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Simulation Analysis for Risk Assessment of Explosions in a Series of Fuel Tanks

Mehmet Savsar

Üsküdar University, Faculty of Engineering and Natural Sciences, Department of Industrial Engineering
Üsküdar, Istanbul, Turkey

(mehmet.savsar@uskudar.edu.tr)

Abstract – This paper presents a risk assessment approach for the case of possible explosions in a series of tanks. Explosion occurs in a tank and spreads to the adjacent or neighboring tanks with certain probabilities. An excel simulation procedure is applied to a case problem with a series of three tanks and the level of risks involved is determined with possible monetary loss values. The simulation is a useful tool for risk assessment of such cases and can be applied to other related problem areas in industry.

Keywords – Risk Assessment, Fuel Storage, Tank Explosions, Hazard Analysis, Safety Evaluation

I. Introduction

Intense fuel and gas consumption all over the world has necessitated storage facilities for this material. Gas tanks, such as TNT tanks, LPG tanks, and other types of chemical tanks, are important storage facilities in chemical enterprises. However, these facilities usually have the risks of explosions, which can result in severe material damage, monetary losses, and life related casualties. It is important to be able to evaluate and estimate possible risks involved with these types of chemical storage systems. Also, risk management has become necessary for security management of different fuel tanks and depots as a result of the continuous increase in their total capacities. Quantitative risk assessment is an essential procedure that must be carried out in the design and operation stages of these explosive tank systems.

Literature is replete with research papers and reports on risk assessment of the use of explosive tanks in industry. Bendixen and O'Neill (1984) presented an analysis of chemical plant risk assessment using HAZOP and fault tree methods. Ozog (1985) presented a systematic way to assess potential hazards to promote safer design for operation of new and existing plants. Ozog and Bendixen (1987) used fault tree analysis in hazard identification and quantification for risk assessment. Chang and Lin (2005) presented a study of accidents that could occur in storage tanks. Dunjó et al. (2009) presented a literature review of hazard and operability (HAZOP) analysis. Casamirra et al. (2009) studied safety of a hydrogen refueling station and analyzed occurrence frequency of different accident scenarios. Kim, et al. (2011) discussed the development of Korean hydrogen fueling station codes through risk analysis. Persson (2014) analyzed fire incidents in tank fires that have occurred. Gholamnia, et al.(2015) presented a fuzzy risk assessment model of fire and explosions in the crude oil storage tanks by using fuzzy hierarchical analysis.

Zengin, et al. (2015) presented the case of a fire disaster caused by LPG tanker explosion at Lice in Diyarbakır, Turkey. They have discussed the casualties and related problems in such an explosion. Zhang et al. (2016) applied Fault Tree Analysis (FTA) and Analytic Hierarchy Process (AHP) for the risk assessment of accidents in fire and explosion accidents of steel oil tanks for crude oil storage. Attanayake, et al. (2019) presented a methodology for quantifying the explosion risk associated with atmospheric liquid fuel storage tanks. They have utilized bowtie and fault-tree analysis to study possible threats that could lead to an explosion and influence of preventive and protective measures were determined. Zhang, et al. (2019) presented a risk evaluation and analysis of a gas tank explosion. A specific program, called FLACS is used to evaluate the risk and the consequences of explosions of a 50,000 m3 gas tanks. ZHAO et al. (2020) also presented a risk evaluation procedure of fire and explosion accidents in oil tank zones. Sevim, A. (2022) presented a risk assessment study and evaluation of hexane storage tank in a sunflower oil plant. Ramezanifar et al. (2023) studied the risk assessment of methanol storage tank fire accident using hybrid FTA (Fault Tree Analysis)-SPA (Set-Pair Analysis).

In this paper, risk assessment of a case of a series of fuel tanks has been considered. A simulation model is developed to assess the expected risks involved in possible explosions and the resulting monetary losses. The simulation procedure is implemented in excel, which facilitates its ease of use in similar applications. In the next section, the possible explosions of the tanks and the interaction between them are explained.

II. Fuel Storage Tank System

The series of tank systems considered in this study is shown in Figure 1. Based on the past experience, and the data related to fuel leakage from the tanks and related resulting series of explosions, the following estimations have been obtained. According to the past experience, gas leakage and ignition almost always starts from the first tanks, which may reach to the second, and then to the third tank with certain percentages. Thus, the analysis presented here is based on the series of possible explosions starting from the first tank. Data are based on the explosions in tanks over a six-month period; numbers of explosions, which start from the first tank follow a uniform distribution. The probability of gas leakage and explosion varies between 0 and 1 times per six months in the ***first tank*** [uniform (0, 1)]. Gas leakage and flammability are classified with 3 ***severity levels*** as ***heavy***, ***medium*** and ***light***. A severity level of 9 is assigned to heavy penetration or ignition, 3 to medium, and 1 to light. The probabilities of these explosion levels were estimated as 0.10, 0.20, and 0.70, respectively. In addition, according to the explosion or flame level situation in each tank, it has been observed that the material damage complies with the normal distribution (the amounts of damage are given in dollars). The amount of material damage in monetary value is proportional to the severity level with the mean value of the normal distribution being μ=5000*severity level; and the standard deviation is approximated by σ=0.2*average damage value.

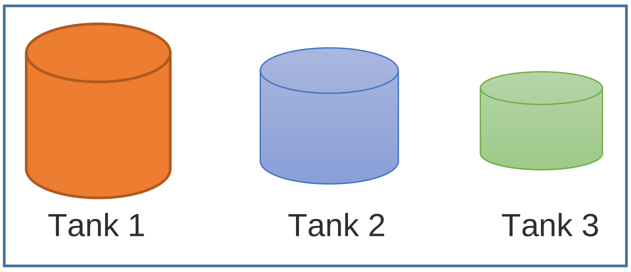

Figure 1. Tank system series studied in the study.

When the first tank leaks and explodes, the probability of the explosion reaching the ***second tank*** is estimated to be 0.25. Explosion severity levels in the second tank are also classified as three values (3, 2, and 1) with the same probabilities as in the first tank. The damage value is normally distributed with less average value, which is estimated as μ=3000*severity level; and standard deviation as σ=0.2*average value. The probability of the explosion reaching to the ***third tank*** is 0.10, while the explosion level (levels 3, 2, and 1) probabilities are still the same as the previous tank, with normally distributed monetary damage value and with much smaller parameters as μ=1000*severity level; standard deviation as σ=0.2*average value. It is required to estimate the monetary damage values that may be experienced from possible explosions of any tank in this series of three-tank system. In particular, average semiannual material loss for the next 10 years was required to be estimated with 95% confidence level. A simulation model was constructed and run on excel to estimate the required damage and losses due to possible explosions of these fuel tanks. Next section explains the simulation results.

III. Risk Analysis of the System by Simulation

Simulation is a powerful and essential tool in analyzing risk assessment problems because of complex randomness in the systems. Therefore, we have used simulation for the analysis of the tank system presented in section 2 to assess the risks involved and the incurred material losses. Excel has some powerful functions for generating random numbers from both empirical distributions and the specific distributions, such as the normal distribution. In case of empirical distributions, we use the empirical data and the excel function VLOOKUP, while for the uniform distribution we use the inverse transformation. For example, for a random variable following uniform distribution between A and B, the probability distribution function (pdf) and the cumulative probability distribution function (cdf) are given as follows:

Probability distribution function: f(x)=1/(B-A)
Cumulative distribution function F(x)=(X-A)/(B-A)

Since 0≤F(x) ≤1, we set F(x)=U, where U is a random number generated in excel between 0 and 1, and find the value of X by inverse transformation as:

X=A+(B-A)*U

In case of normal distribution, we use the excel function NORMINV(U, μ, σ) function to generate a normally distributed variable with mean=μ and standard deviation=σ using again the inverse transformation built in excel, by providing a uniform random number U between 0 and 1. Excel can generate U by the built in function =RAND() Based on these random number generations, it was possible to generate all related random data for the tank explosions and the resulting monetary losses. Tables 1, 2, and 3 provide one excel result for 20 six-months periods of simulation. The tables are parts of the complete excel simulation model. Because of the size of the excel sheet, each tank's results are shown on different tables here. However, the results of each table affect the values in other tables. These tables are only the results of a single sample of size 20, which are repeated n=30 times to obtain the average results as will be discussed later in the section. The data provided on the upper left corner of the table is the cumulative probability range for the severity level of leakage and explosions in each tank. Number of accidents, types of accidents, mean and standard deviation of the monetary losses in each accident and the total cost of each accident are given in different columns of the table. The last column in Table 3 gives the grand total damage costs for all three tanks. The simulation procedure in steps is as follows:

1. Generate semiannual number of explosions of the first tank, if any, as given in column 3.
2. Generate type of accident (3, 2, 1) with severity levels of 9, 3, and 1 (column 5).
3. Generate the mean and standard deviation of the monetary loss (column 6 and 7)
4. Generate the total loss value for the first tank (column 9)
5. Determine the possibility if explosion reaches to tank 2 (column 3 of Table 2)
6. Generate severity level of the explosion in the second tank (column 5 of Table 2)
7. Generate the average and the standard deviation of the loss values (column 6, 7)
8. Generate total loss in explosion, if any, of tank 2 (column 9)
9. Repeat steps 5-8 for tank 3 in columns 2-9 of Table 3.
10. Calculate the grand total loss values for all tanks (column 10 of Table 3)

The columns with the title RAND in each case are uniform (0-1) random numbers used to generate the needed variables by inverse transform given in the following columns. To obtain reliable results from highly random simulation outputs, a concept from the Central Limit Theorem (CLT) is utilized.

Table 1. Simulation results for Tank 1 explosions and costs

0	0.1	9	Heavy					
0.1	0.3	3	Medium					
0.3	1	1	Light					
					Mean 5000*Type			
					Std. Dev.=0.2*Mean			
		Uniform			Normal Dist Cost			
Half Year No.	RAND	Number of Accidents	RAND	Accident Type Tank-1	Mean=5000*Type Mean Cost	Std.Dev=0.2 Mean Std. Dev. Cost	RAND	First Tank Cost
1	0.431	0.00	1.00	0	0	0	0.7014	0.00
2	0.256	0.00	0.15	0	0	0	0.8765	0.00
3	0.708	1.00	0.84	1	5000	1000	0.3916	4724.92
4	0.291	0.00	0.51	0	0	0	0.1972	0.00
5	0.875	1.00	0.84	1	5000	1000	0.5849	5214.55
6	0.682	1.00	0.80	1	5000	1000	0.9915	7386.39
7	0.834	1.00	0.91	1	5000	1000	0.8625	6091.41
8	0.142	0.00	0.45	0	0	0	0.6276	0.00
9	0.118	0.00	0.10	0	0	0	0.0957	0.00
10	0.717	1.00	0.60	1	5000	1000	0.1189	3819.74
11	0.834	1.00	0.83	1	5000	1000	0.8476	6026.02
12	0.084	0.00	0.53	0	0	0	0.4802	0.00
13	0.275	0.00	0.56	0	0	0	0.2523	0.00
14	0.460	0.00	0.08	0	0	0	0.3590	0.00
15	0.573	1.00	0.55	1	5000	1000	0.4111	4775.32
16	0.991	1.00	0.44	1	5000	1000	0.7223	5589.63
17	0.787	1.00	0.70	1	5000	1000	0.3152	4518.96
18	0.477	0.00	0.35	0	0	0	0.3450	0.00
19	0.380	0.00	0.84	0	0	0	0.5008	0.00
20	0.479	0.00	0.26	0	0	0	0.4072	0.00

Table 2. Simulation results for Tank 2 explosions and costs

		Accident (Yes/No)
0	0.25	0
0.25	1	1

Mean 3000*Type
Std=0.2*Mean
Normal Dist Cost
Mean= Std. Dev.=

Half Year No.	RAND	Second Tank Accident (Yes/No)	RAND	Accident Type Tank 2	3000*Type	0.2*Mean	RAND	Second Tank Cost
1	0.4388	0	0.8740	0	0	0	0.4968	0.00
2	0.3873	0	0.2899	0	0	0	0.3831	0.00
3	0.7756	1	0.8933	1	3000	600	0.9182	3835.98
4	0.6095	0	0.4001	0	0	0	0.4129	0.00
5	0.0070	0	0.3699	0	0	0	0.0601	0.00
6	0.1612	0	0.9353	0	0	0	0.0839	0.00
7	0.4984	0	0.8780	0	0	0	0.2523	0.00
8	0.6401	1	0.5077	1	3000	600	0.4651	2947.43
9	0.6619	0	0.9652	0	0	0	0.3868	0.00
10	0.9799	0	0.7245	0	0	0	0.1745	0.00
11	0.6582	0	0.3310	0	0	0	0.5114	0.00
12	0.4152	0	0.4846	0	0	0	0.2251	0.00
13	0.0169	0	0.2312	0	0	0	0.6613	0.00
14	0.7860	0	0.0699	0	0	0	0.2069	0.00
15	0.0965	0	0.9402	0	0	0	0.2383	0.00
16	0.3976	0	0.8224	0	0	0	0.8030	0.00
17	0.5334	1	0.6746	1	3000	600	0.5059	3008.93
18	0.9545	0	0.4401	0	0	0	0.1939	0.00
19	0.9231	0	0.3538	0	0	0	0.2941	0.00
20	0.3013	1	0.7829	1	3000	600	0.3219	2722.58

CLT states that no matter what type of distribution the population variable follows, averages of the n samples taken from such a population (with mean μ and standard deviation σ) follows normal distribution with a mean as the population mean μ, and standard deviation as $\sigma/\sqrt{n}$. Thus, the variability in the sampling process is reduced in this way.

Table 3. Simulation results for Tank 3 explosions and damages

		Accident (Yes/No)
0	0.1	0
0.1	1	1

Mean 1000*Type
Std=0.2*Mean
Normal Dist Cost

Half Year No.	RAND	Third Tank Accident (Y/N)	RAND	Accident Type Tank 3	Mean= 1000*Type	Std. Dev= 0.2*Mean	RAND	Third Tank Cost	Total Expected Cost
1	0.2693	1	0.2831	3	3000	600	0.5120	3018.09	12280.31
2	0.6333	1	0.7282	1	1000	200	0.6414	1072.42	9008.70
3	0.1336	0	0.2310	0	0	0	0.4915	0.00	0.00
4	0.3261	0	0.8470	0	0	0	0.7779	0.00	0.00
5	0.4906	0	0.2813	0	0	0	0.9281	0.00	0.00
6	0.1620	0	0.1643	0	0	0	0.9728	0.00	0.00
7	0.5958	1	0.1639	3	3000	600	0.7045	3322.39	30223.00
8	0.6941	0	0.5702	0	0	0	0.1116	0.00	0.00
9	0.2275	0	0.4897	0	0	0	0.9432	0.00	0.00
10	0.0945	0	0.3205	0	0	0	0.8434	0.00	17274.84
11	0.8772	0	0.8421	0	0	0	0.8665	0.00	0.00
12	0.4668	0	0.2770	0	0	0	0.9909	0.00	0.00
13	0.3706	1	0.2028	3	3000	600	0.6419	3218.13	12709.58
14	0.4160	0	0.2251	0	0	0	0.6021	0.00	0.00
15	0.7730	0	0.8284	0	0	0	0.8801	0.00	0.00
16	0.6401	0	0.5859	0	0	0	0.0927	0.00	0.00
17	0.6957	0	0.1514	0	0	0	0.8511	0.00	18976.65
18	0.7116	1	0.5522	1	1000	200	0.3068	899.00	16832.64
19	0.5673	0	0.3910	0	0	0	0.6941	0.00	0.00
20	0.0543	0	0.6309	0	0	0	0.3107	0.00	18787.80

Table 4 shows 30 sample means taken from the total cost population as obtained by simulation. The average of the means of these samples of size 20 is calculated, and a confidence interval is obtained as follows:

Average of means of 30 samples, X=9593.95 dollars
Standard deviation S =3046.82 dollars

Confidence intervals on the population mean are obtained by $\mu \pm Z_{\alpha/2}\, \sigma/\sqrt{n}$, where population mean μ is estimated by the average of the sample means and population standard deviation σ is estimated by standard deviation of the sample means S. $Z_{\alpha/2}$ corresponds to the Z value obtained from the normal distribution with 1-α percent area within the limits. Thus the 95% confidence interval on the average total damage cost would be calculated as follows:

$$[9593.95 \pm 1.96*3046.82/\sqrt{30}], \text{ which is: } [9593.95 \pm 1090.29] \text{ or } [\mathbf{\mathit{8503.66, 10684.24}}].$$

Thus, the probability that the total cost will be between 8503.66 dollars and10684.24 dollars is 95%. We are 95% sure that the average 6-months cost will be within these limits. Note that the half width (h) of the confidence interval here is $Z_{\alpha/2}\, \sigma/\sqrt{n}=1090.29$. If one wants to reduce this half width to obtain more accurate results, more simulation runs must be performed.

Let $h=Z_{\alpha/2}\, \sigma/\sqrt{n}$; $h_0= Z_{\alpha/2}\, \sigma/\sqrt{n_0}=1090.29$

Suppose $h_1=1/2(h_0)$ is required. Then $h_0/h_1= (Z_{\alpha/2}\, \sigma_1/\sqrt{n_0})/(Z_{\alpha/2}\, \sigma_0/\sqrt{n_1})$. Assuming σ_1 is estimated by σ_0 obtained from the initial n_0 runs; then, to reduce the half width by 1/2,

$$n_1=(n_0)(h_0/h_1)^2=30*(2)^2=30*4=120$$ runs is needed.

Table 4. Total costs for 30 samples of size 20.

Sample of 20	Mean	Sample of 20	Mean	Sample of 20	Mean
1	11,691.23	11	9313.19	21	7242.85
2	10,003.66	12	4645.92	22	5671.16
3	5,013.54	13	11800.05	23	4514.46
4	5,661.13	14	11685.59	24	7710.54
5	9,459.00	15	5261.16	25	11384.75
6	9,729.81	16	9255.33	26	7322.57
7	15,468.41	17	13845.28	27	11316.45
8	8,575.71	18	13386.83	28	7619.93
9	9,543.90	19	8195.27	29	14015.72
10	12,775.37	20	7559.75	30	7911.01

Suppose that a half width or an accuracy of ±100 dollars is required in estimation results; then the number of runs required would be about:

$$n_1=(n_0)(h_0/h_1)^2=30*(1090.29/100)^2=3566 \text{ runs}$$

Simulation is a useful tool in these types of analysis and can provide useful results if sufficient numbers of runs are made in estimating the mean values.

IV. CONCLUSIONS

One of the problems faced in industry is the safe storage of fuel tanks, which are prone to explosions. If a series of such tanks are stored close to each other due to excessive storage requirements, it becomes essential to study and analyze the risks involved in these systems. This paper considers a tank system, which includes three tanks of different sizes that are placed next to each other and have effects on one another if gas leakage and ignition starts in one of them. This is a typical case that can be seen in industry frequently. A simulation modeling procedure is shown and applied to the case problem to determine the risks involved, which is measured in monetary losses. These losses could include casualties if it applies. Simulation proved to be a very useful tool in these types of analysis since there is too much variability and randomness in the events that could occur. The procedure is based on excel and could be easily applied to other case problems by safety engineers and managers.

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