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Fault Tree Analysis of Tanker Accidents during Loading and Unloading Operations at the Tanker Terminals

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Abstract

One of the most important elements of maritime transportation which is a way of the world trade is the ships. Depending on their purpose, the vessels include many classifications, such as; commercial vessels, service vessels and war ships. Commercial vessels include tankers. Therefore, tankers that are an important point of trade have been developing together with technology. However, the measures taken by the developing technology and the regulations in the maritime sector made cannot reduce the sea accidents to zero. In this study, marine accidents occurred during loading and unloading operations at the tanker terminals were analyzed in terms of human factor and safety. Reports in between 2000 and 2014 of IMO (International Maritime Organization) GISIS (Global Integrated Shipping Information System), MAIB and Maritime Safety Authority of New Zealand and others were investigated. A total of 10 vessel accidents involving the appropriate data were analyzed and classified according to the results. Fault Tree Analysis (FTA) method was used to create the causes of accidents and the results have been tested with Monte Carlo Simulation. As a conclusion, failure to comply with operating procedures and lack of knowledge were found to be the most important factors.

Keywords: *Tanker, Ship accident, Human Factor, Fault Tree Analysis.*

Tanker Terminallerinde Yükleme ve Tahliye Operasyonları Sırasında Gemilerde Meydana Gelen Kazaların Hata Ağacı Yöntemi ile Analizi

Öz

Dünya ticaretinin karşılanmasında bir yol olan deniz yolu taşımacılığının en önemli unsurlarından biri de gemilerdir. Gemiler kullanım alanlarına göre ticaret gemileri, servis gemileri ve savaş gemileri gibi birçok sınıf içerir. Tanker gemileri ticari gemiler kısmında yer almaktadır. Dolayısıyla ticaretin önemli bir noktası olan tanker gemileri teknolojiyle birlikte daha da gelişmektedir. Ancak gelişen teknoloji ve yapılan düzenlemelerle alınan önlemler deniz kazalarını sıfıra indirememektedir. Bu çalışmada tanker terminallerinde yükleme ve boşaltma operasyonları sırasında gemilerde meydana gelen kazalar insan faktörü ve emniyet bakımından incelenmiştir. Çalışma kapsamında Uluslararası Denizcilik Örgütü (IMO) Küresel Bütünleşik Deniz Taşımacılığı Bilgi Sistemi (GISIS), MAIB ve Maritime Safety Authority of New Zealand gibi kuruluşlar tarafından 2000-2014 yolları arasında yayınlanmış raporlar incelenmiştir. Uygun veriler içeren toplam 10 gemi kazası, sonuçlarına göre sınıflandırılmış ver irdelenmiştir. Kaza nedenlerinin oluşturulmasında

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Hata Ağacı Analizi (FTA - Fault Tree Analysis) yöntemi kullanılmış ve sonuçlar Monte Carlo Simülasyonu ile sınanmıştır. Sonuç olarak prosedüre uymama ve bilgi eksikliği en önemli etmenler olarak bulunmuştur.

Anahtar Kelimeler: *Tanker Gemileri, Deniz Kazası, İnsan Hatası, Hata Ağacı Analizi.*

1. Introduction

The transportation is defined as the appropriate and economical displacement of persons and goods to benefit [1, 2]. These motions are provided by rail transport, road transport, sea and inland water transport, air transport, pipeline transport and wired transport systems (Özer, 2010 as cited from Kişi) [2]. One of the items of maritime transport is the ships. There are many classifications for ships and these classifications include merchant vessels. Tanker ships are one type of that class. SOLAS Chapter I Reg 2 defines a tanker as "a cargo ship constructed or adapted for the carriage in bulk of liquid cargoes of an inflammable nature" [3].

Based on The Review of Maritime Transport 2016 published by UNCTAD (United Nations Conference on Trade and Development) covers data and events from January 2015 until June 2016, falling short of expectations and below the pre-financial crisis levels, growth in world GDP expanded by 2.5 per cent in 2015, the same rate as in 2014. Global merchandise trade by volume (that is, trade in value terms, adjusted to account for inflation and exchange rate movements) increased by 1.4 per cent in 2015, down from 2.3 per cent in 2014.The volume of maritime transport that the backbone of globalization and lies at the heart of cross-border transport networks that support supply chains and enable international trade has exceeded 10 billion tons. About 3 billion tons of this total belongs to oil and gas products. On the other hand, the world fleet grew by 3.5 per cent in the 12 months to 1 January 2016. This is the lowest growth rate since 2003, yet still higher than the 2.1 per cent growth in demand [4]. There are many reasons for this growth in trade volume. These can be technological, economic and sociocultural causes. While the gross tonnage of the maritime trade fleet was around 80 million tons in 1950, it reached 883 million tons in 2009[5] and this figure reached about 1,8 billion tons in 2016 [4]. The increase in the ship's fleet between 1950 and 1978 also led to an increase in the number of marine accidents. After IMO (International Maritime Organization) put into force regulations such as SOLAS (International Convention for The Safety of Life at Sea) and MARPOL (International Convention for the Prevention of Pollution from Ships), the number of marine accidents decreased. The sum of sea accidents shows a decrease in the long-term, nevertheless it also increases visibly at certain times [5].

There are many reasons for sea accidents. However, the most common cause is the human. The terms of human factor, human element and human error are used for this expression. In the literature, these three terms are used without any difference. But they have different meanings in different uses [6]. Considering the difficulties encountered in the field of human factors in maritime industry, problems such as fatigue, inadequate communication, inadequate general knowledge of own ship systems, poor design automation, decisions based on inadequate information, faulty standards/policies or practices, poor maintenance and dangerous natural environment draw attention (Pazara et al., 2008 as cited in Huey, D., 1993) [7].

The second one, Human element is defined as a structure formed by people factor, organization on board, working and living conditions, ship factors, shore-side management, external influences and environmental influences. Human error which is the last one, is described as; departure from acceptable or desirable practice on part of an individual or group of individuals that can result in unacceptable or undesirable results [8].

2. Method and Literature

Tankers transport annually more than 200 million tons of chemicals. The number of ships carrying hazardous noxious substance cargoes is growing steadily, therefore the risk of tanker accidents is increasing [4] [19]. To identify increasing tanker accident risks and their consequences, a systematic approach must be undertaken. By this way, tanker accident risks can be minimized by appropriate safety measures [20]. There are many techniques for risk analysis. One of them is Fault Tree Analysis.

The Fault Tree is a technique that can be used both for a qualitative and a quantitative analysis. Qualitatively it is used to identify the individual scenarios that lead to the top event, while quantitatively it is used to estimate the frequency of that event. The basic elements of a Fault Tree may be classed as the top event, primary events, intermediate events and logic gates [10]. A simple fault tree is shown in Figure 1. In this figure, "D output" is illustrated as a top event. "A" is illustrated as a primary event. "B or C Fails" is illustrated as an intermediate event. If all of the input faults happen, "And gate" is used between inputs and output. If least one of the input faults happens, "Or Gate" is used between inputs and output [14, 15].

The aim of fault tree analysis is to determine the possible combinations of reasons that may give rise to some undesired events called top events. A fault tree consists of various levels of event connected in such a way that each event, at a given level, is a results of events at the level just below, through several logical gates. Events may be equipment failures, human errors, software errors, etc. that are likely to cause an undesired outcome [9].

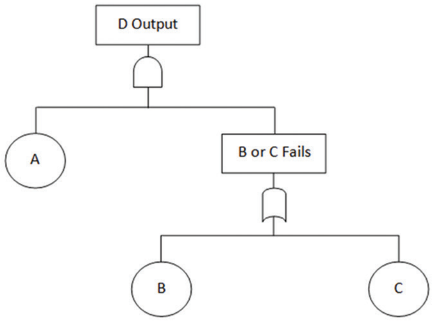

Figure 1. *Simple Fault Tree [14, 15]*

Fault tree analysis, which has been used many times since 1960s when it was developed, proceeds from known effects to investigate unknown causes. In this period, a quantitative assessment could not available at any time. At that time, it has need for probabilities bound up with primary event and it is not possible to associate probabilities with some failure modes in fault trees program [9].

To calculate probabilities with failure mode, Computer-aided Open FTA can be used. This program includes Monte Carlo Simulation. Monte Carlo Simulation is a modeling technique that enables to monitor under different conditions' real system behaviors on a computer model by carrying the cause and effect relationships to the computer [20].

The advantages and disadvantages of Monte Carlo Simulation are described below [21, 22, 23]:

a) Advantages
- It can be applied to all kind of distributions.
- The simulation model can include any complex portfolios.
- The model is fit to data only once. This can be a great advantage when using models that take long time to converge.
- It can be used in situations where bootstrapping is not feasible

b) Disadvantages
- This simulation is very complex and highly depending on abilities of large amount of computations.

- Some situations are not included in the distribution.

Some studies using this method for maritime transportation are given below. One of these is "Fault Tree Models of Accident Scenarios of RoPax" which was written by Antao and Soares in 2006 [10]. The accidents of RoPax vessels are evaluated using the Fault Tree Analysis method and the importance of root causes are revealed. In this study, fault trees belonging to the collision accidents are shown.

Another study is a paper entitled "Fault Tree Analysis as a Tool for Modeling the Marine Main Engine Reliability Structure" which was written by Laskowski [12] in 2015. In the study, Fault Tree Analysis allows detailed study of the working principles of the system during design, operation and accident investigations, and is indicated that this analysis method is useful for marine engineering applications. It is presented in the form of creating the system model with the Fault Tree Analysis application. The reliability structure of the tested machine is modeled using Reliability Block Diagrams as well as Fault Tree Analysis.

Another study is a paper entitled "Marine Accident Analysis for Collision and Grounding in Oil Tanker Using FTA method" which was written by Uğurlu et al. [18] in 2015. The collision and grounding accidents of oil tanker are evaluated using Fault Tree Analysis method. According to the study's results, the main reason for the accidents originating from human error is as follows: for collision accidents, Convention on the International Regulations for Preventing Collisions at Sea (COLREG) violation and the lack of communication between vessels; and for grounding accidents, the interpretation failure of the officer on watch and lack of communication in the bridge resource management.

Another study is a paper entitled "Assessment of Navigational Safety in Vessel Traffic in an Open Area" which was written by Pietrzykowski [13] in 2017. In the study, an algorithm has been demonstrated for the ascertain of vessel collision probability in an open area by fault tree analysis and event tree analysis. It is stated that the ships which encounter will collide if the mistakes happen on both ships. Namely, if both ships make mistake of deviating from collision course, ship collision will happen. For error of collision course deviation, there are two possibilities. First situation happens when error of collision situation identification and no error detected are occurred together. Second situation happens when error of preventive maneuver performance and no error detected when occur together. Both situations are shown by fault tree in the study.

The purpose of this paper is to investigate the accidents occurred during loading and unloading operations on the tankers in terms of human factor and safety. The reports of accidents were collected from the database of MAIB (Marine Accident Investigation Branch), Isle of Man Marine Administration Oaseirys Lhuingys, The Government of Hong Kong Special Administrative Region Marine Department, Marine Safety Investigation Unit Malta Transport Centre, Brazilian Navy Directorate of Ports and Coasts, Maritime Safety Authority of New Zealand and GISIS (Global Integrated Shipping Information System).

In this study, accidents occurred in the vessels located at the tanker terminals were taken into account between 2000 and 2014. A total of 19 accident reports were reached. These accidents were also examined in terms of the results, the location of the accident and the occurrence of the accident and the sufficient data during loading and unloading periods. As a result of that, 10 of 19 ship accidents were evaluated and analyzed within the sample. Nine other ship accidents were excluded.

The following Figure 2 that is a flow chart was followed in the study.

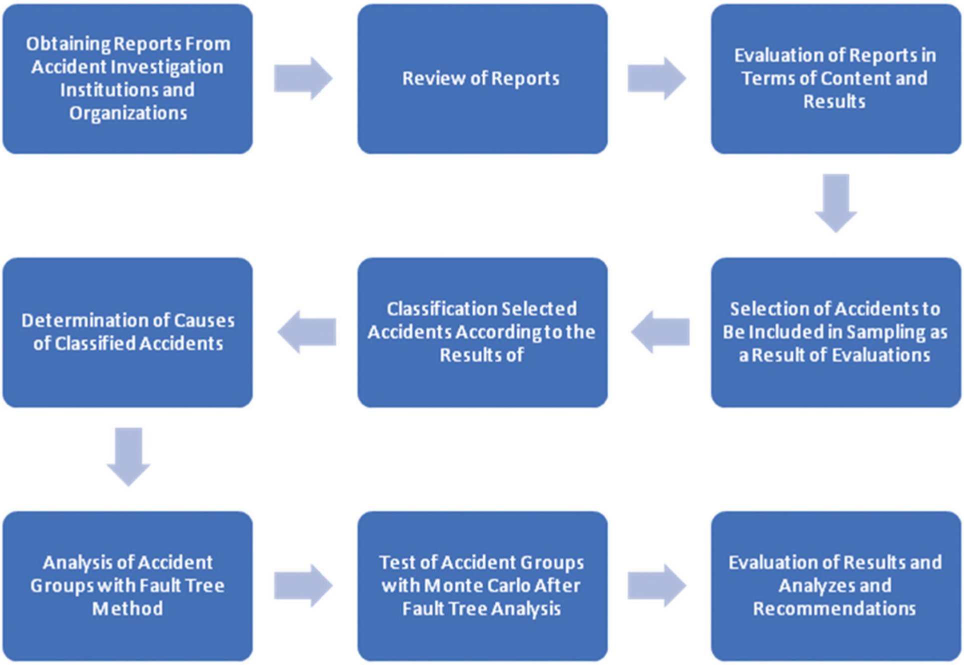

Figure 2. *Flow Chart of the Study*

3. Findings and Analysis

In this study which is about human factor and safety of the accidents occurred during loading and unloading operations on the ships, there are 4 type of accident results. There are 5 fire/explosion accidents, 2 marine pollution accidents, 2 gas poisoning/asphyxia accidents and 1 personal injury accident due to sudden fluid flow. The root causes and repetitions of root causes for these accidents are numbered. The sum of the root causes obtained for these events is found as 43 items and the sum of frequencies of these root causes is found as 58.

The total contribution and probability values for these root causes were calculated by using the following formulas [16, 17]:

Total Contribution of Accident Cause = 1/(Root cause number) (ship accident 1)
+ 1/(Root cause number) (ship accident 2)+⋯
+1/(Root cause number) (ship accident n)

For example:
Disobey to Warning Procedure
=1/5 Ship accident x+1/5 Ship accident y+1/6 ship accident z
=0.566666667

Probability Value of Accident Cause = (Total Contribution of Accident Cause) / (Ship number*Total year)

For example:
Probability Value of Disobey to Warning Procedure
=0.566666667/ (10*13,71)
=0.004133236

All the obtained data concerning root causes are shown in Table 1.

Table 1. *Accident Causes and Frequency of Their Occurrence*

No	Accident Causes	Frequency	Total Contribution	Probability
1	Bad Weather and Sea Conditions	2	0.366666667	0.002674447
2	Cargo Vapor / Poisonous Gas / Toxic Substance	4	0.692857143	0.005053663
3	Technical Equipment Malfunction	3	0.533333333	0.003890105
4	Oxygen Deficiency	1	0.25	0.001823487
5	Miscommunication	1	0.166666667	0.001215658
6	Risk Assessment Deficiency	4	0.733333333	0.005348894
7	Lack of Knowledge About Equipment Usage	1	0.1	0.000729395
8	Crew's Lack of Knowledge About Cargo	3	0.55	0.00401167
9	Company Staff's Lack of Knowledge About Cargo	1	0.2	0.001458789
10	Terminal Staff's Lack of Knowledge About Cargo	1	0.1	0.000729395
11	Surveyor's Lack of Knowledge About Cargo	1	0.142857143	0.001041992
12	Surveyor's Lack of Knowledge of Foreign Language	1	0.142857143	0.001041992
13	Crew's Lack of Information About Own Ship	1	0.1	0.000729395
14	Crew's Lack of Experience About Cargo	1	0.1	0.000729395
15	Lack of Experience About Used Material	1	0.166666667	0.001215658
16	Lack of Experience About Equipment Usage	1	0.1	0.000729395
17	Deficiency of Alarm System About Accident Cause	1	0.166666667	0.001215658
18	Disobey to Terminal Emergency Procedure	1	0.1	0.000729395
19	Disobey to ISPS Procedure	1	0.142857143	0.001041992
20	Disobey to Enclosed Space Entry Procedure	1	0.25	0.001823487
21	Disobey to Loading/Discharging Plan Procedure	1	0.166666667	0.001215658
22	Disobey to Sampling Procedure	2	0.392857143	0.002865479
23	Not Taking Required Safety Precautions for the Environment	1	0.2	0.001458789
24	Disobey to Warning Procedure	3	0.566666667	0.004133236
25	Disobey to Standing Orders Procedure	1	0.166666667	0.001215658
26	Disobey to Tank Cleaning Procedure	1	0.1	0.000729395
27	Disobey to Working Hours Procedure	1	0.166666667	0.001215658
28	Not Wearing Proper Personal Protective Equipment	1	0.2	0.001458789
29	Not Controlling Material Used in Port Operations	1	0.166666667	0.001215658
30	Sloppy Approach to Stowage Plan	1	0.1	0.000729395
31	Deficiency of Procedure About Accident Cause	1	0.2	0.001458789
32	Fatigue	2	0.366666667	0.002674447
33	Absence of Work Plan	1	0.2	0.001458789
34	Wrong Material Usage	1	0.142857143	0.001041992
35	Material Usage In Wrong Time	1	0.142857143	0.001041992
36	Corrosion in Cargo Pump	1	0.25	0.001823487

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Table 1. Accident Causes and Frequency of Their Occurrence (Cont')

No	Accident Causes	Frequency	Total Contribution	Probability
37	Foreign Objects in the Load Pump	1	0.25	0.001823487
38	Damage or Temporary Solutions of Load Pump	1	0.25	0.001823487
39	Reluctance to Work	1	0.166666667	0.001215658
40	Relation between Inferior and Superior	1	0.166666667	0.001215658
41	Usage of Non-Ex-Proof Material	1	0.166666667	0.001215658
42	Deficiency of Concentration	1	0.2	0.001458789
43	Deficiency of Situational Awareness	1	0.166666667	0.001215658
	Total	58	10	0.072939468

All causes and values of accidents are shown in Table 1. Three major accident results were examined and FTA of fire/explosion is shown in Figure 3; FTA of marine pollution is shown in Figure 4 and FTA of gas poisoning/asphyxia is shown in Figure 5.

Each accident analysis is evaluated within itself according to the results. After that all of them were tested with the Monte Carlo Simulation in the OpenFTA program. According to this, 23 root causes for explosion/fire accidents occurred, 10 root causes for sea pollution accidents occurred, and 13 root causes for gas poisoning or asphyxia occurred.

A variety of cut sets and probability values are obtained for the fault trees generated from the 3 accident types evaluated. Probability values and 22 minimum cut sets from 23 initial events were obtained for explosion/fire accidents. The most probable value of this minimum cut set is for Cargo Vapor/Poisonous Gas/Toxic Substance and Risk Assessment Deficiency. Probability values and 10 minimum cut sets from 16 initial events were obtained for marine pollution. The most probable value of this minimum cut set is for Disobey to Warning Procedure and Technical Equipment Malfunction. Probability values and 13 minimum cut sets from 22 initial events were obtained for gas poisoning/asphyxia. The most probable value of this minimum cut set is for Cargo Vapor/Poisonous Gas/Toxic Substance and Crew's Lack of Experience about Cargo.

All of three types of accidents were tested with Monte Carlo Simulation using Open FTA program. Contribution ratios and importance levels for each root cause were obtained.

17 failure modes from 23 initial events were found for explosion / fire accidents. Sum of failure number for these failure modes is 40. The values for these data are given in Table 2. KS-2 which is named as Cargo Vapor/Poisonous Gas/Toxic Substance has the most important and the biggest contribution.

10 failure modes from 16 initial events were found for marine pollution. Sum of failure number for these failure modes is 43. The values for these data are given in Table 3. KS-3 which is named as Technical Equipment Malfunction has the most important and the biggest contribution.

13 failure modes from 13 initial events were found for gas poisoning/asphyxia. Sum of failure number for these failure modes is 40. The values for these data are given in Table 4. KS-2 which is named as Cargo Vapor/Poisonous Gas/Toxic Substance has the most important and the biggest contribution.

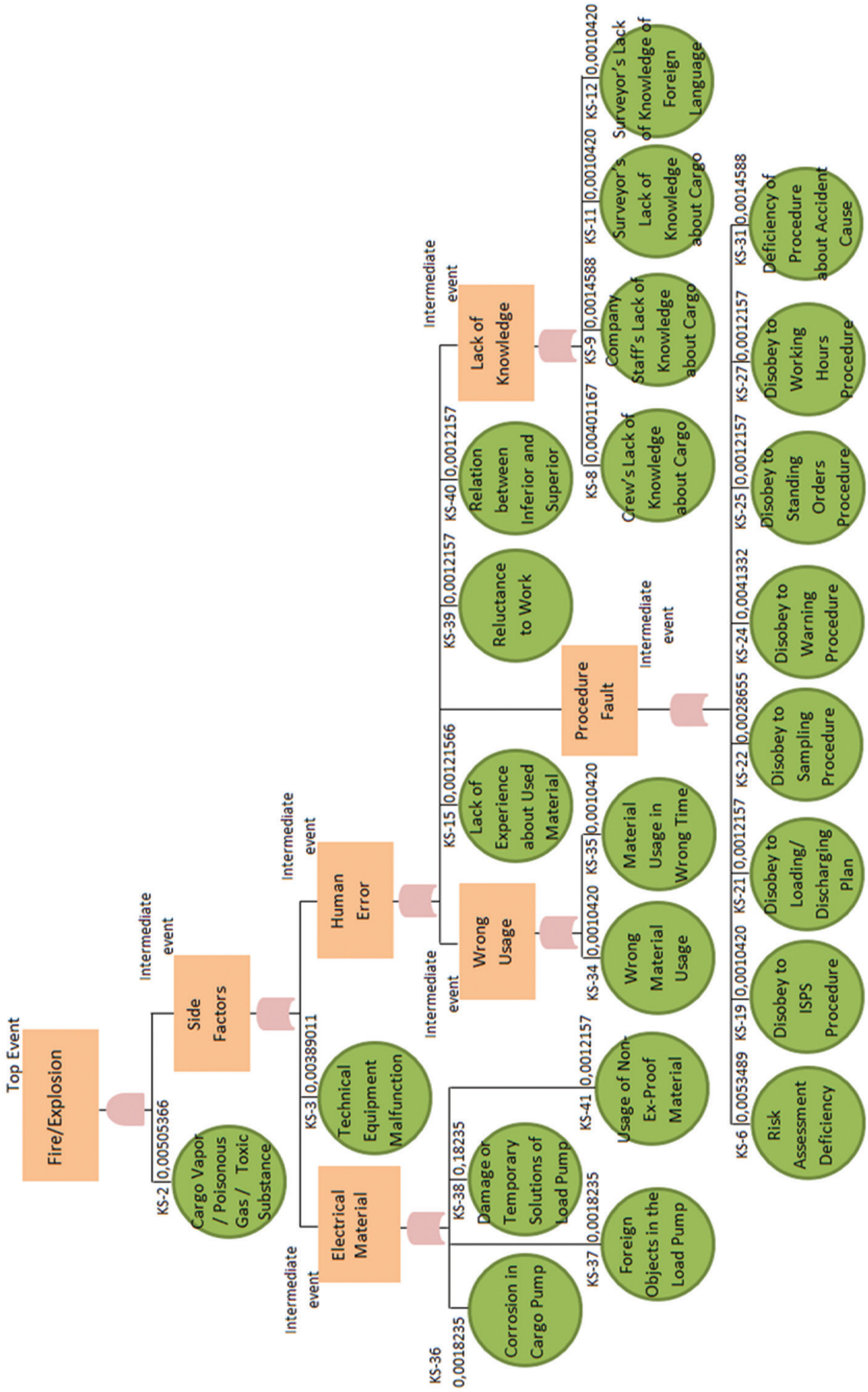

Figure 3. *Fault Tree for Fire/Explosion*

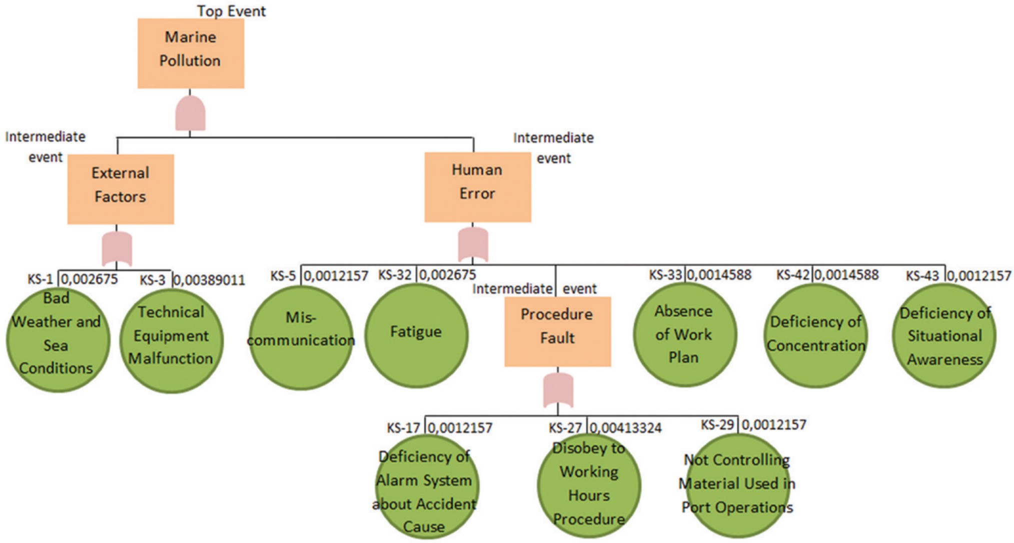

Figure 4. *Fault Tree for Marine Pollution*

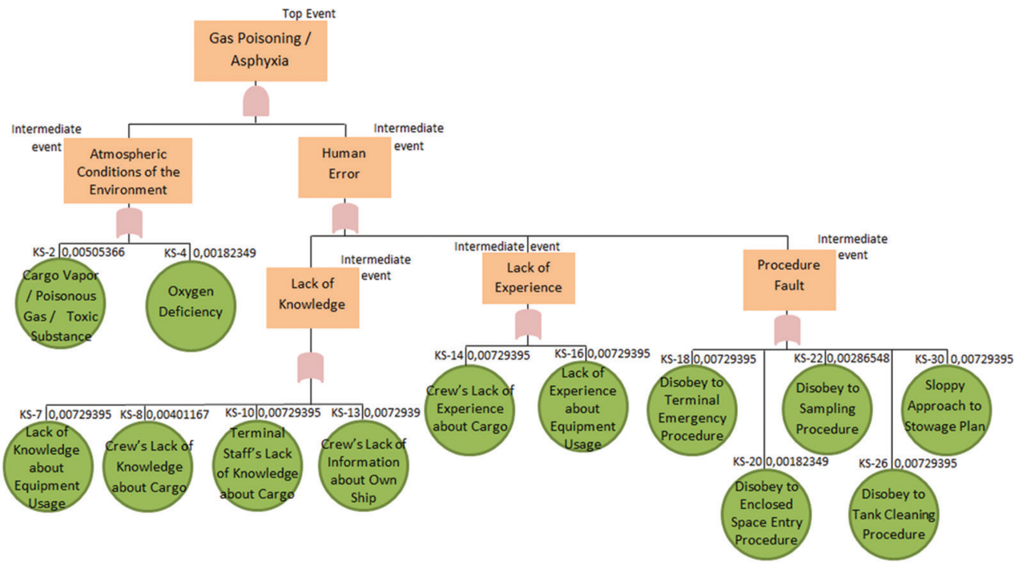

Figure 5. *Fault Tree for Gas Poisoning/Asphyxia*

Table 2. *Monte Carlo Simulation Initial Event Contribution Rates for Explosion / Fire Accidents*

No	Initial Event	Failure Contribution	Importance Level	Percentage Rate
1	KS-2	0.0001854863	100.0	50.00
2	KS-24	0.0000231858	12.5	6.25
3	KS-19	0.0000185486	10.0	5.00
4	KS-3	0.0000185486	10.0	5.00
5	KS-8	0.0000185486	10.0	5.00
6	KS-38	0.0000139115	7.5	3.75
7	KS-6	0.0000139115	7.5	3.75
8	KS-12	0.0000092743	5.0	2.50
9	KS-15	0.0000092743	5.0	2.50
10	KS-22	0.0000092743	5.0	2.50
11	KS-27	0.0000092743	5.0	2.50
12	KS-31	0.0000092743	5.0	2.50
13	KS-37	0.0000092743	5.0	2.50
14	KS-21	0.0000046372	2.5	1.25
15	KS-34	0.0000046372	2.5	1.25
16	KS-39	0.0000046372	2.5	1.25
17	KS-41	0.0000046372	2.5	1.25
18	KS-9	0.0000046372	2.5	1.25
19	KS-11	0.0000000000	0.0	0.00
20	KS-25	0.0000000000	0.0	0.00
21	KS-35	0.0000000000	0.0	0.00
22	KS-36	0.0000000000	0.0	0.00
23	KS-40	0.0000000000	0.0	0.00

Table 3. *Monte Carlo Simulation Initial Event Contribution Rates for Marine Pollution*

No	Initial Event	Failure Contribution	Importance Level	Percentage Rate
1	KS-3	0.0000607785	67.44	32.27
2	KS-24	0.0000398204	44.19	21.14
3	KS-1	0.0000335298	37.21	17.8
4	KS-32	0.0000125749	13.95	6.67
5	KS-33	0.0000104791	11.63	5.56
6	KS-42	0.0000083832	9.3	4.45
7	KS-43	0.0000083832	9.3	4.45
8	KS-17	0.0000062874	6.98	3.34
9	KS-5	0.0000062874	6.98	3.34
10	KS-29	0.0000020958	2.33	1.11

Table 4. Monte Carlo Simulation Initial Event Contribution Rates for Gas Poisoning/Asphyxia

No	Initial Event	Failure Contribution	Importance Level	Percentage Rate
1	KS-2	0.0000763745	90.0	43.902
2	KS-8	0.0000339442	40.0	19.512
3	KS-22	0.0000190936	22.5	10.976
4	KS-20	0.0000127291	15.0	7.317
5	KS-4	0.0000106076	12.5	6.098
6	KS-14	0.0000042430	5.0	2.439
7	KS-16	0.0000042430	5.0	2.439
8	KS-26	0.0000042430	5.0	2.439
9	KS-7	0.0000042430	5.0	2.439
10	KS-18	0.0000021215	2.5	1.220
11	KS-30	0.0000021215	2.5	1.220
12	KS-10	0.0000000000	0.0	0.000
13	KS-13	0.0000000000	0.0	0.000

4. Discussion and Limitations

In this study, reports in between 2000 and 2014 of IMO (International Maritime Organization) GISIS (Global Integrated Shipping Information System), MAIB and Maritime Safety Authority of New Zealand and others were investigated. But the study was limited due to the insufficient and incomplete data in the reports published by these organizations and other reviewed organizations. Therefore, this is the main limitation of this research work. In addition, collecting data from legal sources and filtering the issues with comprehensive precision results in a small number of comprehensive analyses of accident events. This is another limitation because study requires a larger sampling.

In this research, a total of 10 vessel accidents involving the appropriate data were analyzed and classified according to the results. There are 4 type of accident results. There are 5 fire/explosion accidents, 2 marine pollution accidents, 2 gas poisoning/asphyxia accidents and 1 personal injury accident due to sudden fluid flow. The most important and the biggest contribution to occurrence of human error in these types of accidents are negligence of rules, lack of information, poor training and fatigue. These results in the study are similar to the previous studies. In the study about of human error in marine incidents conducted by Mokhtari and Khodadadi Didani in 2013 [11], 1816 accidents were investigated and 17 factors are known to be effective in occurrence of human error in these accidents. The four most important factors of them are listed as follows negligence, poor training, inadequate tools, and lack of skill and experience. Another similar study of human error was written by Antao and Soares in 2006 [10]. This study about collision of ro-ro vessels for cargo and passengers shows that human factor is the dominant factors towards the accidental event. This contribution is a change of almost 90% in the probability of the occurrence of these terminal events for groundings and collisions. Another study about human error was written by Uğurlu et al. [18] in 2015. According to the results of study on collision and grounding in oil tanker, the main reason for the accidents originating from human error is as follows: for collision accidents, Convention on the

International Regulations for Preventing Collisions at Sea (COLREG) violation and the lack of communication between vessels; and for grounding accidents, the interpretation failure of the officer on watch and lack of communication in the bridge resource management.

5. Conclusion

Some of examinations of the reports of the accidents that occurred during the loading and unloading operations at the tanker terminals are listed below:

- 10 ship accident reports were examined in detailed. 4 of Malta, 2 of Norway, 1 of Hong Kong, Chile and Man Island are flagged. 1 flag of ship is not specified.
- When the root causes of the accidents were handled one by one, the root causes with the greatest number which had the same number of repetitions are Risk Assessment Deficiency and Cargo Vapor / Poisonous Gas / Toxic Substance.

It is seen that causes of the accidents occurred in the vessels at the tanker terminals are human errors which is the most important factor and other factors. At the end of this work, some suggestions for reducing the number of similar incidents on ships at tanker terminals are listed below:

- To increase awareness of human factor on ship accidents, scientific studies should be increased and supported by the elements in the industry such as companies and institutions. At this stage, the idea that the accidents will create a bad image for the companies should be torn down and it should be reminded that each accident is a preventive element in future accidents.
- Standardization should be established on the reporting of accidents so that sea accidents can be assessed correctly and their re-occurrence can be avoided. Under these standards, information about ships and accident should be provided; accidents should be analyzed by appropriate analysis methods; possible root causes of the accidents and their preventive activities should be defined.
- In the case of work intensity, a correct work plan should be made. This should be done considering the level of importance of the work, the size of the job and other circumstances.
- To provide and enhance the knowledge and experience of the seafarers about the system, the necessary formations should be provided. For this, the units in the sector should work together. Education departments or schools should establish training programs on these topics and increasing experience of the seafarers by necessary simulations must me aimed.

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