
Design for acceptable risk in transportation pipelines

Alex. W. Dawotola*, P.H.A.J.M. van Gelder
and J.K. Vrijling

Hydraulic Engineering Section,
Delft University of Technology,
Stevinweg 1, 2600GA, Delft, Netherlands
E-mail: a.w.dawotola@tudelft.nl
E-mail: p.h.a.j.m.vangelder@tudelft.nl
E-mail: j.k.vrijling@tudelft.nl
*Corresponding author

Abstract: In this work, the probabilistic methods have been used to produce a methodology capable to estimate the acceptable level of risk in a cost-benefit framework. The benefits and the costs are weighed against associated risks to aid the decision making process on risk acceptance, from both the individual and societal perspective. Thereafter, acceptable individual and societal risk levels are defined based on historical trend of non-voluntary deaths and overall national fatalities. An example is used to explore the practical application of the method to critical infrastructures such as petroleum pipelines. The results show that the cost-benefit risk framework provides a safety standard that is acceptable from both individual and societal perspectives.

Keywords: risk assessment; acceptable risk; pipelines; cost-benefit.

Reference to this paper should be made as follows: Dawotola, A.W., van Gelder, P.H.A.J.M. and Vrijling, J.K. (2012) 'Design for acceptable risk in transportation pipelines', *Int. J. Risk Assessment and Management*, Vol. 16, Nos. 1/2/3, pp.112–127.

Biographical notes: Alex Dawotola is a PhD researcher of the Probabilistic Design Group at Delft University of Technology, the Netherlands. His research focus is on risk assessment, pipeline reliability, maintenance optimisation, and statistical analysis of repairable systems. He has presented and published part of his research work in leading conferences in North America and Europe. He obtained his BSc in Mechanical Engineering from University of Lagos, Nigeria, MSc in Mechanical Engineering from Delft University of Technology, Netherlands, and MBA (Energy) from University of Oklahoma, USA. He presently works for SBM Offshore in Houston, Texas as a Package Manager.

P.H.A.J.M. van Gelder is a full-time Associate Professor of probabilistic methods in Civil Engineering at Delft University of Technology. He has been involved in research and education on safety and reliability for over 15 years. His research interest is in risk-based hydraulic structural design and extreme value statistics for hydraulic loads determination.

J.K. Vrijling became a Professor of Hydraulic Engineering at Delft University of Technology in 1989. Since 1995, he is a Full Professor at Delft and an Advisor to the Civil Engineering Division. His expertise is in hydraulic structures and probabilistic design.

1 Introduction

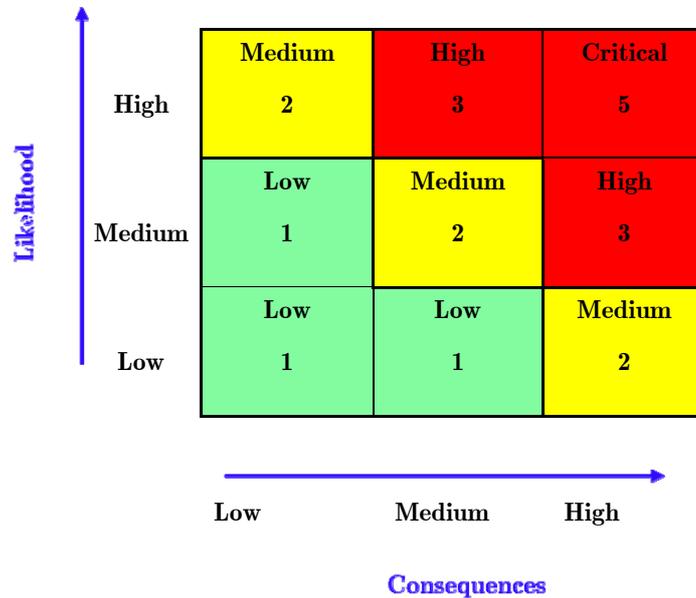
Risk assessment entails the study of the probability of failure and any associated consequences. The two general classifications of risk to human life are the individual and societal risks. Individual risk is the annual risk of death or serious injury to which specific individuals are exposed. The acceptability of the risk can be judged relatively easily as individuals knowingly take and accept risks all the time, weighing the benefits with the cost associated with risk taking. Societal risk is expressed as the relationship between the probability of a disaster, expressed as the average frequency with which it can be expected to occur, and its consequences. It is usually represented as an F-N curve. F-N curve is the graph that plots the expected annual frequency (F) of the number (N or more) of casualties in the whole surrounding area arising from all possible dangerous incidents at a hypothetical hazardous site.

Pipelines carry products that are very vital to the sustenance of national economies and remain a reliable means of transporting gas and liquids in the world. In the USA for example, the Department of Transportation, Office of Pipeline Safety (DOT-OPS) oversees 2.2 million miles of pipeline, of which about 157,000 miles carry more than 550 billion gal annually of crude oil and petroleum products, including a natural gas pipeline system that consists of approximately 333,000 miles of transmission pipeline and 1.7 million miles of distribution pipelines (Trench, 2000). Health and Safety Executive (HSE, 2010) estimated that the UK has nearly 22,000 km of high pressure gas and petrochemical pipelines, 1,000 km transporting ethylene and the remainder transporting spiked crude oil, LNG and other hydrocarbons. Nigeria, Russia, Saudi Arabia and other major oil producing nations equally boast of thousands of kilometres of liquid and natural gas pipelines.

In general, pipelines content generally pose no health hazard to persons near the pipeline as long as the pipeline maintains its integrity, and there is no loss of containment of the pipeline. De Wolf (2003) expressed that pipelines possess relatively low safety and environmental risks compared with other means of fuel transportation. The conclusion by De Wolf stems out of a study that provided an estimated fatalities per billion ton-miles of about 0.03 for pipelines compared with 1.2 for rail and 9.22 for highway transportation. As pointed out by Kirchoff and Doberstein (2006), a pipeline that results in product release poses risks to the people within the vicinity of the release due to the attended health and environmental hazards. In other words, it will be unreasonable to think of pipelines as being absolutely safe.

The consequences of pipeline failures cannot be overemphasised, particularly as it relates to human health problems and environmental degradation. Human lives are threatened by the rupture of major accident hazard pipeline, such as a high-pressure gas main or a petrochemical pipeline such as ethylene, oil or gasoline, and as such should be taken very seriously. As a matter of fact, the explosion of natural gas released from a pipeline could produce toxic flames emanating from vapour cloud emissions released. There is also high likelihood of thermal radiation and torch fire. Similarly, liquid petroleum product such as gasoline is a flammable liquid, producing consequences related with flammability under failure. As explained by Muhlbauer (2004), the typical hazards expected under gasoline pipeline failure will be overpressure and pool fire.

Figure 1 A simple risk matrix (see online version for colours)



Over the past years, two broad categories of risk assessments have been used, namely qualitative risk assessment and quantitative risk assessments (QRA). In a qualitative risk assessment, the likelihood and consequences of a hazard are combined to determine the level of risk of the hazard. The results are often shown in the form of a risk matrix with one axis representing likelihood of failure of a system and the other axis representing the associated consequences. A simple risk matrix is shown in Figure 1. The risk score shown in the risk matrix is obtained by combining the likelihood and impact ratings and values. The risk score may be used to aid decision making and help in deciding what action to take in view of the overall risk. Interpretation of risk scores is shown in Table 1 below.

Table 1 Interpretation of risk scores

<i>Risk ranking</i>	<i>Interpretation</i>
5	Risk very likely to occur and have very dire consequences
3	Risk likely to occur and have serious consequences
2	Risk possibly could occur with moderate consequences
1	Risk unlikely to occur with negligible consequences

However, there are some limitations in the application of qualitative risk assessment. Khan and Haddara (2003) explained that the outcome of a qualitative risk assessment is a relative value which may be meaningless outside the framework of the matrix. Another shortcoming of qualitative risk assessment is the level of subjectivity inherent in the decision making process. The presence of subjectivity means the outcome could be greatly influenced by the decision maker (Dey, 2004).

Quantitative Risk Assessment uses numerical values (rather than the descriptive scales used in qualitative analysis) for the assessment of probabilities and assessment of consequences. According to Sii et al. (2001), quantitative risk assessment techniques

have been increasingly developed and applied by both safety analysts and designer engineers. In particular, approaches such as fuzzy logic (Oke et al., 2006), neural network (Wang et al., 2004), Taguchi methods (Sii et al., 2001), and neuro-fuzzy methods (Oke et al., 2005) have been proposed for use in offshore structures. In addition, probabilistic design techniques have also been applied to model failures in oil and gas pipelines by several authors, such as Ahammed and Melchers (1996), Pandey (1998), and Teixeira et al. (2008).

Although QRA has many benefits, a number of disadvantages can be identified as well. Quantitative risk assessment is very data intensive, and in reality, sufficient data are generally not available to cover the entire analysis that may be required. In addition, quantitative risk assessment can be very complicated, employing series of analyses and calculations in simulating the effects of different hazard scenarios. According to Landoll (2006), complex risk assessment calculations may be difficult to present to non-experts, and the outcome may become unclear and unacceptable. Also, the considerable uncertainty associated with the assessments of both the frequency of failure and consequences may give misleading results.

After risk estimation, the value of risk estimated is then evaluated for decision making. Risk evaluation is the process of judging the significance of absolute or relative values of the estimated risk, including the identification and evaluation of options for managing risk. The main question in risk evaluation is: *how safe is safe enough?*, as explained by authors such as Derby and Keeney (1981) and Vrijling et al. (1995). This is a very controversial stage of risk assessment, since the definition of acceptable risk varies on whether it is viewed from personal perspective or societal perspective. Many researchers such as Vrijling et al. (1998), Kirchoff and Doberstein (2006), have proposed different strategies for defining what constitutes acceptable risk criteria. However, the bottom line is that acceptable risk criteria are highly subjective and depend on individual choices or societal norms.

The outcome of risk assessment and risk evaluation can be very useful, for example in accepting whether a new construction could be approved or not based on potential level of risk exposure. A major part of risk assessment is risk management. Risk management involves the decision making for managing risk. Risk assessment of pipelines for example, is applicable to the decision-making process in the design, construction, operation, inspection, monitoring, testing, maintenance, repair, modification, rehabilitation, and abandonment of pipelines.

The idea of acceptable risk for different countries and installations may be influenced by historical catastrophic incidents. Individuals and society alike often set-up the so called acceptable risk, with a view to mitigating the risk level to what can be termed 'bearable'. The decision process on the acceptability of risk is generally based on the development of risk acceptance criteria, with the view of using such criteria as a tool to facilitate decision making, as shown by Kirchoff and Doberstein (2006). The definition of acceptable risk is different for both individual and societal risk, since individual preferences may allow for additional risks, which may not be acceptable to the society.

For example, in the Netherlands, third party or external risk level must be less than 1×10^{-5} per year to be adjudged acceptable for existing facilities, and 1×10^{-6} for new facilities (Ale, 1991). In the UK, an individual risk level of less than 1×10^{-6} is defined as acceptable, according to HSE (2001). The Western Australia's maximum acceptable risk

level also stands at $1 \cdot 10^{-6}$ (Environmental Protection Agency, 2000). Hong Kong has acceptable risk of $1 \cdot 10^{-5}$ (Hong Kong Government Planning Department, 2008).

Probabilistic design theory provides a good standard for rational decision making in risk assessment. The theory has found successful applications in different engineering structures (Kumamoto and Henley, 1996). To enable a proper decision making in the context of risk evaluation of petroleum assets, a set of guidelines for risk acceptability is proposed in this paper based on probabilistic theory. The work is a contribution towards the definition of functional risk acceptance criteria for the Nigerian State in line with international standards.

2 A framework for risk acceptance

The framework presents a set of rules that takes into account the cost-benefit and the voluntariness aspect of risk in formulating risk acceptance levels. The assumption in the model is that the pattern of accident statistics can be approximated as the outcome of the cost-benefit weighting. The framework accounts for both acceptable individual and societal risks.

2.1 Determination of individually acceptable level of risk

In modelling the correct level of personally acceptable level of risk, the trend is to look for a balance between the cost for safety and the benefit for human life extension (Streicher et al., 2008). Similarly, Vrijling et al. (1998) demonstrated that the observation of accident statistics has shown statistical stability in pattern over the years and approximately equal, especially in western countries thereby indicating a consistent pattern of preferences. Therefore, the personally acceptable level of risk for an individual can be estimated by looking at the pattern of preferences for risk, observed in the historical data of accident occurrences.

Mathematically, individual risk can be stated as:

$$IR_{x,y} = \lambda \sum_i \sum_j P_i \cdot L_{i,j} \cdot P_{\phi,i,j} \cdot P_{\phi,i} \cdot \sum_k P_{i,j,k} \quad (1)$$

where λ is the failure frequency per km-year; P_i is the release probability for release event i ; $L_{i,j}$ is the length of release location zone j for release i (in km); $P_{\phi,i,j}$ is the probability that wind blows in release location zone j leading to event i ; $P_{\phi,i}$ is the probability of weather condition required for release i . $P_{i,j,k}$ is the probability of fatality at location x, y for a given release i given that incident outcome k occurs for release location zone j .

Based on the level of consistency observed over the years in the level of the death risks discussed, a broader set of risk standards ranging from voluntary activities to more involuntary occurrences can be determined from the calculation of the personally acceptable probability of failure given by (TAW, 1985):

$$P_{fi} = \frac{\beta_i \cdot 10^{-4}}{P_{d|fi}} \text{ (per year)} \quad (2)$$

In other words, the criterion for acceptable individual risk will be:

$$P_{fi} * P_{d|fi} < \beta_i * 10^{-4} \quad (3)$$

where P_{fi} is the probability of death per year and $P_{d|fi}$ is the probability of being killed in the event of an accident. β_i is the policy factor.

Table 2 Policy factor based on the degree of voluntariness and benefit

β_i	Degree of voluntariness	Level of benefit	Examples
0.01	None	None	Cross-country pipelines
0.1	None	Some	Factory
1.0	Neutral	Direct	Car driving
10	Voluntary	Direct	Motor biking
100	Completely voluntary	Direct	Mountain climbing

The policy factor (β_i) ranges from 100, for complete voluntary activity with direct benefit to the exposed individual to 0.01, for an involuntary activity with little or no benefit to the affected person. Installations such as cross-country pipelines are considered involuntary and possess no direct benefit; hence a β_i value of 0.01 will be suitable. In Table 2, adapted from (Vrijling et al. 2005) is a proposal for the choice of values for the policy factor for different activities.

2.2 Determination of societal risk

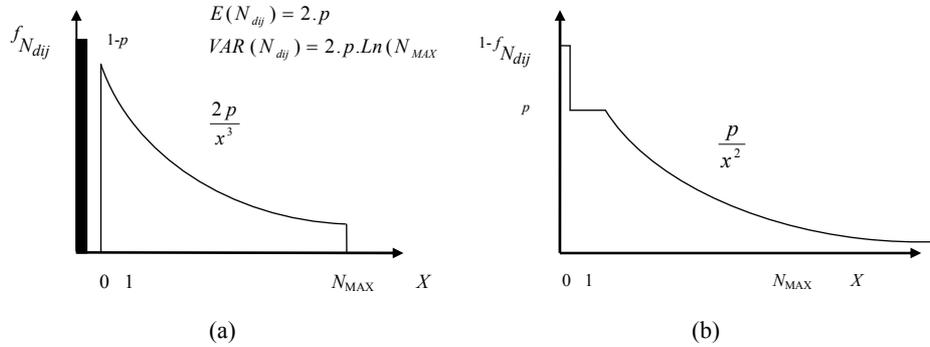
Institute of Chemical Engineers (1985) defined societal risk as the relationship between frequency and the number of people suffering from a specified level of harm in a given population due to the realisation of specified hazards. It is also defined as the likelihood that a group of more than N people would be killed as a result of accident located within the hazardous activity area (Bottelberghs, 2000). A simple measure of societal risk is potential loss of life (PLL), given as:

$$E(N) = \int x \cdot f_{N_{dij}}(x) \cdot dx \quad (4)$$

where $E(N)$ is the expected value of the number of deaths per year and $f_{N_{dij}}$ is the probability density function of the number of deaths resulting from activity i in location j per year.

Societal risk can be modelled by the frequency of exceedance curve of the number of deaths (the FN-curve) due to a specified hazard, if the specified level of harm is limited to loss of life. In an FN-curve, the probability of exceedance or cumulative frequency, $F(\geq N)$, of N or more fatalities per year can be plotted, with $F(\geq N) = \sum f(N)$, summed from N to N_{\max} . Figures 2(a) and 2(b) depict examples of probability mass function and frequency of exceedance curve, respectively.

Figure 2 (a) The probability density function for number of deaths by an inverse quadratic Pareto
 (b) Probability of exceedance curve for number of deaths by an inverse quadratic Pareto



The basis for the societal risk is an evaluation of risks due to a certain activity on a national level, which is an aggregate of the risks from local installations or activities. The acceptable level of risk is determined based on the assumption that the accident statistics of a society is a reflection of a social process of cost-benefit appraisal.

The nationally acceptable level of risk is given as:

$$P_{fi} \cdot N_{pi} \cdot P_{d|fi} < \beta_i \cdot F_N \tag{5}$$

where N_{pi} is the population exposed to activity i and F_N is a country specific multiplication factor which is based on the value of the minimum death rate of the population, the ratio of the non-voluntary accident rate excluding diseases to the minimum death rate, the number of hazardous activities in the country (over an average of 20 sectors) and the population size of the country.

Therefore, F_N is calculated using the expression:

$$F_N = \frac{\text{total annual deaths} * (\text{prob. of non-voluntary deaths} / \text{prob. of deaths})}{\text{no of hazardous activities}} \tag{6}$$

In addition to the nationally acceptable level of risk derived above, *total risk (TR)* can be derived by considering the risk aversion in a society. *TR* accounts for risk aversion in a society by adding the desired multiple k (called risk aversion index) of the standard deviation to the mathematical expectation of the total number of deaths per year, $E(N)$. In other words, total risk is calculated as:

$$TR = E(N) + k \cdot \sigma(N) \tag{7}$$

The nationally acceptable level of risk can then be re-defined as:

$$E(N) + k \cdot \sigma(N) < \beta_i \cdot F_N \tag{8}$$

The standard states that an activity i is permissible as far as the number of deaths per year associated with it is less than $\beta_i \cdot F_N$. The norm with $k = 1, 2,$ and 3 has been tested for

several activities in the Vietnam by MaiVan (2010), and the support for the model with a risk aversion index is found within the broad range of policy factors from 3 to 7.5 and $F_N = 450$.

The Dutch Ministry of Housing, Spatial, Planning and Environment (VROM) sets a minimal risk criterion for existing plants based on the number of resulting deaths. The locally acceptable level of risk for such installations is defined as:

$$1 - F_{N_{dij}}(x) < \frac{C_i}{x^2} \text{ for all } x \geq 10 \quad (9)$$

where x is the number of independent installations. VROM proposes $C_i = 10^{-3}$.

Similarly, assuming a Bernoulli distribution (that is, having an outcome of zero or N fatalities) for the number of casualties at each of N_{Ai} independent locations, with p_{fi} probability of failure at a location and $N_{dij|f}$ as the number of fatalities given failure, the nationally expected value and standard deviation of the casualties are respectively:

$$\begin{aligned} E(N_{di}) &= N_{Ai} \cdot p_{fi} \cdot p_{d|i} N_{dij|f} \\ \sigma(N_{di}) &= N_{dij|f} \cdot \sqrt{N_{Ai} \cdot p_{fi} \cdot (1 - p_{fi})} \end{aligned} \quad (10)$$

The expected value of the number of deaths is generally expected to be lower than the standard deviation of deaths, and it follows from (8) that C_i can be represented by:

$$C_i = \left[\frac{\beta_i \cdot F_N}{k \cdot \sqrt{N_{Ai}}} \right]^2 \quad (11)$$

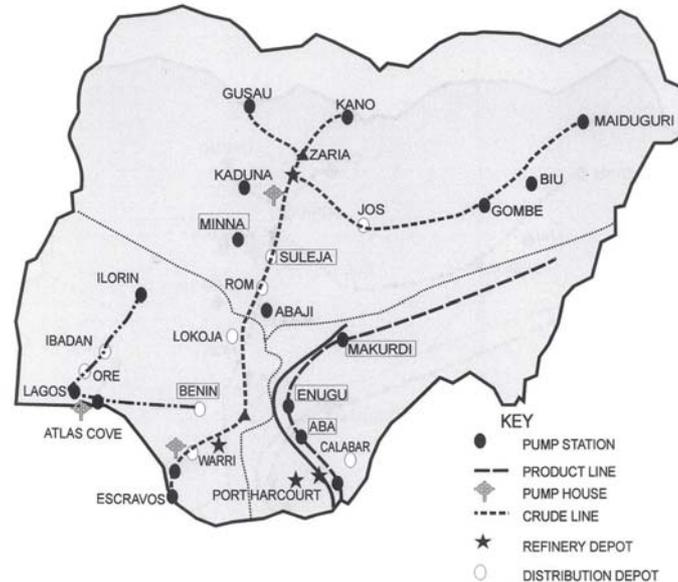
In other words, locally acceptable risk follows from nationally acceptable risk criterion based on:

$$1 - F_{N_{dij}}(x) < \frac{C_i}{x^2} \text{ for all } x \geq 10 \text{ where } C_i = \left[\frac{\beta_i \cdot F_N}{k \cdot \sqrt{N_{Ai}}} \right]^2 \quad (12)$$

3 Societal acceptable level of risk: a case study of Nigeria

3.1 Overview of risk policy in Nigeria

Nigeria is the fifth largest oil producing nation, producing over 10 million barrels of crude oil per day. It derives its basic revenue from proceeds generated from oil and gas commodities, mostly exported to western countries, including USA, Netherlands and UK. Similar to other oil producing nations, the country relies on pipelines to transport petroleum products from one part of the country to another, and there are well over 6,000 km network of such pipelines as depicted in Figure 3.

Figure 3 A map of Nigeria showing locations of crude oil and products pipeline network

Unfortunately, degradation due to corrosion and intentional damage continue to cost the state billion worth of dollars in product loss, with unfavourable consequences on human lives and the environment (NNPC, 2008). In 2007 alone, over twenty cases of pipeline fatalities were recorded. In 2008, the failure rate had grown to over thirty per year. This rate of failure is unacceptable, both personally and societally. The economic and strategic importance of oil and gas production in the country means the industry have to continue to be both efficient and effective in its operations in other to guarantee the prosperity of the nation. Therefore, it is no doubt that there has been a growing interest on the application of risk based decision making in the petroleum industry.

Up till now, the application of minimum risk standard, such as ALARP has been explored in the industry and is part of the requirements of the national Department of Petroleum Industry (DPR) in citing new petroleum facilities (DPR, 2007). However, there has not been any official guidance on how risk should be quantified and what would constitute an acceptable risk. The framework developed in Section 2 will be applied to develop acceptable risk, both individually and societally in two contexts in Nigeria. First, risk acceptance criteria are developed for Nigeria and second, acceptance criteria for petroleum pipelines are developed. The results would be beneficial in both short-term and long-term safety planning processes.

3.2 *Acceptable societal risk in Nigeria*

The historical data of pipeline failures in Nigeria emphasise the need for a standardised way of defining societal acceptable risk for pipeline installations in the country. For critical infrastructures such as pipelines, if $E(N)$ and $\sigma(N)$ can be estimated from historical records of failure of the structure, then the policy values of β_i for Nigeria can be obtained using equations (6) and (7). The acceptable level of risk for a society can be measured from historical records of accidents. This follows the explanation in

Section 2.2, that the societal acceptable risk level is based on the assumption that accident statistics is a reflection of social process of cost-benefit appraisal.

The multiplication factor, F_N given in equation (5) is utilised to calculate the safety norm for Nigeria, using the World Health Organization's (WHO) estimates of mortality (WHO, 2009). From the data, the estimated probability of deaths is $13.1 \cdot 10^{-3}$ per year (1.97 million deaths per 150 million population). The probability of deaths due to non-voluntary activities is given as $9.54 \cdot 10^{-5}$ per year based on the value of unintentional deaths, excluding road traffic accidents and other voluntary activities (14,400 deaths per 150 million population). The result gives:

$$F_N (\text{Nigeria}) = \frac{1.97 \text{million} * (9.54 * 10^{-5} / 13.1 * 10^{-3})}{20} \cong 720$$

For the pipeline installation, with a $\beta_i = 0.01$, the norm is given as:

$$P_{fi} \cdot N_{pi} \cdot P_{d|fi} < 7.2 \text{ or } E(N) + k \cdot \sigma(N) < 7.2 \tag{13}$$

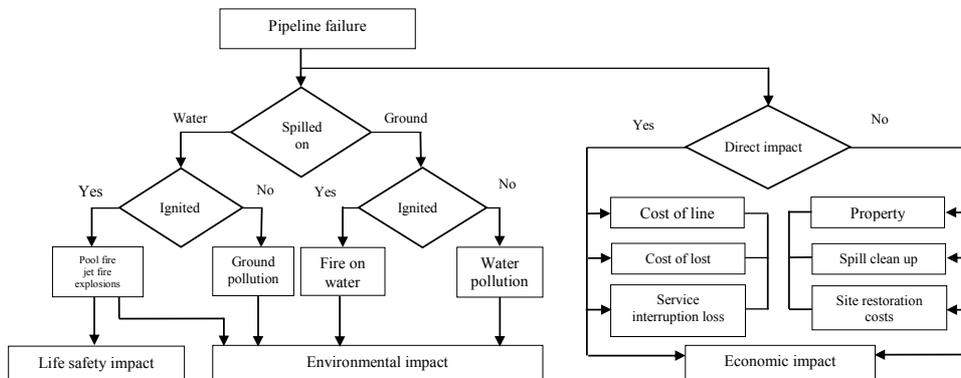
In addition, the approach results in F_N of 460 and 260 for male and female segments of the population in Nigeria respectively. F_N obtained for Nigeria, 720 compares favourably with the factors of 100 and 750 obtained for the Netherlands and South Africa respectively by Vrijling et al. (2005).

4 Level of risk acceptance of pipeline failure in Nigeria

The application of the proposed model is illustrated based on the case study of a crude oil pipeline in Nigeria. The pipeline system was commissioned in 1989 and supply crude oil within the south western region of Nigeria. The pipeline is 24 inch in diameter, total length 340 km, with design pressure and operating temperature of 100 bar and 26.8°C respectively. A detail description of the case study, including event tree of oil spill due to corrosion and risk analysis is presented in Dawotola et al. (2011).

The tree diagram for the consequence analysis part of the risk assessment is shown in Figure 4. Statistical data of failure records are fitted to homogenous Poisson process and power law process to determine the best estimate for the frequency of failure. The calculated frequency of failure due to corrosion is $3.6 \cdot 10^{-3}$ per km.yr.

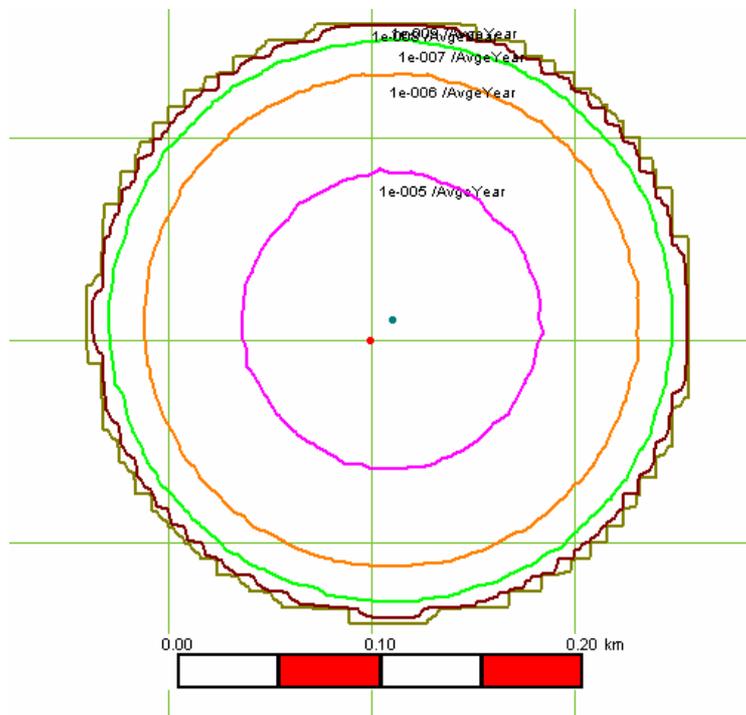
Figure 4 Steps for consequence analysis of oil spill from gasoline pipeline



4.1 Calculation of individual risk due to pipeline location

Individual risk is calculated based on loss of containment of cross-country product (gasoline) pipeline, causing human life, environmental and financial consequences. The software PHAST FX 6.5.1 is used. The values obtained range from 1×10^{-5} to 1×10^{-9} per year for uniform corrosion, pitting corrosion and stress corrosion cracking. Among the three corrosion types, we found that pitting corrosion generally possess the highest individual risk followed by stress corrosion cracking. This is due to the pit generated that could enhance leakage of oil, which may eventually lead to explosion. A plot of individual risk contour due to oil spill causing explosion is given in Figure 5.

Figure 5 Individual risk contours for oil spill of gasoline pipeline in Nigeria (see online version for colours)



4.2 Criteria for acceptable risk of pipeline failure

In establishing an acceptable risk policy, two points of view are considered. First is the point of view of the individual who decides to undertake a risky activity, having a pre-knowledge of the consequences of such activities and weighting it with direct and indirect benefits derived from its performance. Second, is the perspective of the society, in which an activity is judged acceptable, based on the risk-benefit trade-off for the total population.

The individually acceptable level of risk based on the proposal of the Dutch Technical Advisory Committee on Water Defences (TAW, 1985) could be adopted. That is, individual risk is found acceptable if:

$$IR = P_{fi}P_{d|fi} < \beta_i * 10^{-4}.$$

As explained in Section 2.1, the value of β_i varies with the degree of voluntariness of an activity, and solely depends on the level of risk and individual is willing to take, irrespective of the nationality. Installations such as gasoline station or cross-country pipelines which are considered involuntary and possess no direct benefit have a policy factor of $\beta_i = 0.01$.

As noted earlier, the calculated values for individual risk due to corrosion range from $1*10^{-5}$ to $1*10^{-9}$ per year, based on the location of an individual in the risk contour. The part of the contour with a risk value of $1*10^{-5}$ is less than the acceptable risk of $1*10^{-6}$. The risk level can be reduced through a reduction in the probability of failure, by applying adequate and well managed inspection and maintenance strategy.

4.3 Risk based planning of pipeline location

The safety planning around the pipeline is formulated so that the population around the pipeline does not exceed the acceptable risk. Considering eq. 12, the probability of failure for the pipeline is estimated based on historical records of failure. Statistical data of failure history are fitted to homogenous Poisson process and power law process to determine the best estimate for the frequency of failure. The expression for calculating P_{fi} from the frequency of failure is given as:

$$P_{fi} = 1 - e^{-\lambda LT} \quad (14)$$

where λ is frequency of failure (per km.yr), L is length of pipeline (km) and T is planning period (yr)

The frequency of failure due to pitting corrosion and SCC follows HPP while uniform corrosion follows a power law process. The relative failure frequency of each corrosion type due to small leak, large leak and rupture of the pipeline is further obtained. The hole size distribution used is 49% for small leak, 39% for large leaks and 12% for ruptures (HSE, 1999). The failure frequency due to corrosion for the pipeline is $3.6*10^{-3}$ per km.yr.

The probability of failure (per year) from equation (12) for a 20 km segment of the pipeline is 0.07 per year. If the probability of death given failure ($P_{d|fi}$) of pipeline is $1.25*10^{-3}$ for individuals within 5 km radius of the pipeline. Based on equation (12), the maximum population around the pipeline (N_{pi}) that will satisfy the level of societal risk acceptance should not exceed the 82,900.

4.4 Sensitivity analysis of risk parameters

For planning purposes, it will be beneficial to understand how a population increase actually impacts in broader terms, safety around the pipelines. The relationship established in equation (13), indicates that the probability of failure, probability of death given failure and number of inhabitants directly influence the risk level. If one of these factors increases, a reduction in at least one of the other factors will be required to maintain the acceptable risk level.

A sensitivity analysis is thereby conducted to observe the robustness of the model, as well as measure the sensitivities of the factors with respect to overall risk. The outcome

(Table 3) reveals that when other parameters are held constant, for every rise in the number of habitants around the fatality zone, probability of failure P_{fi} must reduce in other to comply with minimum acceptable risk.

Table 3 Sensitivity outcome of probability of failure with population around pipeline

Probability of failure	0.01	0.035	0.07	0.14	0.35	0.7
Change in population	4X	2X	X	0.5X	0.2X	0.1X

5 Summary

A comprehensive framework using historical records of accident as a basis for cost-benefit analysis is the primary contribution of the paper. The approach follows the notion that the acceptable level of risk in a society can be determined based on the assumption that accident statistics is a reflection of social process of cost-benefit appraisal. The outcome of the analysis reflects a minimum acceptable risk for voluntary installations, from both individual and societal perspectives. Based on the analysis of historical non-voluntary and overall deaths, a safety norm has been proposed for the Nigerian society.

The proposed safety norm for the society is:

$$P_{fi} \cdot N_{pi} \cdot P_{d|fi} < 720 * \beta_i \text{ or}$$

$$E(N) + k \cdot \sigma(N) < 720 * \beta_i$$

When the risk consideration is from individual perspective, the acceptable norm is:

$$IR = P_{fi} P_{d|fi} < \beta_i * 10^{-4}$$

In the case of an individual, β_i reflects the amount of risk the individual is willing to bear, after considering the direct and indirect benefits. The individual risk for pipeline installations, with $\beta_i = 0.01$ is therefore $1 * 10^{-6}$.

The approach of using accident statistics and voluntary risks for cost-benefit criteria to formulate acceptable risk for oil pipelines, presented in this paper, compare favourably with the work of a number of authors. For example, MaiVan proposes a value of $F_N = 450$ for acceptable risk in Vietnam based on the benefit-cost perspective. The work of MaiVan demonstrates the validity of cost-benefit approach in determining the acceptable risk level for probabilistic design of coastal flood defences. Similarly, Pandey and Nathwani (2003) present a life quality index (LQI) to determine acceptable air-quality standards in Canada. The LQI also centres on cost-benefit approach and the outcome is a confirmation of the viability of the cost-benefit approach in formulating acceptable risk levels.

However, one of the limitations of the model is subjectivity that may be present in the benefit-cost analysis. For example, a wrong subjective estimate of the policy factor β_i could yield an inaccurate level of acceptable individual risk. Therefore, more data may be required to establish the most acceptable norm values from both individual and societal perspective. In addition, defining acceptable risk based on accident statistics in a society

may not be an accurate representative of the cost-benefit perspective in the society. Involuntary deaths may vary with generational change, causing accident statistics to change over time. Moreover, measuring the acceptable level of risk based on a cost-benefit framework may not always go well with national regulatory agencies, and the society at large.

To improve the acceptability of the model, it may be interesting to investigate risk-based decision model from the perspectives of both the pipeline operator and the regulators. While regulators may be more interested in minimising risk, operators would most likely prefer to maximise profit. A utility approach that will satisfy multicriteria goals from these perspectives will be beneficial. In addition, since probability of failure vary for different installations based on different factors such as location, failure mechanisms, flow medium etc., it may be interesting to investigate how acceptable risk for different facilities will vary. The minimum safety distance that will maintain acceptable risk levels can be modelled under different failure scenario. Furthermore, the impact of changes in population on safety vicinity can be investigated.

In conclusion, the results appear to reflect rational decision making based cost-benefit weighting, in the sense that for the individual, the safety level is dependent on the level of risk a risk-taker is willing to take after weighing the benefits derived against the cost of risk. The risk based decision for the society is based on the number of people at risk and the economic importance of the area. The work aims to contribute to the present debate on risk management in the petroleum industry, by demonstrating the usability of probabilistic methods in facilitating decision making on the safety of technical installations. It should be noted however that the quantitative analysis presented is only to aid policy makers in the decision making process, and not intended to replace stakeholder's consultation, where required.

References

- Ahamed, M. and Melchers, R.E. (1996) 'Reliability estimation of pressurized pipelines subject to localized corrosion defects', *International Journal of Pressure Vessels and Piping*, Vol. 69, No. 3, pp.267–272.
- Ale, B.M.J. (1991) 'Risk analysis and risk policy in the Netherlands and the EEC', *Loss Prevention in Process Industries*, Vol. 4, No. 1, pp.58–64.
- Bottelberghs, P.H. (2000) 'Risk analysis and safety policy developments in the Netherlands', *Journal of Hazardous Materials*, Vol. 7, No. 71, pp.59–84
- Dawotola, A.W., Trafalis, T.B., Mustaffa, Z., van Gelder, P.H.A.J.M. and Vrijling, J.K. (2011) 'Data-driven risk based maintenance optimization of petroleum pipelines subject to corrosion', *In Proc., Twenty-first (2011) International Offshore and Polar Engineering Conference*, Maui, Hawaii, USA, 19–24 June.
- De Wolf, G.B. (2003) 'Process safety management in the pipeline industry: parallels and differences between the pipeline integrity management (IMP) rule of the office of pipeline safety and the PSM/RMP approach for process facilities', *Journal of Hazardous Materials*, Vol. 104, Nos. 1–3, pp.169–192.
- Department of Petroleum Resources (DPR) (2007) *Guidelines and Procedures for the Design, Construction, Operation and Maintenance of Oil and Gas Pipelines Systems in Nigeria*, Department of Petroleum Resources, Nigeria.
- Derby, S.L. and Keeney, R.L. (1981) 'Risk analysis: understanding "how safe is safe enough"', *Risk Analysis*, Vol. 1, No. 3, pp.217–224.

- Dey, P.K., Ogunlana, S.O. and Naksuksakul, S. (2004) 'Risk -based maintenance model for offshore oil and gas pipelines: a case study', *Journal of Quality in Maintenance Engineering*, Vol. 10, No. 3, pp.169–183.
- Environmental Protection Authority (2000) 'Guidance for risk assessment and management: off-site individual, risk from hazardous industrial plant', *Western Australia*, No. 2.
- Health and Safety Executive (HSE) (1999) 'Assessing the risk from gasoline pipelines in the United Kingdom based on a review of historical experience', Contract Research Report, 210/1999, prepared by WS Atkins Safety & Reliability.
- Health and Safety Executive (HSE) (2001) 'Reducing risks, protecting people; HSE's decision-making process', Health and Safety Executive, UK.
- Health and Safety Executive (HSE) (2010) 'HSE – keeping UK's pipelines safe', *Pipelines International*, December.
- Hong Kong Government Planning Department (2008) *Hong Kong Planning Standards & Guidelines*, Chapter 12.
- Institute of Chemical Engineers (1985) 'Nomenclature for hazard and risk assessment in the process industries', Institution of Chemical Engineers
- Khan, F.I. and Haddara, M. (2003) 'Risk-based maintenance (RBM): a quantitative approach for maintenance/inspection scheduling and planning', *Journal of Loss Prevention in Process Industries*, Vol. 16, No. 6, pp.561–573.
- Kirchoff, D. and Doberstein, B. (2006) 'Pipeline risk assessment and risk acceptance criteria in the State of Sao Paulo, Brazil', *Impact Assessment and Project Appraisal*, Vol. 24, No. 3, pp.221–234.
- Kumamoto, H. and Henley, E.J. (1996) *Probabilistic Risk Assessment and Management for Engineers and Scientists*, 2nd ed., IEEE Press, New York.
- Landoll, D.J. (2006) *The Security Risk Assessment Handbook: A Complete Guide for Performing Security Risk Assessments*, CRC Press, Taylor & Francis Group, Boca Raton, FL.
- MaiVan, C. (2010) 'Probabilistic design of coastal flood defences in Vietnam', PhD thesis, Delft University of Technology.
- Muhlbauer, W.K. (2004) *Pipeline Risk Management Manual*, 3rd ed., Gulf Professional Publishing, Burlington, Ontario.
- Nigerian National Petroleum Company (NNPC) (2008) *Annual Statistical Bulletin*, Nigeria.
- Oke, S.A., Charles-Owaba, O.E., Johnson, A.O. and Omogoroye, O.O. (2006) 'A fuzzy safety control framework for oil platforms', *International Journal of Quality & Reliability Management*, Vol. 23, No. 5, pp.564–582.
- Oke, S.A., Johnson, A.O. and Omogoroye, O.O. (2005) 'A neuro-fuzzy theoretic approach to safety control at crude oil exploration platforms', *Disaster Prevention and Management: An International Journal*, Vol. 14, No. 4, pp.454–461.
- Pandey, M.D. (1998) 'Probabilistic models for condition assessment of oil and gas pipelines', *NDT E International*, Vol. 31, No. 5, pp.349–358.
- Pandey, M.D. and Nathwani, J.S. (2003) 'Canada wide standard for particulate matter and ozone: cost-benefit analysis using a life-quality index', *Risk Analysis*, Vol. 23, No. 1, pp.55–68.
- Sii, H.S., Wang, J. and Ruxton, R. (2001) 'Novel risk assessment techniques for maritime safety management system', *International Journal of Quality & Reliability Management*, Vol. 18, No. 9, pp.982–1000.
- Streicher, H., Joanni, A. and Rackwitz, R. (2008) 'Cost-benefit optimization and risk acceptability for existing, aging but maintained structures', *Structural Safety*, Vol. 30, No. 5, pp.375–393.
- TAW (1985) 'Some considerations of an acceptable level of risk in the Netherlands', Technical Advisory Committee on Water Defences, the Netherlands.
- Teixeira, A.P., Soares, C.G., Netto, T.A. and Estefen, S.F. (2008) 'Reliability of pipelines with corrosion defects', *International Journal of Pressure Vessels and Piping*, Vol. 85, No. 4, pp.228–237.

- Trench, C. (2000) 'The safety performance of natural gas transmission and gathering systems', GRI-00/0077, Gas Technology Institute, Des Plaines, IL (formerly Gas Research Institute, Chicago, IL).
- Vrijling, J.K., van Gelder, P.H.A.J.M. and Ouwerkerk, S.J. (2005) 'Criteria for acceptable risk in the Netherlands. Infrastructure risk management processes: natural, accidental and deliberate hazards', *ASCE*.
- Vrijling, J.K., van Hengel, W. and Houben, R.J. (1995) 'Framework for risk evaluation', *Journal of Hazardous Materials*, Vol. 43, No. 3, pp.245–261.
- Vrijling, J.K., van Hengel, W. and Houben, R.J. (1998) 'Acceptable risk as a basis for design', *Reliability Engineering and System Safety*, Vol. 59, No. 1, pp.141–150.
- Wang, J., Sii, H.S., Yang, J.B., Pillay, A., Yu, D., Liu, J., Maistralis, E. and Saajedi, A. (2004) 'Use of advances in technology for maritime risk assessment', *Risk Analysis*, Vol. 24, No. 4, pp.1041–1063.
- World Health Organization (WHO) (2009) *Mortality and Burden of Disease Estimates*, Department of Measurement and Health Information.