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Comparative analysis of individual risk using different Probit functions in estimating heat radiation consequences

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Abstract. The impact of technological processes on the environment has become a particular problem of the process industries and due to the complexity of operating conditions, severe industrial accidents can occur with major consequences on the environment and especially on local communities located close to industrial areas and plants. An important contribution to the number of major accidents in the oil and gas processing industries is represented by the oil spills, followed by fires and explosions. In this case, the production process involves significant amounts of flammable hydrocarbons stored in large tanks. This paper presents a comparative analysis of the consequences of thermal radiation on the population and provides individual risk calculations using different Probit functions proposed in the literature. By comparing the results of the case study, it can be concluded that the use of different Probit functions in consequence estimation does not influence significantly the risk levels, but the use of the new Probit functions proposed by Pérez et al (2009) shows more conclusive and closer to reality results.

Key Words: thermal radiation, environment, industrial accident, oil spills.

Introduction. Industrial plants located near residential areas have produced over time major accidents with severe consequences on the population, leading to the adoption of the Directive 2012/18/EU, named Seveso III Directive, concerning the control of major accident risks, involving hazardous substances (Ozunu 2013).

The chemical process industry is characterized by the use, processing and storage of large amounts of dangerous chemical substances and/or energy. In the processing of the hydrocarbons, spills of flammable substances from pipes or storage tanks may occur, which can cause fires and explosions (Nivolianitou et al 2012).

The effects of a fire are represented by the thermal radiation, which can cause burns on unprotected skin if the intensity increases and the exposure time is sufficient. The burns caused by a fire are classified in first, second and third degree burns. A first degree burn is superficial and is characterized by a red, dry and painful skin. The second degree burn affects the epidermis and dermis and is characterized by blister formation and a wet and red skin. The third degree burns affect the dermis and hypodermis, skin tissue and structures being destroyed (Van den Bosch & Twilt 1989).

In a quantitative risk-analysis, the level of the damage is determined by the magnitude of the consequences (Török et al 2009). The analysis of the probability of consequences is performed using Probit functions, being expressed as a relationship between the intensity of the thermal radiation and exposure time (Uijt de Haag & Ale 2005).

In different sources of literature different Probit functions are proposed for the same types of burns, which can lead to a different assessment of the fires consequences. The aim of the study is a comparative analysis of the Individual Risk using different Probit function proposed in the literature (Pérez et al 2009; Van den Bosch & Twilt 1989) for estimating fires consequences.

Material and Method. The thermal radiation consequence assessment was performed as follows. The calculation of the Individual Risk involves the calculation of the probability of death of a person at a given exposure. The probability of death (Pd) is calculated using Probit functions. The relation between the probability of an effect (P) and the corresponding Probit function (Pr) is given by equation 1 (Uijt de Haag & Ale 2005):

$$P = 0.5 \cdot \left[1 + erf\left(\frac{\mathrm{Pr} - 5}{\sqrt{2}}\right)\right] \quad \text{(eq. 1)}$$

where: Pr – Probit function and erf(x):

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2}\, dt \qquad \text{(eq. 2)}$$

Probit functions allow the correlation of the effect of thermal radiation to the percentage of people affected for a certain level of damage (first, second and third degree burns) (Pérez et al 2009). TNO's experts proposed the following Probit functions to calculate the percentage of the population affected by thermal radiation from hydrocarbon fires (Van den Bosch & Twilt 1989):
-for first degree burns:

$$Pr = -39.83 + 3.0186 \cdot \ln\left(t \cdot q^{4/3}\right) \quad \text{(eq. 3)}$$

-for second degree burns:

$$Pr = -43.14 + 3.0186 \cdot \ln\left(t \cdot q^{4/3}\right) \quad \text{(eq. 4)}$$

-for third degree burns:

$$Pr = -36.38 + 2.56 \cdot \ln\left(t \cdot q^{4/3}\right) \quad \text{(eq. 5)}$$

where: q – heat radiation (W/m2)
t – exposure time(s).

Using empirical information, new Probit Functions were proposed by Pérez et al (2009) to estimate the fire consequences (first and second degree burns):
-for first degree burns:

$$Pr = -11.65 + 6.95 \cdot \log\left(t \cdot q^{4/3}\right) \quad \text{(eq. 6)}$$

-for second degree burns:

$$Pr = -13 + 6.95 \cdot \log\left(t \cdot q^{4/3}\right) \quad \text{(eq. 7)}$$

where: q – heat radiation(kW/m2)
t – exposure time(s).

No empirical data have been found for third degree burns, therefore no alternative equation was proposed; for consequence calculations the equation proposed by TNO will be used.

The case study considers a petrochemical site in Romania, which lies on an area of approximately 200 hectares and is located on the outskirts of a city. For the comparative consequence assessment of thermal radiation from fires a retention vat containing two n-hexane storage tanks was considered, with storage capacities of 800 m^3 and 2000 m^3 and total amount of 1320 tons. The area of the retention vat is 1740 m^2. N-hexane is a highly flammable hydrocarbon (Gheorghiu et al 2014).

The meteorological conditions considered in the case study are: wind speed of 4 m/s; ambient temperature 20°C; atmospheric stability class D (Pasquill classification).

Results and Discussion

Accidental scenarios considered in the risk calculation for the n-hexane storage involves catastrophic tank rupture from internal causes and the release of the entire amount of substance.

The top event scenario was analyzed using the ET (Event Tree), resulting two scenarios in which the accident may lead to severe consequences with burns (Poolfire and Flash Fire) (Sklet 2006). The frequencies of Poolfire and Flash Fire scenarios (Table 1) were calculated using the ET (Figure 1) using the top event frequency of 5×10^{-6} y^{-1} (Uijt de Haag & Ale 2005) and the probability values for conditioning events (Mannan 2005) (Table 2).

Table 1

Frequency calculations for the possible scenarios

Scenario	*Frequency*
Extinguished fire	$F_1 = 5 \times 10^{-6} \times 0.1 \times 0.88 = 4.44 \times 10^{-7}$
Pool fire	$F_2 = 5 \times 10^{-6} \times 0.1 \times 0.1125 = 5.625 \times 10^{-8}$
Release and evaporation	$F_3 = 5 \times 10^{-6} \times 0.9 \times 0.5 = 2.25 \times 10^{-6}$
Flash fire	$F_4 = 5 \times 10^{-6} \times 0.1 \times 0.5 = 2.50 \times 10^{-7}$

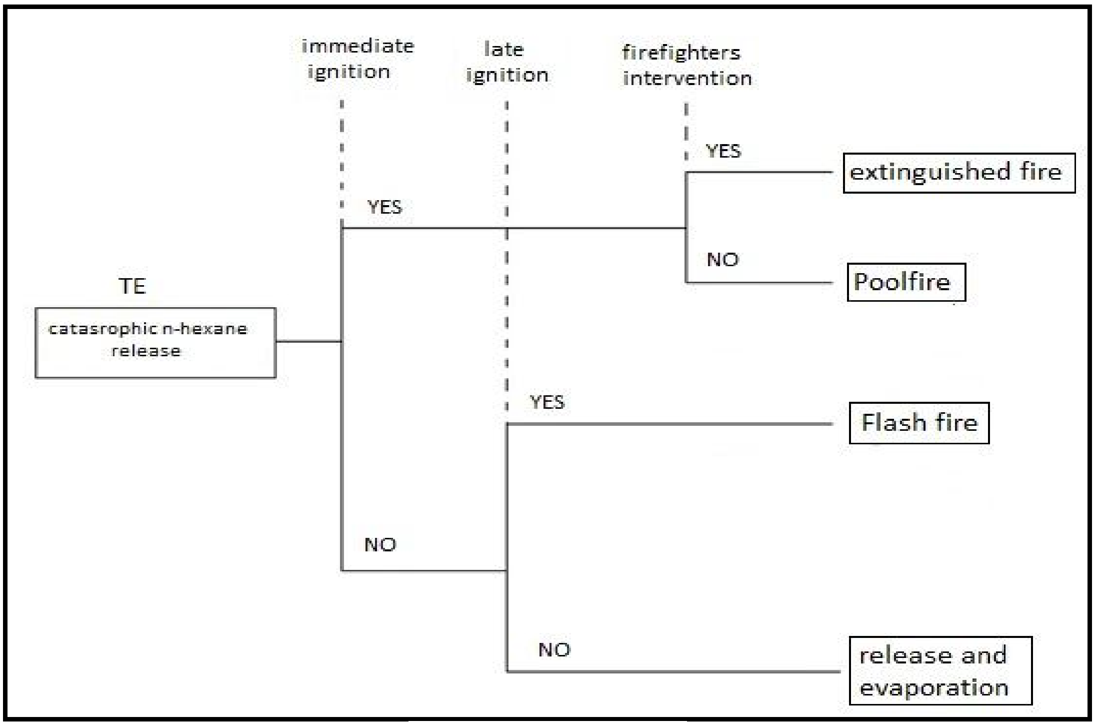

Figure 1. Event tree.

Table 2

Probability values for conditioning events (CEs) (Mannan 2005)

Conditioning event (CE)	*Probability values*
Immediate ignition	0.1
Late ignition	0.5
Firefighters intervention	0.88
Assets or persons in the affected area	0.5
Fatalities in case of exposure	0.5

The physical effects (heat radiation vs. distance) of the possible accidents that could result from the spill of n-hexane were calculated using EFFECTS software from TNO (TNO 1989).

The consequences of the scenarios were calculated using the Probit functions presented in section 2. From conservative reasons the exposure time is considered to be 20 s in all the calculations (Uijt de Haag & Ale 2005).

For each type of burns is calculated the percentage of the population affected by different doses of thermal radiations versus distance. The results are shown in Table 3.

Table 3

Probability of burns - P_b (I^{st}, II^{nd}, III^{rd}) vs. distance using different Probit functions – Pr_{TNO} and $Pr_{Pérez}$

		TNO						Pérez et al (2009)			
D (m)	Q (w/m^2)	Pr_{TNO} (I^{st})	Pr_{TNO} (II^{nd})	Pr_{TNO} (III^{rd})	P_b (I^{st})	P_b (II^{nd})	*P_b (III^{rd})	$Pr_{Pérez}$ (I^{st})	$Pr_{Pérez}$ (II^{nd})	P_b (I^{st})	P_b (II^{nd})
25	16250	8.24	4.93	4.38	1.00	0.47	0.27	8.61	6.39	1.00	0.92
30	13000	7.34	4.03	3.62	0.99	0.17	0.08	7.71	5.49	1.00	0.69
35	11000	6.67	3.36	3.05	0.95	0.05	0.03	7.04	4.82	0.98	0.43
40	9500	6.08	2.77	2.55	0.86	0.01	0.01	6.45	4.23	0.93	0.22
45	8250	5.51	2.20	2.07	0.69	0.00	0.00	5.88	3.66	0.81	0.09
50	7150	4.93	1.62	1.58	0.47	0.00	0.00	5.31	3.09	0.62	0.03
55	6250	4.39	1.08	1.12	0.27	0.00	0.00	4.77	2.55	0.41	0.01
60	5250	3.69	0.38	0.53	0.09	0.00	0.00	4.07	1.85	0.18	0.00
65	4500	3.07	-0.24	0.00	0.03	0.00	0.00	3.45	1.23	0.06	0.00
70	3750	2.34	-0.97	-0.62	0.00	0.00	0.00	2.71	0.49	0.01	0.00
75	3100	1.57	-1.74	-1.27	0.00	0.00	0.00	1.95	-0.25	0.00	0.00

*Pd (III^{rd}) is the same in both cases, using the Probit function proposed by TNO.

It can be observed for some thermal radiation values that the sum of percentage of first, second and third degree burns is higher than 100%. This is due to the fact that an accident causes victims in different classes of injuries and the fraction of victims in a class of injury is also included in all subsequent classes. For example, the population affected by third degree burns is also affected by first and second degree burns. Therefore, the actual percentage of the population affected by second degree burns must be obtained by discounting the percentage of population suffering third degree burns from the total amount of population suffering second degree burns. In the same way the actual percentage of population affected only by first degree burns must be obtained by discounting the actual percentage of population suffering second degree burns (obtained after the above calculation) from the total amount of population suffering first degree burns (Pérez et al 2009).

Table 4

Corrected percentage of burns versus distance using different Probit functions

d[m]	Burns (TNO)				Burns (Pérez et al 2009)			
	Burns % 1^{st} degree	Burns % 2^{nd} degree	Burns % 3^{rd} degree	Total burns %	Burns % 1^{st} degree	Burns % 2^{nd} degree	Burns % 3^{rd} degree	Total burns %
25	52.9	20.2	26.9	99.9	8.2	64.9	26.9	100
30	82.5	8.1	8.4	99.0	30.7	60.5	8.4	99.7
35	90.2	2.4	2.6	95.2	55.0	40.4	2.6	97.9
40	84.6	0.6	0.7	85.9	70.5	21.4	0.7	92.7
45	69.2	0.1	0.2	69.4	72.1	8.9	0.2	81.2
50	47.3	0.0	0.0	47.3	59.3	2.8	0.0	62.1
55	27.1	0.0	0.0	27.1	40.1	0.7	0.0	40.8
60	9.5	0.0	0.0	9.5	17.4	0.1	0.0	17.5
65	2.7	0.0	0.0	2.7	6.0	0.0	0.0	6.0
70	0.4	0.0	0.0	0.4	1.1	0.0	0.0	1.1
75	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1

Table 4 presents the corrected results for the population affected by first, second and third degree burns.

Figure 2 and 3 represents the percentage of burns versus distance obtained using the Probit functions proposed by TNO (1989), and Pérez et al (2009) respectively.

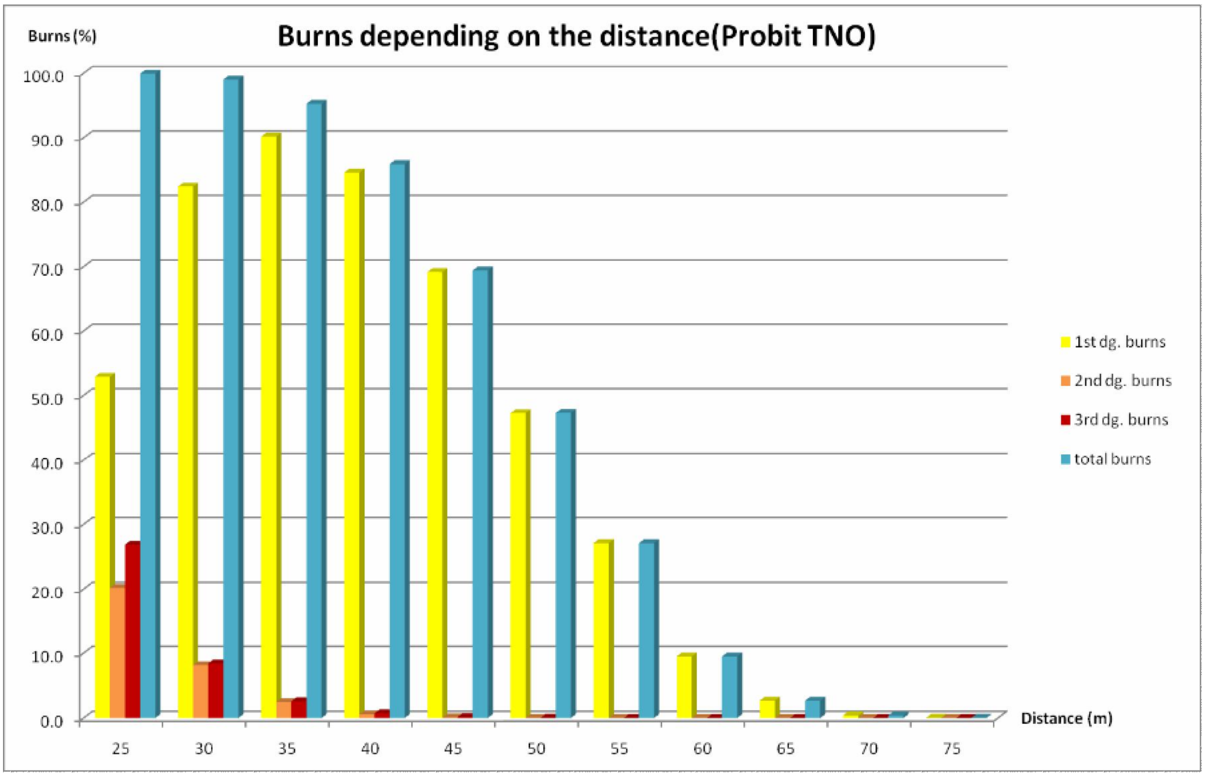

Figure 2. Percentage of burns versus distance – Probit function from TNO.

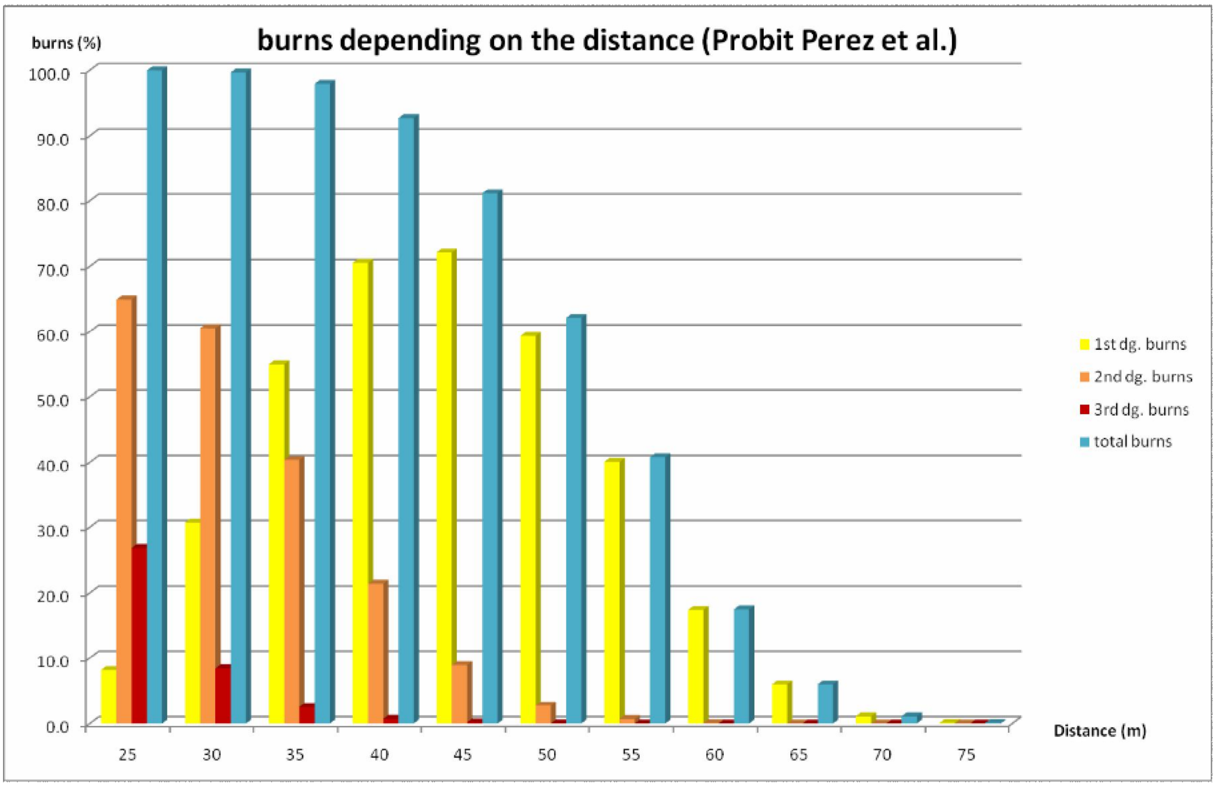

Figure 3. Percentage of burns versus distance – Probit function from Pérez et al (2009).

Comparing figures 2 and 3, it can be observed that in case of the calculations using the Probit functions proposed by TNO (1989), the percentage of 3rd degree burns is higher than the percentage of 2nd degree burns, but using the Probit functions proposed by Pérez et al (2009) the order of burns is logical, having a higher percentage of 2nd degree burns than 3rd degree burns. According to Mannan (2005) the population affected by third degree burns is also affected by second and first degree burns, so the percentage of population affected by second degree burns must be higher than the percentage of third degree burns.

In Figure 3 it can be observed a difference in the case of 1st degree burns values, where the percentage is lower than 2nd degree burns at close distances to the center of the fire (Figure 3).

The Individual Risk (IR) calculation. The total Individual Risk is calculated by summing up the individual risks of the Poolfire and Flash fire scenarios. To calculate the IR for the Poolfire scenario it will be considered the scenario frequency 5.625 x 10^{-8} (Table 1), the probabilities of death vs. distance (Table 4) and the weather probability. For Flash fire scenario Pd = 1 in the area in which the vapor concentration is C ≥ LEL (inside the flame envelope), and Pd = 0.01 in the area in which the vapor concentration is between ½ LEL ≤ C < LEL (Uijt de Haag & Ale 2005). The wind speed probability was considered to be 1 in this case study.

$$\Delta RI_{Poolfire} = F_2 \times P_d \times P_{weather} \times P_w \quad \text{(eq. 8)}$$
$$\Delta RI_{Flash\ fire} = F_4 \times P_d \times P_{weather} \times P_w \quad \text{(eq. 9)}$$

In Figure 4 the individual risk curves versus distance are presented considering the two different sets of Probit functions: TNO (1989), and Pérez et al (2009) respectively.

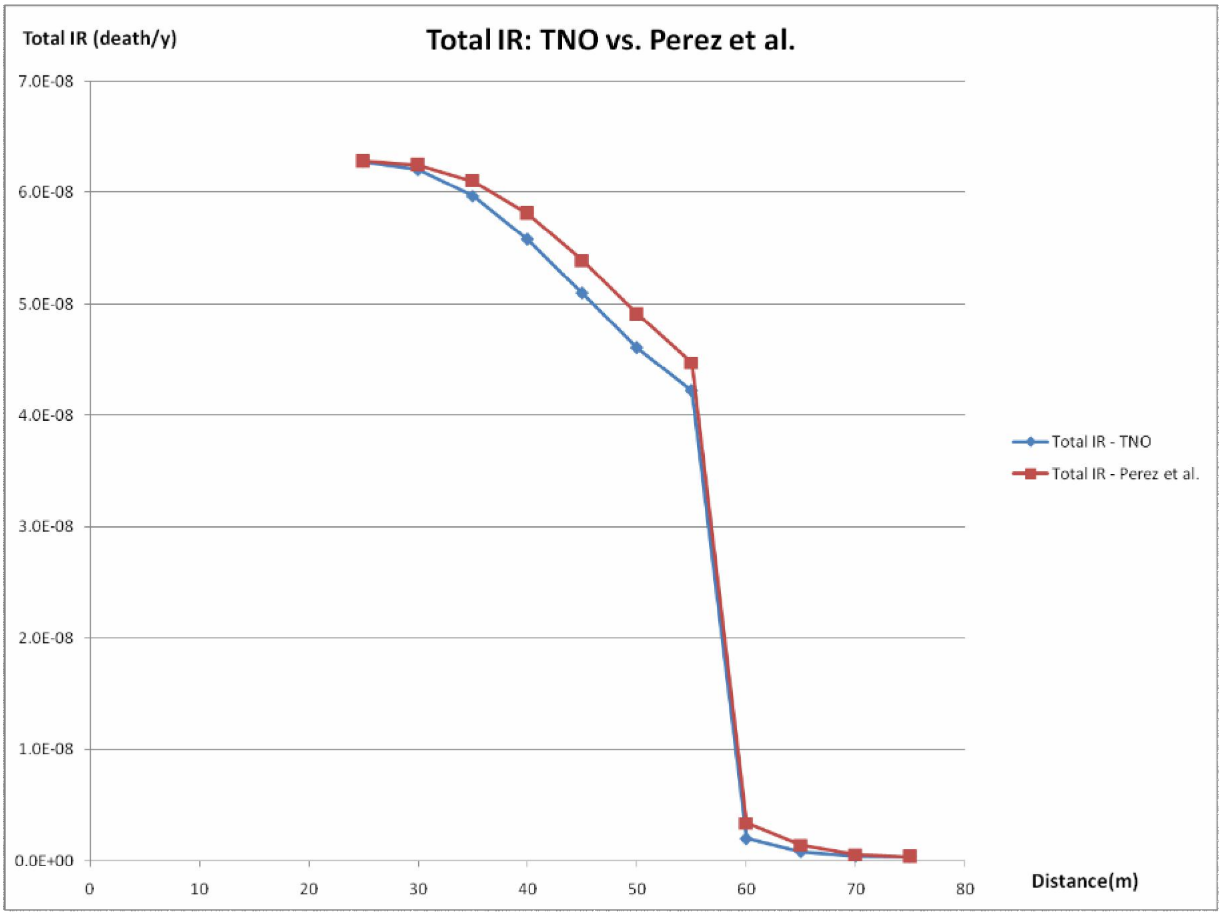

Figure 4. IR comparison using the two different Probit function sets.

Analyzing Figure 4, it can be observed that the differences between the risk values of the two cases are not significant, falling in the same order of magnitude at certain distances.

Conclusions. This paper presented a comparative analysis of the consequences of thermal radiation on population and of the IR using different Probit functions proposed in the literature.

The probability of death was calculated using two types of Probit Functions, then the results obtained were compared.

It can be concluded that using the new Probit Functions proposed by Pérez et al (2009), more accurate estimations of the consequences and conclusive results can be obtained than those obtained by using the Probit functions of TNO (1989). The more accurate the calculation of Individual Risk it is, the more efficient measures of prevention and protection can be taken.

References

Gheorghiu A. D., Török Z., Ozunu A., Antonioni G., Cozzani V., 2014 Comparative analysis of technological and NaTech risk for two petroleum products tanks located in a seismic area. Environmental Engineering and Management Journal 13(8):1887-1892.

Mannan S., 2005 Lees' loss prevention in the process industries. Hazard Identification, Assessment and Control. Elsevier, Third Edition, Oxford.

Nivolianitou Z., Argyropoulos C., Christolis M., Markatos N., 2012 A methodology for the hazard assessment in large hydrocarbon fuel tanks. Available at: http://www.aidic.it/cet/12/26/029.pdf.

Ozunu A., 2013 Seveso Directives – Historical background and current situation. Environmental Engineering and Sustainable Development Entrepreneurship 2(4):9-18.

Pérez J. F. S., Ferradás E. G., Alonso F. D., García D. P., Cano M. V. M., Cotorruelo J. A. B., 2009 New Probit equations for the calculation of thermal effects on humans. Process Safety and Environmental Protection 88(2):109-113.

Sklet S., 2006 Hydrocarbon releases on oil and gas production platforms: Release scenarios and safety barriers. Journal of Loss Prevention in the Process Industries 19:481-493.

Uijt de Haag P. A. M, Ale B. J. M., 2005 Guidelines for quantitative risk assessment. "Purple Book", VROM, Third Edition, The Hague, The Netherlands.

Van den Bosch I. C. J. H., Twilt I. L., 1989 Damage caused by heat radiation. In: Methods for the determination of possible damage. TNO (eds), Chapter 1, "Green Book", Voorburg, The Netherlands.

Török Z., Ajtai N., Ozunu A., Cordoş E., 2009 Chemical risk area estimation as a tool for efficient emergency planning. Studia Universitatis Babeş-Bolyai Chemia 1:49-58.

TNO Effects, 1989 Available at: https://www.tno.nl/downloads/EFFECTS%209%20 brochure2.pdf Accessed in September, 2014.

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