CHEMICAL ENGINEERING TRANSACTIONS
VOL. 31, 2013

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

Guest Editors: Eddy De Rademaeker, Bruno Fabiano, Simberto Senni Buratti
Copyright © 2013, AIDIC Servizi S.r.l.,
ISBN 978-88-95608-22-8; **ISSN** 1974-9791

DOI: 10.3303/CET1331027

Application of Fuzzy Logic Approach to Consequence Modeling in Process Industries

Adam S. Markowski and Dorota Siuta

Safety Engineering Department, Faculty of Process and Environmental Engineering, Lodz University of Technology, 90-924 Lodz, ul. Wolczanska 213, Poland
markows@wipos.p.lodz.pl, siutadorota@gmail.com

In this paper, a general framework for deal with uncertainties in each stage of consequence modeling is presented. In the first part of the framework, the sources of uncertainty are identified and confirmed by sensitivity analysis for the source term, dispersion, physical effects and consequence analysis. While the second part comprises an application of the fuzzy logic system to each step of the consequence modeling. The proposed procedure is verified by the case study for a liquefied natural gas (LNG) release on water. The results in terms of hazard zones are compared with calculations obtained using the Monte Carlo method and with experimental data. The fuzzy logic approach provides less uncertain and more precise results in comparison to the deterministic approach.

1. Introduction

The intensive development of new manufacturing technologies, the use of hazardous materials, more complicated installations and extreme conditions of the processes have resulted in a series of major incidents and accidents in recent years. It has led to massive loss of human life, environmental damage and economic loss. At present, the total elimination of potential hazards and their consequences is not possible in chemical industries. Therefore, an important issue is to perform the consequence analysis for all possible undesirable events and fault conditions for a given facility which is an essential part of the risk assessment process and safety reports. This analysis is used to predict hazard zones and the extent of effects associated with the release, dispersion, fire and explosion of hazardous substances, that are expressed in terms of injuries, deaths and damage to buildings, infrastructures and the environment. The main scheme of the consequence assessment procedure is presented in Figure 4. The modeling contains uncertainties that come from the variability of data, insufficient, incomplete knowledge about the particular phenomenon (e.g. large fire), assumptions in mathematical formulation (e.g. one dimension), empirical relations, constants obtained from limited experimental information and various measurement techniques. Moreover, uncertainties may propagate from one part of a model to another having a significant effect on hazard predictions. One solution to this problem is to propose the general framework to handle the consequence analysis with uncertainties that the prediction of final results will be more accurate. The proposed framework is verified by the case study for the release of liquefied natural gas (LNG) on water.

2. General Framework for Dealing with Uncertainties

The general framework for dealing with uncertainties in the consequence assessment of the process industries is shown in Figure 1. It can be only applied to parameter because of uncertainty connected with imprecision, inaccuracies and variability in the model parameters which are used as inputs to consequence analysis. The first element of the framework is the selection of the potential representative accident scenario which might be based on historical accident data, the process hazard analysis and expert judgment. The most likely scenario or worst-case scenario is typically considered, although this is a primary source of qualitative uncertainties which will not be undertaken in this project. The second part focuses on the choice of the consequence model for a type of the material and a given accident scenario TNO (1997). The consequence model consists of different parameters which affect the final calculation.

Please cite this article as: Markowski A. and Siuta D., 2013, Application of fuzzy logic approach to consequence modeling in process industries, Chemical Engineering Transactions, 31, 157-162 DOI: 10.3303/CET1331027

It is primarily to identify uncertainties in the model being analyzed and their importance. Therefore, the third part concerns a sensitivity analysis to identify the most important parameters amongst a large number that affect model outputs. Usually, sensitive parameters are the most uncertain parameters in each step of consequence modeling.

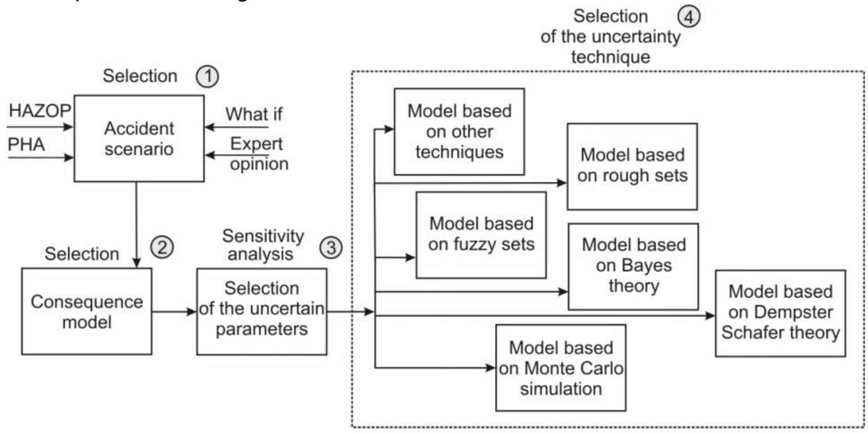

Figure 1: The general framework for dealing with uncertainties in the consequence assessment of the process industries

The next part provides an application of an uncertainty technique used to include the uncertainty aspects in consequence analysis. The selection of the uncertainty technique depends on the types of uncertainties existing in consequence model. Usually two types of uncertainties can be distinguished - aleatory and epistemic. The aleatory uncertainty is related to the stochastic distribution of the physical parameters in models, and the epistemic uncertainty is connected with insufficient knowledge. The fuzzy sets technique is particularly recommended when mixed types of uncertainty exist. On the other hand, the Monte Carlo technique is mainly used for representation the aleatory uncertainty. Other techniques are not suitable for consequence modeling e.g. generally, the Bayesian approach and Dempster - Shafer theory of evidence are applied to reliability analysis. The proposed framework for the calculation of the consequences of taking into consideration the uncertainty is demonstrated in the following case study.

3. Case Study

The case study concerns the consequence calculations of pool fire for an incident involving the release of potential LNG (Liquefied Natural Gas) vessel cargo during transit and while at berth.

3.1 Selection of a accident scenario

The detailed description of the selected accident scenario is presented in Table 1 and recommended by Federal Energy Regulatory Commission (ABS Consulting 2004), Sandia National Laboratories (Luketa - Hanlin et al. 2008).

Table 1. Description of the accident scenario

Accident scenario
Puncture both the inner and outer hulls, the insulation layer, and the LNG cargo tank (volume 25 000 m^3, T = 161 •€, P = 101325 Pa), the unconfined release of liquid LNG above the water level in a membrane type carrier from 1m hole (total quantity spilled 12 500 m^3, the initial height of liquid above the hole 13 m), an immediate ignition, a pool fire on water, possible injury to people and damage to structures.

The hole was assumed to be uniform in diameter and to penetrate through the outer and inner hulls and the cargo tank. All input parameters were taken from ABS Consulting report (2004). Calculations were conducted for pure methane and three threshold values of thermal radiation 5 KW/m^2, 12.5 KW/m^2, 37.5 KW/m^2 which are related to specific consequences.

3.2 Selection of mathematical models

Consequence calculations for the accident scenario were performed using models developed by ABS Consulting (2004). The models use Bernoulli's equation to calculate the release rate, the Webber’s gas accumulation over spreading pools model to determine the burning rate and pool radius, the solid flame model to calculate thermal radiation hazard distances associated with marine transportation of LNG and probit models for estimating the effects on people and structures that result from thermal radiation exposure. Detailed descriptions, assumptions and equations of each model can be found in references ABS Consulting (2004) and TNO (1997).

3.3 Sensitivity analysis

A local sensitivity analysis of the selected models was conducted due to the simplification of calculations. It referred to calculations of sensitivity indexes S_i which can be determined as follows:

$$S_i = \frac{\partial y}{\partial x_i} \cdot \frac{x_i}{y} \tag{1}$$

where x_i is a given parameter from each physical and consequence model, y is output from the model. The value of the sensitivity index that is the largest, determines the most sensitive parameter of the model. For instance, the equation and results of the sensitivity analysis for the Thomas correlation (1968), used to estimate the LNG flame height on water in the solid flame model are depicted in Equation 2 and Figure 2,

$$S_i = \frac{\partial \left(55 \cdot D \cdot \left(\frac{m_b}{\rho_a \cdot \sqrt{g \cdot D}}\right)^{2/3} \cdot \left(\frac{u}{\left(\frac{m_b}{\rho_v} \cdot g \cdot D\right)^{1/3}}\right)^{-0.21}\right)}{\partial x_i} \cdot \frac{x_i}{L} \tag{2}$$

where x_i is each parameters of the correlation such as: D is the fire diameter, L is the height of fire, g is the acceleration due to gravity, m_b is the mass burning rate per unit area, u is the average wind speed, ρ_a is the ambient air density, ρ_v is the vapor density at LNG boiling point.

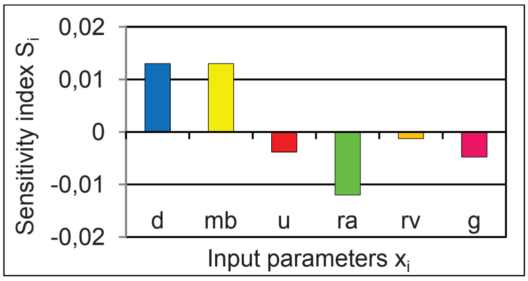

Figure 2: Results of the sensitivity analysis for the Thomas correlation used to calculate the flame height

As seen in Figure 2, the diameter of the fire diameter and the mass burning rate of LNG have the largest value of the sensitivity index. This means that those parameters will have a critical impact to predict the flame height, and can represent a significant source of the parameter uncertainty. All sensitive parameters in all models are indicated in Figure 4 (marked as gray triangles).

3.4 Methods for estimating and analyzing the effect of uncertainties

Then, two uncertainty techniques such as the fuzzy sets and Monte Carlo methods were applied.

3.4.1 Fuzzy set technique

A typical structure of a fuzzy logic system is shown in Figure 3 and developed previously by Mendel 1995, Markowski et. al 2010.

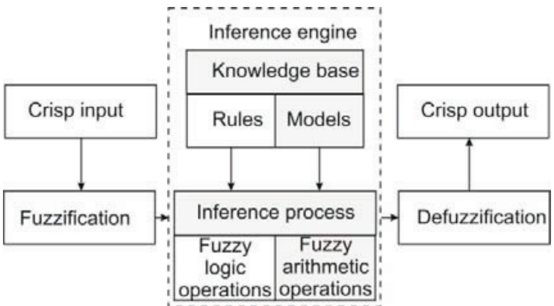

Figure.3: General structure of a fuzzy logic system (Markowski et. al 2010)

In this part of the calculations, the fuzzification of uncertain parameters was carried out. It means that the universe of discourse (range) of each of these parameters was determined, the shapes of membership functions were defined, and parameters were transformed into fuzzy numbers. Categorization of the fuzzification is summarized in Table 2. The triangular type of membership function was selected due to data fitting and usually used in the literature. The universe of discourse (range) of all values of uncertain parameters was based on data provided in literature and several LNG spill on water experiments.

Table 2. Fuzzy numbers for uncertain parameters

Fuzzy numbers	Left boundary value	Mean value	Right boundary value
Hole diameter [m]	0.7	1	1.3
Discharge coefficient [-]	0.6	0.82	1
Mass burning rate [kg/m2s]	0.1	0.28	0.358
Ambient temperature [K]	294	299	304
Relative humidity [%]	30	70	90
Surface emission power SEP [KW/m^2]	248	265	326
Wind speed [m/s]	1.5	8.94	20
Exposure time [s]	10	30	60

Next, parameters presented in form of fuzzy numbers entered in equations described the release rate, spread rate of an unconfined pool on water, mass burning rate, size of a pool fire, thermal radiation from a pool fire on water, effects of thermal radiation on people, effects on structures using fuzzy arithmetic operations based on both the Zadeh's extension principle and the • •cut with interval arithmetic method (Zadeh 1978). Then, the results obtained in the form of fuzzy numbers were converted into crisp values or real numbers using the centroid method of deffuzification as the most natural and popular choice for the process safety analysis. Calculation flow sheet for LNG consequence analysis is given in Figure 4, where the overview of fuzzy model inputs, outputs and basic interactions between parameters are given.

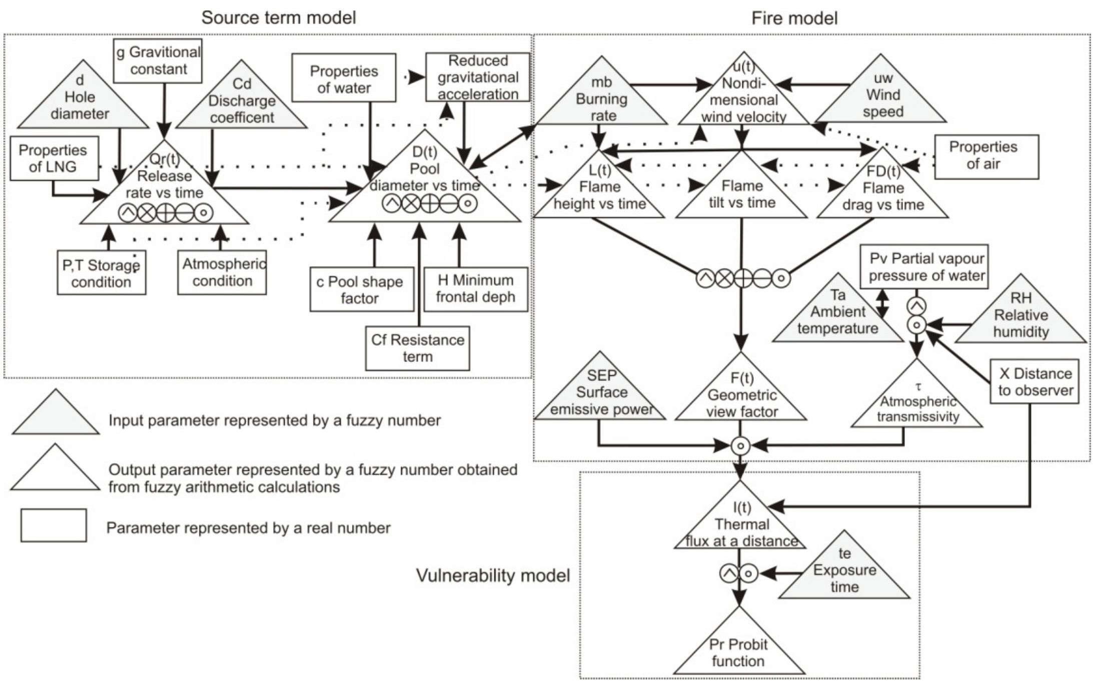

Figure 4: Flow sheet for LNG consequence analysis

For example, the graphical representation for LNG release model is shown in Figure 5. Multiplication of the fuzzy numbers fCd*fd using the • •cut interval is presented in Figure 5a. Then, the fuzzy number of fCd*fd is multiplied by parameters represented by the real numbers in this model. The results of the release rate for each flow time in form of fuzzy numbers are shown in Figure 5b. The final crisp outputs of release rate versus spill duration are obtained using the deffuzification process and are presented in Figure 6. Calculations were performed in Matlab.

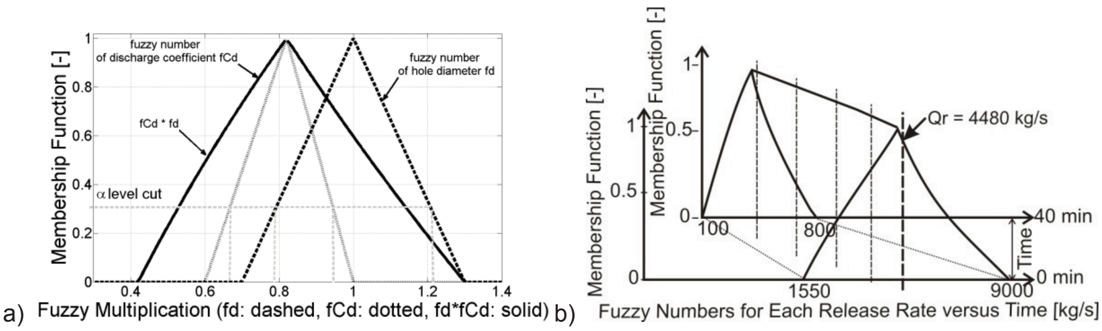

Figure 5: Graphical representation of the application of the fuzzy technique to the LNG release model

3.4.2 Monte Carlo simulation

A similar procedure was carried out using a Monte Carlo simulation. In the case study, sensitive parameters were presented in the form of probabilistic distributions. A triangular distribution was selected. Ranges of the distribution were the same as the scopes of the fuzzy numbers. Samples were obtained from the distributions using the Monte Carlo method with 100,000 simulation runs. The final estimate for each parameter was the average of the sample values (Siuta et al. 2012).

4. Results

Some of the results for three models: the classic ABS Consulting model, ABS Consulting model based on fuzzy sets and ABS Consulting model based on Monte Carlo simulation are summarized in Table 3 and presented in graphical form in Figure 6.

Table 3. Comparison approaches for ABS Consulting model

Approach	Classic (CL)	Fuzzy (FN)	Monte Carlo (MC)
Maximum release rate	5299 kg/s	4480 kg/s	4338 kg/s
Spill duration	33.2 min	39.2 min	40.5 min
Maximum pool radius	74 m	70.1 m	70.2 m
Total fire duration	33.2 min	39.2 min	40.5 min
Maximum flame height	282 m	265 m	267 m
Downwind distance to 5 kW/m^2	870 m	830 m	810 m
Downwind distance to 12.5 kW/m^2	604 m	579 m	576 m
Downwind distance to 37.5 kW/m^2	392 m	381 m	384 m

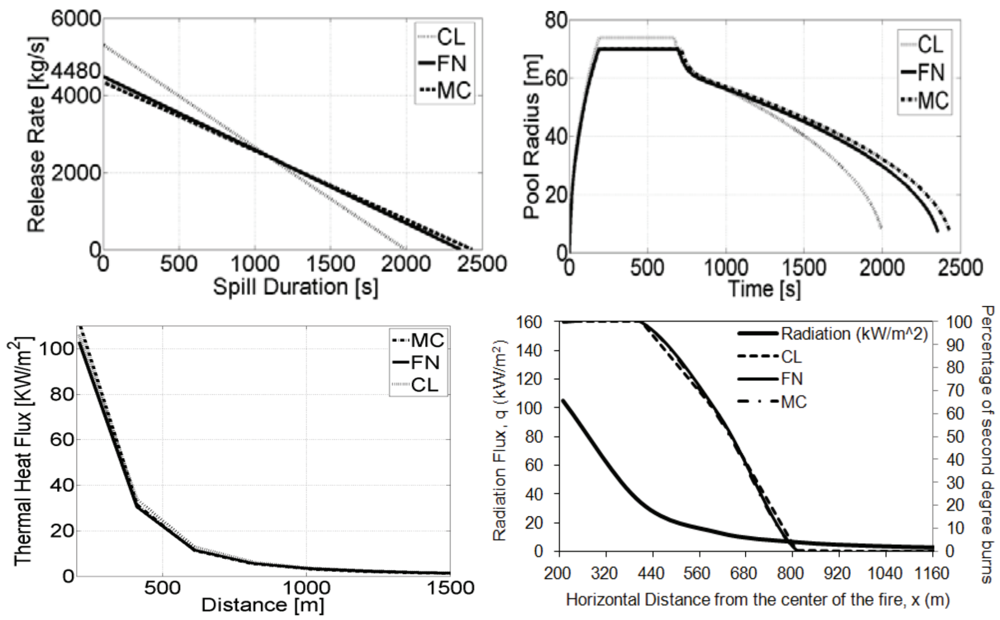

Figure 6. Comparison of the proposed approaches and classic approach (ABS Consulting model) for LNG pool fire modeling on water

Most of the results differ significantly for each consequence model based on fuzzy sets, Monte Carlo simulation and classic model. The difference is approximately of 5 % to 30 %. As can be seen in Table 3, Figure 6, downwind distances obtained from the classic model are higher by about 5% for radiation levels 5 kW/m^2, 12 kW/m^2, 37.5 kW/m^2 compared to models based on fuzzy sets and Monte Carlo approaches. The above concept has been compared to fire experimental data obtained by Croce et al. (1984). Shown in Figure 7 is a comparison of these models to experimental data.

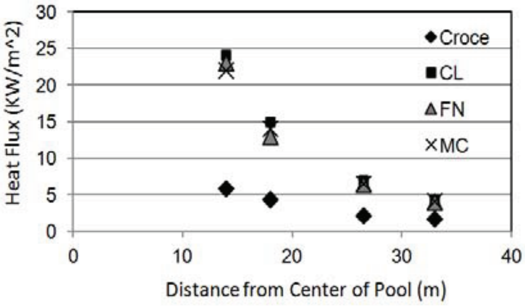

Figure 7. Comparison of the proposed approaches, classic approach with experimental data for hazardous distance versus heat flux

Results indicate considerable overestimation of hazard zones using classic approach compared to models based on fuzzy sets and Monte Carlo approaches and confirm that proposed fire models predicted the results closer to reality.

5. Conclusions

1. Consequence analysis in process industries is used for estimating hazard zones but the calculation contains a number of uncertainties of different types (aleatory and epistemic). These uncertainties can result in significant differentiation of final results which have the practical significance to optimize plant layout, evaluation of the mitigation system and emergency management.
2. The paper shows the framework for dealing with uncertainties in consequence calculations. The proposed framework is based on sensitivity analysis to select uncertain parameters. Subsequent steps consist of an application of fuzzy sets and Monte Carlo methods.
3. The case study concerning the LNG pool fire calculations using uncertainty techniques (fuzzy sets, Monte Carlo simulation) proved that the extent of the hazardous zone is precisely determined in comparison to the classic (deterministic) model.
4. ABS Consulting models based on fuzzy sets and Monte Carlo simulation indicate good agreement with experimental data which confirms equally the possibility of applying both models.

References

ABS Consulting (2004): ’’Consequence Assessment Methods for Incidents Involving Releases from Liquefied Natural Gas Containers”, Report GEMS 1288209 for Federal Energy Regulatory Commission, Contract Number FERC04C40196.

Croce P. A., Mudan K.S., Moorhouse J. (1984): "Thermal Radiation from LNG trench fires’’, vols. 1 and 2, GRI Report No.84/0151.1.

Luketa-Hanlin A., Hightower M.M., Attaway S. (2008): ’’Breach and Safety Analysis of Spills over Water from large Liquefied Natural Gas Carriers’’, Sandia report 2008 - 3153.

Markowski A. S., Mannan M. S., Kotynia A. and Siuta D. (2010): "Uncertainty Aspects in Process Hazard Analysis", Journal of Loss Prevention in the Process Industries vol. 23, pp.446-454.

Mendel I.M. (1995): "Fuzzy Logic Systems for Engineering: A tutorial”, Proceedings of the IEEE, vol. 83., No. 3, pp. 345-377.

Siuta D., Markowski A.S., Mannan M.S. (2012): "Uncertainty Techniques in Liquefied Natural Gas (LNG) dispersion calculations", Journal of Loss Prevention in the Process Industries.

TNO (1997): "Committee for Prevention of Disasters: Methods for the calculation of physical effects (Yellow book)", CPR 14E, The Netherlands.

Zadeh, L.A. (1978): "Fuzzy Sets as a Base for a Theory of Possibility", Fuzzy Sets and Systems 1, 3–28.