4.2. Importance of age compared with education level

No of experts	**Qualitative terms**	**Corresponding triangular fuzzy sets**
Expert 1	Neutral	(1,1,1)
Expert 2	Moderately unimportant	(1/5,1/3,1)
Expert 3	Moderately unimportant	(1/5,1/3,1)
Expert 4	Moderately unimportant	(1/5,1/3,1)
Using Eq 3.2, Average = $[(1,1,1) \otimes (1/5,1/3,1) \otimes (1/5,1/3,1) \otimes (1/5,1/3,1)]^{1/4} = \left[(1 \times \frac{1}{5} \times \frac{1}{5} \times \frac{1}{5})^{1/4}, (1 \times \frac{1}{3} \times \frac{1}{3} \times \frac{1}{3})^{1/4}, (1 \times 1 \times 1 \times 1)^{1/4}\right]$		(0.299, 0.438,1)

Table 4.3 shows the experts' answer to the first question of the questionnaire related to the importance of the criterion of "age" compared to the criterion of "job tenure".

Table 4.3. Importance of age compared with job tenure

No of experts	**Qualitative terms**	**Corresponding triangular fuzzy sets**
Expert 1	Neutral	(1,1,1)
Expert 2	Moderately unimportant	(1/5,1/3,1)
Expert 3	Moderately unimportant	(1/5,1/3,1)
Expert 4	Moderately unimportant	(1/5,1/3,1)
Average		(0.299, 0.438,1)

Table 4.4 shows the experts' answer to the first question of the questionnaire related to the importance of the criterion of "age" compared to the criterion of "experience".

Table 4.4. Importance of age compared with experience

No of experts	Qualitative terms	Corresponding triangular fuzzy sets
Expert 1	Moderately important	(1,3,5)
Expert 2	Moderately important	(1,3,5)
Expert 3	Moderately unimportant	(1/5,1/3,1)
Expert 4	Moderately unimportant	(1/5,1/3,1)
Average		(0.477,1,2.236)

Table 4.5 shows the experts' answer to the first question of the questionnaire related to the importance of the criterion of "education level" compared to the criterion of "job tenure".

Table 4.5. Importance of education level compared with job tenure

No of experts	Qualitative terms	Corresponding triangular fuzzy sets
Expert 1	Moderately important	(1,3,5)
Expert 2	Moderately important	(1,3,5)
Expert 3	Moderately important	(1,3,5)
Expert 4	Moderately important	(1,3,5)
Average		(1,3,5)

Table 4.6 shows the experts' answer to the first question of the questionnaire related to the importance of the criterion of "education level" compared to the criterion of "experience".

Table 4.6. Importance of education level compared with experience

No of experts	Qualitative terms	Corresponding triangular fuzzy sets
Expert 1	Neutral	(1,1,1)
Expert 2	Moderately important	(1,3,5)
Expert 3	Neutral	(1,1,1)
Expert 4	Neutral	(1,1,1)
Average		(1,1.31,1.49)

Table 4.7 shows the experts' answer to the first question of the questionnaire related to the importance of the criterion of "job tenure" compared to the criterion of "experience".

Table 4.7. Importance of education level compared with experience

No of experts	Qualitative terms	Corresponding triangular fuzzy sets
Expert 1	Moderately important	(1,3,5)
Expert 2	Very important	(3,3,5)
Expert 3	Moderately unimportant	(1/5,1/5,1)
Expert 4	Moderately unimportant	(1/5,1/5,1)
Average		(0.588,1,1.69)

In the next step, according to the results which are obtained from the above tables, the matrices of dual comparison between criteria are developed. The results are shown in the following tables 4.7-4.10.

Table 4.8. Paired comparison matrices of criteria to compute the weight

Criterions	Age	Education Level	Job tenure	Experience
Age	(1,1,1)	(0.299, 0.438,1)	(0.299, 0.438,1)	(0.477,1,2.236)
Education Level	(1,2.279,3.34,)	(1,1,1)	(1,3,5)	(1,1.31,1.49)
Job tenure	(1,2.279,3.34)	(0.299,0.577,1.49)	(1,1,1)	(0.588,1,1.69)
Experience	(0.477,1,2.236)	(0.668,0.759,1)	(0.588,1,1.69)	(1,1,1)

According to fuzzy AHP process, following computations are done to find the final weight of each criterion (Table 4.9).

Table 4.9. Geometric weight of each criterion (Using Eq 3.2)

Criterions	Geometric weight
Age	Average = $[(1,1,1) \otimes (0.299, 0.438,1) \otimes (0.299, 0.438,1) \otimes (0.477,1,2.236)]^{1/4} = \left[(1 \times 0.299 \times 0.299 \times 0.477)^{1/4}, (1 \times 0.438 \times 0.438 \times 1)^{1/4}, (1 \times 1 \times 1 \times 2.236)^{1/4}\right] = (0.454,0.661,1.22)$
Education Level	(1,1.729,2.233)
Job tenure	(0.647,1.070,1.702)
Experience	(0.657,0.933,1.39)

For each criterion, fuzzy weights are defined as follows in Table 4.10.

Table 4.10. Fuzzy weights of each criterion (Using Eq 3.3)

Criterions	Geometric fuzzy weights
Age	$(0.454,0.661,1.22) \otimes [(0.454,0.661,1.22) \oplus (1,1.729,2.233) \oplus (0.647,1.070,1.702) \oplus (0.657,0.933,1.39)]^{-1} = \left[\left(\frac{0.454}{0.454+1+0.647+0.647}, \frac{0.661}{0.454+1+0.647+0.647}, \frac{1.22}{0.454+1+0.647+0.647}\right]\right. = (0.165,0.150,0.186)$
Education Level	(0.363,0.393,0.341)
Job tenure	(0.235,0.243,0.260)
Experience	(0.239,0.212,1.212)

The crisp weight of each criterion is computed as follows.

Table 4.11. The Crisp weights of each criterion (Using Eq 3.4)

Criterions	Crisp weights
Age	$\frac{[(0.186-0.150)+(0.165-0.150)]}{3} + 0.150 = 0.167$
Education Level	0.365
Job tenure	0.249
Experience	0.221

4.2 Determining the weight of each expert

With respect to background of employed experts (Table 4.1), the comparison matrix of experts for each criteria are created as follows.

Table 4.12 shows the comparison of experts for criterion “Age”, the geometric mean, fuzzy weight, crisp weigh of each expert.

Table 4.12. Comparison of experts for criterion “Age”

Criterion Age							
	Expert 1	Expert 2	Expert 3	Expert 4	Geometric mean	Fuzzy weight	Crisp weigh
Expert 1	(1,1,1)	(1,1,1)	(1,1,1)	(1/5,1/3,1)	(0.668,0.759,1)	(0.219,0.166,0.157)	0.178
Expert 2	(1,1,1)	(1,1,1)	(1,1,1)	(1/5,1/3,1)	(0.668,0.759,1)	(0.219,0.166,0.157)	0.178
Expert 3	(1,1,1)	(1,1,1)	(1,1,1)	(1/5,1/3,1)	(0.668,0.759,1)	(0.219,0.166,0.157)	0.178
Expert 4	(1,3,5)	(1,3,5)	(1,3,5)	(1,1,1)	(3.04,4.54,3.34)	(0.328,0.499,0.526)	0.645
							Total=1

Table 4.13 shows the comparison of experts for criterion “Education Level”, the geometric mean, fuzzy weight, crisp weigh of each expert.

Table 4.13. Comparison of experts for criterion “Education Level”

Criterion Education Level							
	Expert 1	Expert 2	Expert 3	Expert 4	Geometric mean	Fuzzy weight	Crisp weigh
Expert 1	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(0.447,0.508,0.759)	(0.135,0.096,0.106)	0.112
Expert 2	(1,3,5)	(1,1,1)	(1,3,5)	(1/5,1/3,1)	(0.668,1.31,2.236)	(0.202,0.248,0.315)	0.255
Expert 3	(1,1,1)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(0.447,0.508,0.759)	(0.135,0.248,0.315)	0.112
Expert 4	(3,5,5)	(1,3,5)	(3,5,5)	(1,1,1)	(1.73,2.94,7.09)	(0.525,0.558,0.47)	0.521
							Total=1

Table 4.14 shows the comparison of experts for criterion “Job tenure”, the geometric mean, fuzzy weight, crisp weigh of each expert.

Table 4.14. Comparison of experts for criterion “Job tenure”

Criterion Job tenure							
	Expert 1	Expert 2	Expert 3	Expert 4	Geometric mean	Fuzzy weight	Crisp weigh
Expert 1	(1,1,1)	(1,1,1)	(1/5,1/3,1)	(1/5,1/5,1/3)	(0.447,0.508,0.759)	(0.135,0.096,0.106)	0.112
Expert 2	(1,1,1)	(1,1,1)	(1/5,1/3,1)	(1/5,1/5,1/3)	(0.447,0.508,0.759)	(0.135,0.096,0.106)	0.112
Expert 3	(1,3,5)	(1,3,5)	(1,1,1)	(1/5,1/3,1)	(1.73,2.94,7.09)	(0.202,0.428,0.314)	0.254
Expert 4	(3,5,5)	(3,5,5)	(1,3,5)	(1,1,1)	(3.292,5.266,7.088)	(0.525,0.558,0.47)	0.522
						Total=1	

Table 4.15 shows the comparison of experts for criterion “Experience”, the geometric mean, fuzzy weight, crisp weigh of each expert.

Table 4.15. Comparison of experts for criterion “Experience”

Criterion Job tenure							
	Expert 1	Expert 2	Expert 3	Expert 4	Geometric mean	Fuzzy weight	Crisp weigh
Expert 1	(1,1,1)	(1/5,1/5,1/3)	(1/5,1/3,1)	(1/5,1/3,1/3)	(0.229,0.0.40,0.577)	(0.088,0.066,0.088)	0.08
Expert 2	(3,5,5)	(1,1,1)	(1,3,5)	(1,1,1)	(1.31,1.96,2.23)	(0.389,0.385,0.342)	0.372
Expert 3	(1,3,5)	(1/5,1/3,1)	(1,1,1)	(1/5,1/3,1)	(0.447,0.76,1.50)	(0.132,0.149228,0.314)	0.176
Expert 4	(3,5,5)	(1,1,1)	(1,3,5)	(1,1,1)	(1.31,1.96,2.23)	(0.389,0.385,0.342)	0.372
							Total=1

Table 4.16 shows the final weight of each employed expert with respect to the weight of each criterion.

Table 4.16 The final weight of each expert

Criterion	Age	Education Level	Job tenure	Experience	Final weight
Weight	0.167	0.365	0.246	0.221	
Expert 1	0.178	0.112	0.112	0.08	0.115
Expert 2	0.178	0.255	0.112	0.372	0.232
Expert 3	0.178	0.112	0.254	0.176	0.171
Expert 4	0.645	0.521	0.522	0.372	0.508
					Total=1

4.3 Aggregate experts' opinions for each basic event

Collected data from questionnaires for estimating the possibility of each basic event with respect to experts' opinion in qualitative terms (Table 3.2) are provided in Table 4.17. For example, the possibility of happening BE.5 (Machine damaged) based on four experts' opinions are Medium, Very high, Low, and High.

Table 4.17. Expert judgment on each basic event

TAG reference	Basic events description	Expert 1	Expert 2	Expert 3	Expert 4
BE.1	Hydrocarbon vapors are available in tank	H	H	VL	H
BE.2	Fresh air transfer into the tank	L	M	VL	H
BE.3	There is no ventilation facility	L	L	VL	M
BE.4	Ventilation facility break down	L	H	L	M
BE.5	Machine damaged	M	VH	L	H
BE.6	Improper welding	H	M	L	H
BE.7	Improper installation	H	M	L	H
BE.8	Low resistance	M	M	L	H
BE.9	Exposure with corrosive material	M	M	L	M
BE.10	High salt	M	L	L	M
BE.11	High temperature	L	H	VL	H
BE.12	Low PH	M	VL	L	H

BE.13	Bacteria	L	VL	VL	L
BE.14	With water	M	VL	L	M
BE.15	CO_2	L	H	L	M
BE.16	H_2S	H	H	L	L
BE.17	O_2	M	H	VL	M
BE.18	Flood	VL	M	VL	L
BE.19	Earthquake	VL	VH	VL	L
BE.20	Crumble	VL	VH	VL	L
BE.21	Improper material	L	VH	L	M
BE.22	Improper strength	M	H	L	M
BE.23	Human error	M	H	M	H
BE.24	Collapse with excavation	M	H	L	M
BE.25	Smoking	M	VH	L	L
BE.26	Hot work	H	VH	L	M
BE.27	Non fire proof facility	H	H	L	M
BE.28	Electrostatics devices	M	VH	L	M
BE.29	Non fire proof instrument	M	VH	VL	M
BE.30	Using iron shoes	L	M	VL	L
BE.31	Strikes of metal tools	L	M	VL	L
BE.32	Earth rod broke down	L	H	L	L
BE.33	Lightening rod broke down	H	H	VL	M
BE.34	None protective system	M	H	L	L
BE.35	Direct lightening stroke	H	H	VL	L
BE.36	Indirect lightening stroke	H	H	VL	L
BE.37	Spherical thunder	H	H	VL	L
BE.38	Ground and shoes friction	L	VL	VL	L
BE.39	Ground electrostatic friction	L	VL	VL	L
BE.40	Body and fiber friction	L	L	L	L
BE.41	Hydrocarbons strike to metal	L	M	L	M
BE.42	Splash droplet friction	L	M	L	L
BE.43	Hydrocarbons velocity is high	M	L	L	M
BE.44	Hydrocarbons strike to metal	M	L	L	M
BE.45	Splash droplet friction	L	L	M	L
BE.46	Hydrocarbons velocity is high	L	L	L	M

In order to aggregate experts' opinion, using Table 3.3 the qualitative terms are converted into the fuzzy corresponding number. Table 4.18 provides the corresponding fuzzy number of qualitative terms.

Table 4.18. Corresponding fuzzy number based on expert knowledge

TAG reference	Expert 1	Expert 2	Expert 3	Expert 4
BE.1	(0.7,0.8,0.8,0.9)	(0.7,0.8,0.8,0.9)	(0,0.1,01,0.2)	(0.7,0.8,0.8,0.9)
BE.2	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0.7,0.8,0.8,0.9)
BE.3	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.4	(0,0.1,01,0.2)	(0.7,0.8,0.8,0.9)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.5	(0.4,0.5,0.5,0.6)	(0.8,0.9,0.9,1)	(0,0.1,01,0.2)	(0.7,0.8,0.8,0.9)
BE.6	(0.7,0.8,0.8,0.9)	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0.7,0.8,0.8,0.9)
BE.7	(0.7,0.8,0.8,0.9)	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0.7,0.8,0.8,0.9)
BE.8	(0.4,0.5,0.5,0.6)	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0.7,0.8,0.8,0.9)
BE.9	(0.4,0.5,0.5,0.6)	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.10	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.11	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0.7,0.8,0.8,0.9)
BE.12	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0.7,0.8,0.8,0.9)
BE.13	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.14	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.15	(0,0.1,01,0.2)	(0.7,0.8,0.8,0.9)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.16	(0.7,0.8,0.8,0.9)	(0.7,0.8,0.8,0.9)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.17	(0.4,0.5,0.5,0.6)	(0.7,0.8,0.8,0.9)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.18	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.19	(0,0.1,01,0.2)	(0.8,0.9,0.9,1)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.20	(0,0.1,01,0.2)	(0.8,0.9,0.9,1)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.21	(0,0.1,01,0.2)	(0.8,0.9,0.9,1)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.22	(0.4,0.5,0.5,0.6)	(0.7,0.8,0.8,0.9)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.23	(0.4,0.5,0.5,0.6)	(0.7,0.8,0.8,0.9)	(0.4,0.5,0.5,0.6)	(0.7,0.8,0.8,0.9)
BE.24	(0.4,0.5,0.5,0.6)	(0.7,0.8,0.8,0.9)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.25	(0.4,0.5,0.5,0.6)	(0.8,0.9,0.9,1)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.26	(0.7,0.8,0.8,0.9)	(0.8,0.9,0.9,1)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.27	(0.7,0.8,0.8,0.9)	(0.7,0.8,0.8,0.9)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.28	(0.4,0.5,0.5,0.6)	(0.8,0.9,0.9,1)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.29	(0.4,0.5,0.5,0.6)	(0.8,0.9,0.9,1)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.30	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.31	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0,0.1,01,0.2)

BE.32	(0,0.1,01,0.2)	(0.7,0.8,0.8,0.9)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.33	(0.7,0.8,0.8,0.9)	(0.7,0.8,0.8,0.9)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.34	(0.4,0.5,0.5,0.6)	(0.7,0.8,0.8,0.9)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.35	(0.7,0.8,0.8,0.9)	(0.7,0.8,0.8,0.9)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.36	(0.7,0.8,0.8,0.9)	(0.7,0.8,0.8,0.9)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.37	(0.7,0.8,0.8,0.9)	(0.7,0.8,0.8,0.9)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.38	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.39	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.40	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.41	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.42	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0,0.1,01,0.2)
BE.43	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.44	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)
BE.45	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)	(0,0.1,01,0.2)
BE.46	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0,0.1,01,0.2)	(0.4,0.5,0.5,0.6)

Eq. 3.7 -3.11 is used to aggregate corresponding fuzzy number for each basic event.

As an example the detailed aggregation computation for BE.5 (Machine damaged) are provided as follows.

Expert 1: (0.4,0.5,0.5,0.6)

Expert 2: (0.8,0.9,0.9,1)

Expert 3: (0,0.1,01,0.2)

Expert 4: (0.7,0.8,0.8,0.9)

Aggregation for BE.5:

$$= 0.115 \otimes (0.4,0.5,0.5,0.6) \oplus 0.232 \otimes (0.8,0.9,0.9,1) \oplus 0.171 \otimes (0,0.1,01,0.2) \oplus 0.508 \otimes (0.7,0.8,0.8,0.9)$$

$$= (0.046,0.0575,0.0575,0.069) \oplus (0.185,0.208,0.208,0.232)$$

$$\oplus (0,0.017,0.017,0.0342) \oplus (0.355,0.406,0.406,0.457)$$

$$= (0.587,0.690,0.690,0.792)$$

The aggregation result of other basic events is provided on Table 4.19.

Table 4.19. Aggregation computation for each subjective basic event

TAG reference	Aggregation of each subjective basic event
BE.1	(0.599,0.701,0.701,0.804)
BE.2	(0.460,0.563,0.563,0.665)
BE.3	(0.238,0.431,0.431,0.443)
BE.4	(0.394,0.497,0497,0.599)
BE.5	(0.587,0.690,0.690,0.792)
BE.6	(0.546,0.649,0.649,0.751)
BE.7	(0.546,0.649,0.649,0.751)
BE.8	(0.514,0.614,0.614,0.717)
BE.9	(0.359,0.642,.0642,0.564)
BE.10	(0.290,0.392,0.392,0.495)
BE.11	(0.530,0.632,0.632,0.732)
BE.12	(0.419,0.521,0.521,0.624)
BE.13	(0.062,0.165,0.165,0.268)
BE.14	(0.266,0.369,0.369,0.472)
BE.15	(0.394,0.497,0.497,0.599)
BE.16	(0.311,0.413,0.413,0.516)
BE.17	(0.412,0.514,0.514,0.617)
BE.18	(0.144,0.246,0.246,0.349)
BE.19	(0.236,0.339,0.339,0.442)
BE.20	(0.236,0.339,0.339,0.442)
BE.21	(0.417,0.520,0.520,0.623)
BE.22	(0429,0.531,0.531,0.634)
BE.23	(0.632,0.735,0.735,0.838)
BE.24	(0429,0.531,0.531,0.634)
BE.25	(0.300,0.402,0.402,0.505)
BE.26	(0.486,0.589,0.589,0.692)
BE.27	(0.463,0.566,0.566,0.668)
BE.28	(0.452,0.555,0.555,0.657)
BE.29	(0.435,0.537,0.537,0.460)
BE.30	(0.155,0.258,0.258,0.360)
BE.31	(0.155,0.258,0.258,0.360)
BE.32	(0.205,0.308,0.308,0.410)
BE.33	(0.446,0.549,0.549,0.561)
BE.34	(0.260,0.379,0.379,0.482)
BE.35	(0.294,0.396,0.396,0.499)
BE.36	(0.294,0.396,0.396,0.499)
BE.37	(0.294,0.396,0.396,0.499)

BE.38	(0.074,0.177,0.177,0.279)
BE.39	(0.074,0.177,0.177,0.279)
BE.40	(0.103,0.205,0.205,0.308)
BE.41	(0.235,0.427,0.427,0.530)
BE.42	(0.172,0.275,0.275,0.377)
BE.43	(0.290,0.392,0.392,0.495)
BE.44	(0.290,0.392,0.392,0.495)
BE.45	(0.154,0.257,0.257,0359)
BE.46	(0.255,0.358,0.358,0.460)

For defuzzification, Eqs 3.13-3.15 are used.

As an example, the detailed calculation of BE.5 is provided as following.

$$Crips\ value$$

$$= \frac{1}{3} \times \frac{(0.690 + 0.792)^2 - 0.690 \times 0.792 - (0.587 + 0.690)^2 + 0.690 \times 0.587}{(0.690 + 0.792 - 0.587 - 0.690)}$$

$$= 0.690$$

The details of other crisp values are provided in Table 4.20

Table 4.20. The crisp values of subjective basic events

TAG reference	Deffuzification of subjective basic events
BE.1	0.701
BE.2	0.563
BE.3	0.341
BE.4	0.480
BE.5	0.690
BE.6	0.649
BE.7	0.649
BE.8	0.614
BE.9	0.462
BE.10	0.392
BE.11	0.632
BE.12	0.521
BE.13	0.165
BE.14	0.369
BE.15	0.497

BE.16	0.413
BE.17	0.514
BE.18	0.246
BE.19	0.339
BE.20	0.339
BE.21	0.520
BE.22	0.531
BE.23	0.735
BE.24	0.531
BE.25	0.402
BE.26	0.589
BE.27	0.566
BE.28	0.555
BE.29	0.537
BE.30	0.258
BE.31	0.258
BE.32	0.344
BE.33	0.549
BE.34	0.379
BE.35	0.396
BE.36	0.396
BE.37	0.396
BE.38	0.165
BE.39	0.165
BE.40	0.205
BE.41	0.427
BE.42	0.275
BE.43	0.392
BE.44	0.392
BE.45	0.358
BE.46	0.257

As discussed in chapter 3, in order to compute the probability of each basic event, Onisawa introduced an equation for transferring possibility to probability (Takehisa Onisawa, 1988a, 1988b, 1988b, 1990, 1996; Takeshisa Onisawa & Misra, 1993). Using Eq 3.16, the detailed computation for BE.5 (Machine damaged) is provided as follows.

$$K = \left(\frac{1}{0.690} - 1\right)^{\frac{1}{3}} \times 2.301 = 1.762$$

$$Probbaility_{BE.5} = \frac{1}{10^{1.762}} = 0.0172$$

Table 4.21 presents the probability of all subjective basic events.

Table 4.21. Probability of all subjective basic events

TAG reference	Probability of basic events
BE.1	0.018543707
BE.2	0.007654294
BE.3	0.001354433
BE.4	0.004323484
BE.5	0.017263137
BE.6	0.013310007
BE.7	0.013310007
BE.8	0.010693317
BE.9	0.003786177
BE.10	0.002171969
BE.11	0.011990443
BE.12	0.005800530
BE.13	0.000111829
BE.14	0.001770160
BE.15	0.004888339
BE.16	0.002596126
BE.17	0.005522901
BE.18	0.000455799
BE.19	0.001334619
BE.20	0.001334619
BE.21	0.005748850
BE.22	0.006211161
BE.23	0.023029965
BE.24	0.006211161
BE.25	0.002364162
BE.26	0.009100860
BE.27	0.007822592
BE.28	0.007259312
BE.29	0.006473416
BE.30	0.000532173
BE.31	0.000532173
BE.32	0.001406919
BE.33	0.006984081
BE.34	0.001936075
BE.35	0.002251234
BE.36	0.002251234
BE.37	0.002251234
BE.38	0.000111829

BE.39	0.000111829
BE.40	0.000243429
BE.41	0.002901937
BE.42	0.000661029
BE.43	0.002171969
BE.44	0.002171969
BE.45	0.001595244
BE.46	0.000523829

4.4 Computing the probability of top event

Boolean algebra (Section 3.5.1) is employed to compute the probability of top event. For this purpose, the computations are obtained from down of the tree to the top.

$P_{\text{External corrosion}} = \frac{1}{2} \times BE.8 + BE.9 + BE.10 + BE.11 + BE.12 + BE.13 =$ 0.017277

$P_{\text{Operational Error}} = \frac{1}{2} \times BE.5 + BE.6 + BE.7 =$0.021942

$P_{\text{Internal Corrosion}} = \frac{1}{2} \times (BE.15 + BE.16 + BE.17) \times BE.14 =$1.15126E-05

$P_{\text{Puncture}} = P_{\text{External corrosion}} + P_{\text{Operational Error}} + P_{\text{Internal Corrosion}} =$0.046607

$P_{\text{Natural accident}} = BE.18 + BE.19 + BE.20 =$0.003125

$P_{\text{Improper Design}} = BE.21 + BE.22 =$0.01196

$P_{\text{Improper operation}} = BE.23 + BE.24 =$0.029241

$P_{\text{Rupture}} = P_{\text{Natural accident}} + P_{\text{Improper Design}} + P_{\text{Improper operation}} =$0.044326

$P_{\text{Hydrocarbon Leakage}} = P_{\text{Puncture}} + P_{\text{Rupture}} =$0.090934

$P_{\text{Ventilation is improper}} = BE.3 + BE.4 =$0.005678

$P_{\text{UFL outside of the tank}} = P_{\text{Ventilation is improper}} \times P_{\text{Hydrocarbon Leakage}} =$0.000516

$P_{\text{UFL inside of the tank}} = BE.1 \times BE.2 =$0.000142

$P_{\text{Passing the upper falammibility limit}} = P_{\text{UFL outside of the tank}} +$

$P_{\text{UFL inside of the tank}}$ =0.000658

$P_{\text{Discharge from tank}} = (BE.41 + BE.42 + BE.43) \times (BE.44 + BE.45 +$

$BE.46)$ =2.46088E-05

$P_{\text{Discharge from human body}} = BE.38 + BE.39 + BE.40$ =0.000467087

$P_{\text{Static Spark}} = P_{\text{Discharge from tank}} + P_{\text{Discharge from human body}}$ =0.000491696

$P_{\text{Lighting and thunder storm}} = (BE.32 + BE.33 + BE.34) \times (BE.35 + BE.36 +$

$BE.37)$ =6.9746E-05

$P_{\text{Strike spark}} = BE.30 + BE.31$ =0.000467087

$P_{\text{Electric sparks}} = BE.28 + BE.29$ =0.013732728

$P_{\text{Open Fire}} = BE.25 + BE.27 + BE.26$ =0.019287614

$P_{\text{Reaching to the ignition source}} = P_{\text{Static Spark}} + P_{\text{Lighting and thunder storm}} +$

$P_{\text{Strike spark}} + P_{\text{Electric sparks}} + P_{\text{Open Fire}}$ =0.035113217

$P_{\text{top event}} = P_{\text{Passing the upper falammibility limit}} \times$

$P_{\text{Reaching to the ignition source}}$ =2.19955E-05 per year.

4.5 Finding the critical basic event to happening top event

In order to find out the critical basic events, the probability of top event is computed without considering the specified basic event. The smaller probability of top event in each case shows that the specified basic event is more critical. The computation of new probability of top event is provided on Table 4.22.

Table 4.22. The computation of new probability of top event

Rank	BEs reference	New probability
1	BE.4	9.04E-06
2	BE.26	1.62E-05
3	BE.27	1.7E-05
4	BE.23	1.72E-05
5	BE.28	1.74E-05
6	BE.3	1.78E-05
7	BE.29	1.79E-05
8	BE.5	2.01E-05
9	BE.25	2.04E-05
10	BE.6	2.05E-05
11	BE.7	2.05E-05
12	BE.22	2.06E-05
13	BE.24	2.06E-05
14	BE.11	2.06E-05
15	BE.21	2.07E-05
16	BE.8	2.08E-05
17	BE.12	2.13E-05
18	BE.30	2.15E-05
19	BE.31	2.15E-05
20	BE.19	2.16E-05
21	BE.20	2.16E-05
22	BE.10	2.16E-05
23	BE.9	2.16E-05
24	BE.18	2.18E-05
25	BE.33	2.18E-05
26	BE.35	2.18E-05
27	BE.36	2.18E-05
28	BE.37	2.18E-05
29	BE.13	2.18E-05
30	BE.34	2.18E-05
31	BE.32	2.18E-05
32	BE.17	2.18E-05
33	BE.15	2.18E-05
34	BE.16	2.18E-05
35	BE.40	2.18E-05
36	BE.41	2.18E-05
37	BE.42	2.18E-05
38	BE.43	2.18E-05

39	BE.38	2.19E-05
40	BE.39	2.19E-05
41	BE.44	2.2E-05
42	BE.45	2.2E-05
43	BE.46	2.2E-05
44	BE.14	2.32E-05
45	BE.1	0.000288
46	BE.2	0.000674

4.6 Finding the contribution of each basic event to happening top event

In order to find out the contribution of each basic event in the fault tree, the probability of each basic event is divided by summation of all basic events (in this case the probability of top event). The result is provided as follows (Table 4.23).

Table 4.23. The ranking of BEs based on their contributions

Rank	BEs reference	The contribution
1	BE.13	5.119097905
2	BE.38	5.119097905
3	BE.39	5.119097905
4	BE.40	11.14320006
5	BE.18	20.86464628
6	BE.46	23.97880072
7	BE.30	24.36077500
8	BE.31	24.36077500
9	BE.42	30.25929017
10	BE.19	61.09354272
11	BE.20	61.09354272
12	BE.3	62.00056447
13	BE.32	64.40313923
14	BE.45	73.02393551
15	BE.14	81.03086765
16	BE.34	88.62579299
17	BE.10	99.42407137
18	BE.43	99.42407137

19	BE.44	99.42407137
20	BE.35	103.0525285
21	BE.36	103.0525285
22	BE.37	103.0525285
23	BE.25	108.2219017
24	BE.16	118.8402998
25	BE.41	132.8391258
26	BE.9	173.3160856
27	BE.4	197.9118958
28	BE.15	223.7686811
29	BE.17	252.8164210
30	BE.21	263.1594657
31	BE.12	265.5251429
32	BE.22	284.3222159
33	BE.24	284.3222159
34	BE.29	296.3271969
35	BE.33	319.7034263
36	BE.28	332.3024127
37	BE.2	350.3831135
38	BE.27	358.0871261
39	BE.26	416.6011428
40	BE.8	489.4974823
41	BE.11	548.8747140
42	BE.6	609.2791377
43	BE.7	609.2791377
44	BE.5	790.2376733
45	BE.1	848.8570450
46	BE.23	1054.220103

4.7 Ranking based on both critical basic event and contribution to happening top event

For final ranking, if the number of event was “n”, the normalized weighing S can be computed by the value of critical basic event and contribution as follows.

$S^* = \frac{x_i}{\sum_{i=1}^{n} x_i}$ Eq. 4.1

In this case, i can be considered as critical value or contribution of each basic event.

Therefore, the fina

l ranking is based on $S^*_{\#} = S^*_{critical} + S^*_{contribution}$.

Table 4.24. The final ranking based on the critical and contribution of each basic event to occurring top event

BEs reference	The normalized contribution	The normalized critical	$S^*_{\#}$	Rank
BE.1	8.024954	15.40054	23.42549	2
BE.2	3.312464	36.03144	39.34390	1
BE.3	0.586143	0.953342	1.539485	37
BE.4	1.871026	0.483328	2.354354	22
BE.5	7.470776	1.074903	8.545679	4
BE.6	5.760024	1.096165	6.856189	5
BE.7	5.760024	1.096165	6.856189	6
BE.8	4.627628	1.110240	5.737868	8
BE.9	1.638501	1.156912	2.795413	20
BE.10	0.939939	1.156073	2.096012	30
BE.11	5.18897	1.103263	6.292233	7
BE.12	2.510231	1.136556	3.646787	16
BE.13	0.048395	1.167154	1.215549	46
BE.14	0.766052	1.237593	2.003646	32
BE.15	2.115472	1.167709	3.283181	19
BE.16	1.123496	1.167731	2.291227	23
BE.17	2.390084	1.167703	3.557787	18
BE.18	0.197251	1.162852	1.360103	42
BE.19	0.577568	1.153398	1.730967	35
BE.20	0.577568	1.153398	1.730967	36
BE.21	2.487866	1.105913	3.593779	17
BE.22	2.687935	1.100940	3.788875	13
BE.23	9.966422	0.920015	10.88644	3
BE.24	2.687935	1.100940	3.788875	14
BE.25	1.023112	1.089861	2.112973	28
BE.26	3.938478	0.867901	4.806379	9
BE.27	3.385296	0.910017	4.295313	10
BE.28	3.141532	0.928576	4.070108	12

BE.29	2.801428	0.954470	3.755898	15
BE.30	0.230303	1.150221	1.380524	40
BE.31	0.230303	1.150221	1.380524	41
BE.32	0.608857	1.167442	1.776299	34
BE.33	3.022423	1.166201	4.188624	11
BE.34	0.837854	1.167324	2.005178	31
BE.35	0.974241	1.166989	2.141231	24
BE.36	0.974241	1.166989	2.141231	25
BE.37	0.974241	1.166989	2.141231	26
BE.38	0.048395	1.172091	1.220486	44
BE.39	0.048395	1.172091	1.220486	45
BE.40	0.105346	1.167755	1.273101	43
BE.41	1.255839	1.167755	2.423594	21
BE.42	0.286066	1.167755	1.453822	38
BE.43	0.939939	1.167755	2.107694	29
BE.44	0.939939	1.175776	2.115714	27
BE.45	0.690356	1.175776	1.866132	33
BE.46	0.226692	1.175776	1.402467	39

Chapter 5

DISCUSSIONS AND CONCLUSION

The overall objective of this thesis was to use the FTA methods and Fuzzy approach to analysis the occurrence of fire and explosion in a spherical hydrocarbons storage tank based on experts' judgment. This is an attempt to compute the probability of top event and subsequently identify the critical basic events and their contribution to the happening specified top event. According to results of this research following conclusions are provided.

5.1 Methodology conclusion

- An application of fuzzy methodology for fault tree analysis seems to be an alternative solution to cope with shortages of the conventional approach including lack of information, unreliability of using available handbooks, and hesitating the relative frequencies of hazardous events.

- With respect to qualitative terms, it is possible to manage the vagueness in the expression of the occurrence of each basic event. Moreover, it seems each basic event can be evaluated in a more flexible form using the fuzzy set theory.

- Failure probability is used to compute the top event probability instead of using corresponding fuzzy possibility. It can efficiently obtain the ambiguities of nature of system phenomena and incomplete information. In addition, despite of complexity of system, it may to recognize which basic event is more influence to failure probability of system.

- An improved fuzzy AHP model is used to expert weighing. Conventional AHP method cannot deal with subjective knowledge; therefore, fuzzy AHP is developed to solve the conventional AHP problems. In other words, the main purpose of AHP is obtaining expert opinions; however, conventional AHP cannot reflect the human thinking style. It was shown that using new proposed model of improved AHP is more reliable and realistic which close to the human thinking.

- The importance of basic event can provides useful information for improving the safety performance of the system. Therefore, computing the importance of each basic events help decision makers to identify the critical basic event in the system for reducing the occurrence of likelihood of top event. In addition, it shows that which path from down of the tree to the top is more probable.

5.2 Case study conclusion

As it computed in chapter 4, the probability of tope event is estimated as 2.18455E-05 per year. The figure 5.1 illustrates the probability of 5 most critical basic events in compare of probability of top event.

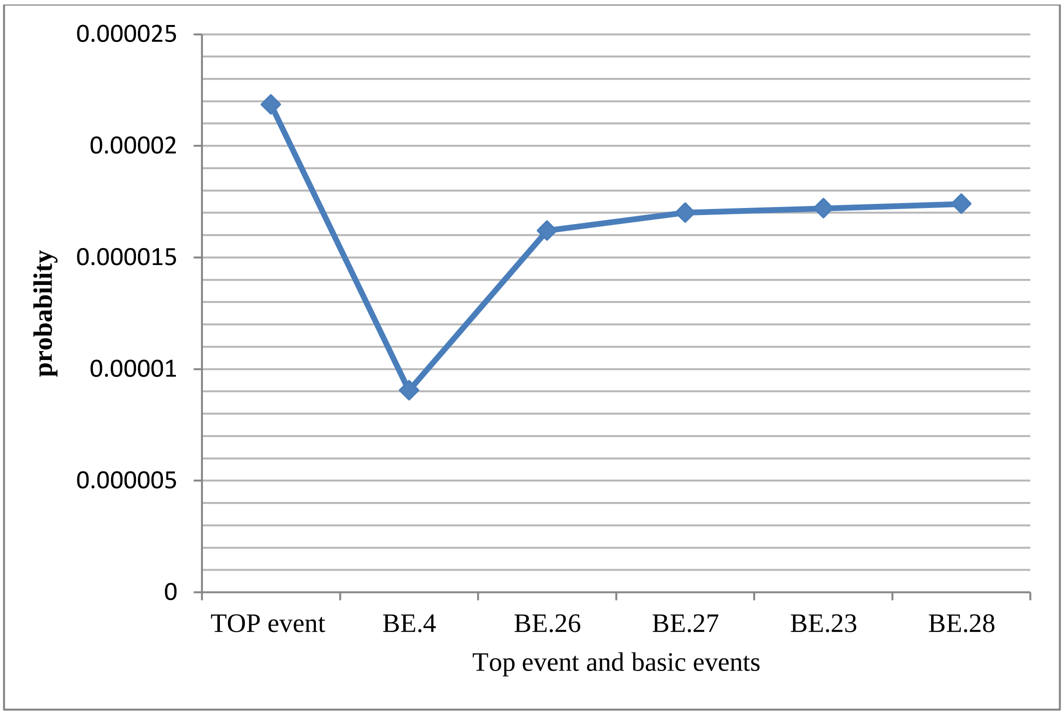


Figure 5.1. The 5 most critical basic events in compare of probability of top event

Figure 5.2 shows the percentage of probability reduction based on 5 most critical basic events. As is illustrated, removing or controlling BE.5 causes the probability of top event face to approximately 60 percent reduction. While, the percentages reduction for BE.26, BE.27, BE.23 and BE.28 are approximately 25, 22, 21, and 20 respectively. It is obvious that the percentages reduction of top event probability is going to be depressed with respect to multiple controlling the critical basic event such controlling BE.4 and BE.26 and etc. Therefore, attending to the critical basic event is vital.

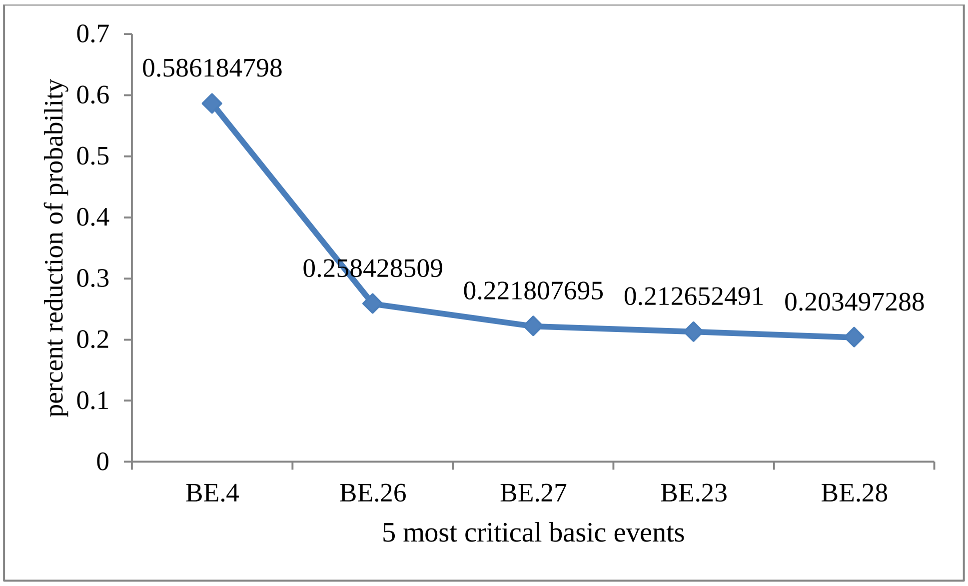


Figure 5.2. The percentage of probability reduction based on 5 most critical basic events

In other side, the 5 significant basic events which have high contribution to the occurring top event is partially different compare to the critical basic events. The 5 highest ones are BE.6, BE.7, BE.5, BE.1, and BE.23. It seems that only BE.23 is common in both critical and contribution list factors. Generally, based on literature and experience, in order to reduce the probability of top event, safety specialist as a decision maker relies on critical ranking with respect controlling or eliminating procedure. Our results, illustrated that having high probabilities for basic events do not mean that the probability of top event should be high. In other words, the path from basic event in order to reach to the top event is the significant issue.

Because of second analysis, of course the total ranking of basic events based on normalization factors including critical and contribution seems to be different. The five priority basic events for consideration further actions are BE.2, BE.1, BE.5, BE.6, and BE.23. It is obvious that only BE.23 is common in the three ranking list.

The recommended controlling procedures for specified basic events are provided as following:

- Controlling BE.4 (Ventilation facility break down)

  As it illustrated in fault tree, ventilation facility causes the hydrocarbons flammability limit is going to be controlled. One way to reduce this failure is using two parallel ventilation facilities as loaded and standby. Another suggestion is based on primary design with natural ventilation instead implementing facility for this purpose.

- Controlling BE.26 (Hot work)

  There is no way to eliminate this task and of course hot work is unavoidable activity in any process industry. Therefore, implementing permit to work and subsequently attending to hot work procedure is vital including gas testing, clarifying ignition source, responsible person, conflict with other activity and etc.

- Controlling BE.27 (Non fire proof facility)

  Non fire proof facility can be a source of ignition as open fire. For this reason based on NFPA 051 standard code, companies should establish the fire proof facilities in flammable areas.

- Controlling BE.23 (Human error)

  Human error is an unavoidable behavior in human life style. Holding various classes including motivation, safety, psychology and etc. by increasing total training hour can help to reduce human error. Excessive monitoring personnel by their working hour, medical usage and so on may help to predict such specified error during the working hour. In addition, it is significant fact that human condition cannot be changed but the conditions where humans work can be totally changed. For example: communication between group shifts and clarifying the communication rules for employees, individual performance based on evaluate the cognitive overload that cause attention and memory failures, and human factor design which contains housekeeping, mental calculation, and work layout.

- Controlling BE.28 (Electrostatics devices)

  Electrostatics devices sparks can be totally eliminated by using ground wire. Ground wire is safest, chipset and easiest to establish though out the necessary places. In addition, OSHA, OHSAS 18001 and many health and safety guidelines express that the company shall provide safety instrument (in this case ground wire) to prevent possible accidents.

As it is discussed in literature part, fault tree analysis is a proper method in design and operating period of industry. Therefore, attending to designs standard such NFPA code for designing, OSHA guidelines for maintaining, OHSAS 18001 based on safety procedures can partially reduce the likelihood of any incident.

5.3 Implication for further research

In chemical complex plant safety under circumstance where lack of data or a high level of uncertainty exist, a large number of assumption, judgment, and opinions need to be involved subjectively in reasoning process. Therefore, attention to increase the objectivity issue is vital. Fuzzy logic in this study is used for this purpose, as a direction for further study the application of machine learning including clustering and decision trees can be obtained.

Other than approximate reasoning approach, new approaches capable of addressing uncertainty and combining expert judgment and empirical data should be developed. Bayesian network as an example has capacity of incorporating expert judgment with the historical data to evaluate the risks. It provides intuitive visual representing with sound mathematical basis in Bayesian probability that translate cause and effect relationship. Moreover, the technique facilities meaningful communication of uncertainties, allowing decision to be made based on expected values such as techniques is also capable of dealing with conditional problem. In addition, when evaluating risk under circumstances of the security of data due to a level of costs of conducting full scale experimentation or some other reason, the use of computer simulation may be potentially useful. It is worthwhile nothing that some computer software the completion procedure. MATLAB, for instance by providing the tool box function, enables safety analysis to perform the function needed by directly the set command.

The chemical industry is moving toward a goal-setting risk based regime. This provides the safety analyst more flexibility to employ novel and the latest risk modeling techniques. Subjective modeling approximate reasoning methods may be one of these useful approaches. It may be beneficial if these novel techniques to chemical complex plant are emphasized. Furthermore, since the methodology proposed in this research can be further applied to facilitate risk modeling; thus, the practical application of such novel techniques to chemical complex plant is emphasized. In addition, since the proposed method in this research is generics, such framework can be further verified for the safety topics outside of the chemical complex plant industry. This will provide an added value to the promotion of their use in different industries.

The main limitation of this study is accepting independent situations such as weather, terrorist attacks, geographical topology, and also independency between basic events. Therefore, in realistic system, dependency should be considered. There are many methods are available for this purpose, but most of them can apply for simple system not complex one with hand computation. Therefore, considering dependency situation recommended as a direction for future study using petri-nets or Markov chains.

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APPENDIX

APPENDIX A: Sample of Questionnaire

Dear respondent

The following questionnaire is planned to evaluate the probability of an event “Fire and explosion in spherical hydrocarbons storage tank” in Iranian Offshore Oil Company (IOOC), Khark Island, based on experts’ knowledge.

The information you present help us to compute the weight of each criteria including “age”, job tenure”, “experience”, and “education level” an finally to aggregate experts’ opinions.

This questionnaire divided in three parts. Part **1** includes personal information of expert based on defined criteria and subsequently in part **2** it is asked to present which criterion is importance than other one.

In this research the relative values of criteria as compared with each other are provided in five options as follows.

A: Very important

B: Moderately important

C: Neutral

D: Moderately unimportant

E: Very unimportant

In part **3**, the fault tree diagram of “Fire and explosion in spherical hydrocarbons storage tank” is designed in details. In order to estimate the probability of each event, it is asked to express your opinion in quantified terms as follows.

Related number	Judgment for probability
10	***Happening (H)***
9	***Certainly high (CH)***
8	***Very high (VH)***
7	***High(H)***
6	***Moderately high (MH)***
5	***Medium (M)***
4	***Moderately low (ML)***
3	***Low (L)***
2	***Very low (VL)***

1	***Certainly low (CL)***
0	***Not happening (NH)***

Thank you very much and honestly appreciate for your valuable time to contribute to this research.

Part 1

Personal information

First name: Surname:

Place of service: Organizational position:

Date when the questionnaire was filled out:

- ✓ **Your Age:**
- ✓ **Your job tenure:**
- ✓ **Your experience in the filed:**
- ✓ **Your education level:**
  - o Ph.D.
  - o Master
  - o Bachelor
  - o Higher national diploma
  - o School level

Part 2

The following questions compare with each other the importance of the following criteria in order to experts weighting.

1. How important is the criterion of "age" as compared with the criterion of "education level"?

A ☐ B ☐ C ☐D ☐ E ☐

2. How important is the criterion of "age" as compared with the criterion of "job tenure"?

A ☐ B ☐ C ☐ D ☐ E ☐

3. How important is the criterion of "age" as compared with the criterion of "experience"?

A ☐ B ☐ C ☐D ☐ E ☐

4. How important is the criterion of "education level" as compared with the criterion of "job tenure"?

A ☐ B ☐ C ☐D ☐ E ☐

5. How important is the criterion of "education level" as compared with the criterion of "experience"?

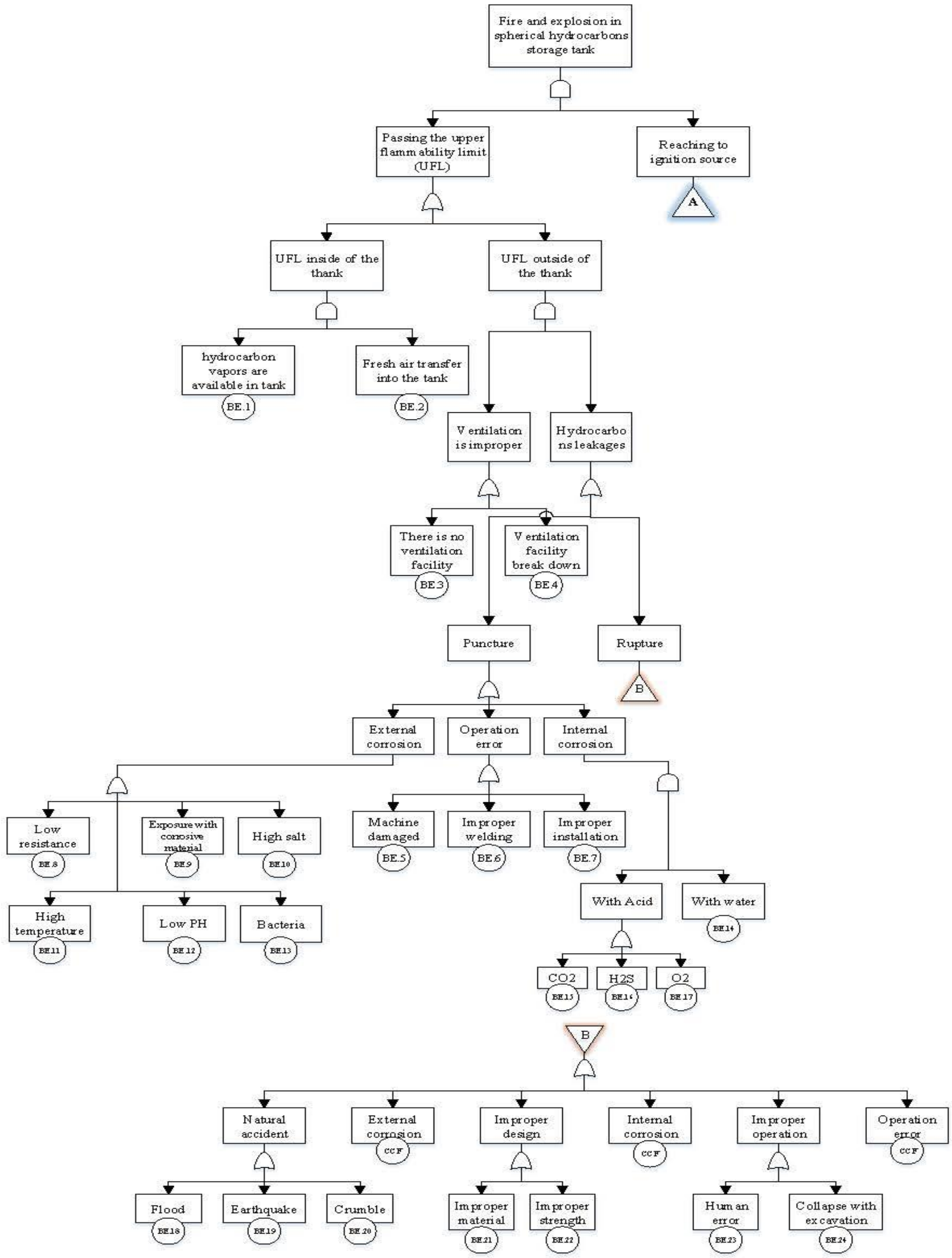
A ☐ B ☐ C ☐ D ☐ E ☐

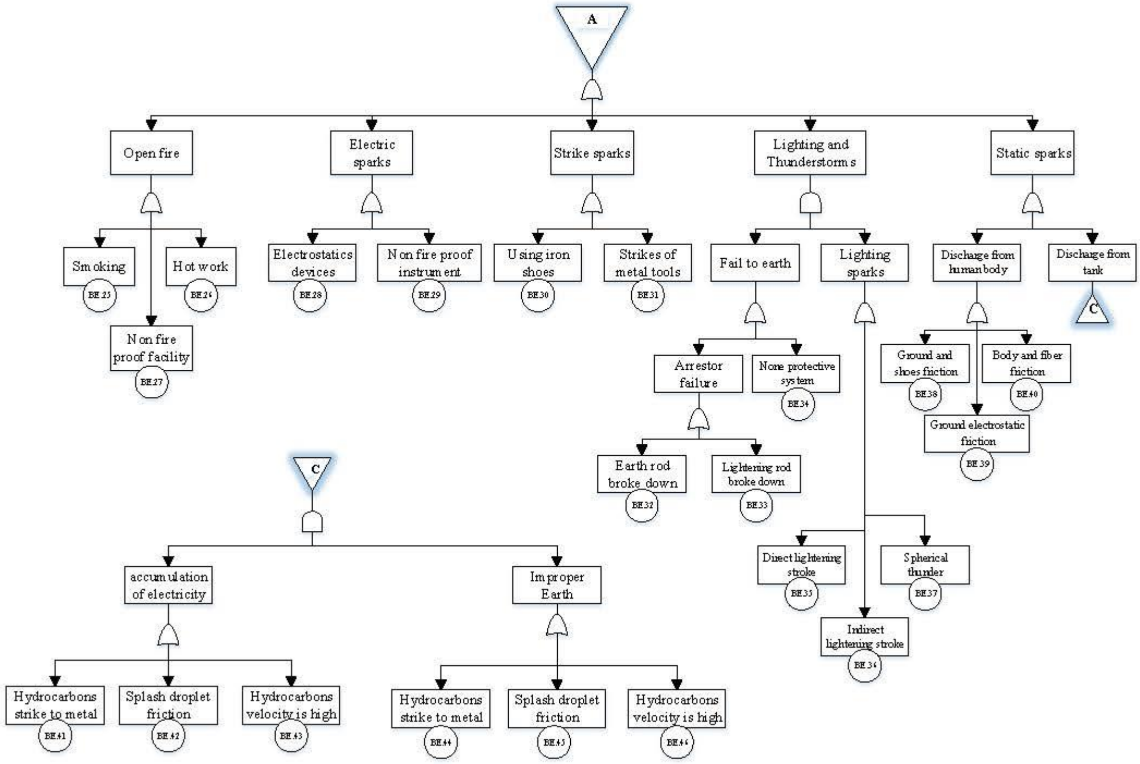
6. How important is the criterion of "job tenure" as compared with the criterion of "experience"?

A ☐ B ☐ C ☐ D ☐ E ☐

Part 3

The fault tree diagram of “Fire and explosion in spherical hydrocarbons storage tank” is provided as follows. Please fill related number of probability in basic events table.




A
Open fire
Electric sparks
Strike sparks
Lighting and Thunderstorms
Static sparks
Smoking
Hot work
Non fire proof facility
Electrostatics devices
Non fire proof instrument
Using iron shoes
Strikes of metal tools
Fail to earth
Lighting sparks
Discharge from human body
Discharge from tank
C
Arrestor failure
None protective system
Earth rod broke down
Lightering rod broke down
Ground and shoes friction
Body and fiber friction
Ground electrostatic friction
Direct lightering stroke
Spherical thunder
Indirect lightening stroke
C
accumulation of electricity
Improper Earth
Hydrocarbons strike to metal
Splash droplet friction
Hydrocarbons velocity is high
Hydrocarbons strike to metal
Splash droplet friction
Hydrocarbons velocity is high

You can find the real size of fault tree in attached file.

TAG	**Basic events**	**Expert opinion 1=none happening and 10=happening**
BE.1	Hydrocarbon vapors are available in tank	
BE.2	Fresh air transfer into the tank	
BE.3	There is no ventilation facility	
BE.4	Ventilation facility break down	
BE.5	Machine damaged	
BE.6	Improper welding	
BE.7	Improper installation	
BE.8	Low resistance	
BE.9	Exposure with corrosive material	
BE.10	High salt	
BE.11	High temperature	
BE.12	Low PH	
BE.13	Bacteria	
BE.14	With water	
BE.15	CO_2	
BE.16	H_2S	
BE.17	O_2	
BE.18	Flood	
BE.19	Earthquake	
BE.20	Crumble	
BE.21	Improper material	
BE.22	Improper strength	
BE.23	Human error	
BE.24	Collapse with excavation	
BE.25	Smoking	
BE.26	Hot work	
BE.27	Non fire proof facility	
BE.28	Electrostatics devices	
BE.29	Non fire proof instrument	
BE.30	Using iron shoes	
BE.31	Strikes of metal tools	
BE.32	Earth rod broke down	
BE.33	Lightening rod broke down	
BE.34	None protective system	
BE.35	Direct lightening stroke	

BE.36	Indirect lightening stroke	
BE.37	Spherical thunder	
BE.38	Ground and shoes friction	
BE.39	Ground electrostatic friction	
BE.40	Body and fiber friction	
BE.41	Hydrocarbons strike to metal	
BE.42	Splash droplet friction	
BE.43	Hydrocarbons velocity is high	
BE.44	Hydrocarbons strike to metal	
BE.45	Splash droplet friction	
BE.46	Hydrocarbons velocity is high	

If any questions arise in your mind please do not hesitate to ask them. Moreover, if you have any comment in order to improve the fault tree diagram please put it as blank follows.

We acknowledge your honest cooperation. Please check out the questionnaire again to make sure that no question in each part was missed, and then return it back.