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POSTGRADUATE THESIS

RISK MANAGEMENT FOR NATURAL GAS PIPELINE DISTRIBUTION NETWORKS

By

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RISK MANAGEMENT FOR NATURAL GAS PIPELINE DISTRIBUTION NETWORKS

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Abstract

Transmission pipelines carrying natural gas in order to distribute it to the final users are routed across the countries, for example highways, populated cities, industrial and agricultural areas. Consequently, there are various hazards such as natural disasters – for example earthquakes - third parties activities, material defects and human errors that are possible to interfere with the integrity of these pipelines. In addition, the combination of these hazards and pipeline route might suggest that people and the surrounding installations and buildings nearby the pipelines are subjected to significant risk in a case of pipeline failure. For all these reasons regulatory authorities and pipeline managers in many countries around the world endeavored to improve the level of safety of pipelines.

The present postgraduate thesis is concerned with the problem of natural pipeline risk assessment and management. Risk management involves assessing the risk sources and designing strategies and procedures to mitigate those risks to an acceptable level with the minimum cost. Various methods of qualitative, quantitative and semi-quantitative risk assessment methods are presented as well as methods of cost – benefit analyses. These methods are also involving the hazard and vulnerability analysis as well as the calculation of societal and individual risk. The main aim of this research is to point out risk management methodology that would be useful for natural gas industries' to decide which mitigation measures to implement on the existing pipelines with the minimum cost in an acceptable level of hazard.

Also, this research identifies the hazard and vulnerability factors of a natural gas pipeline network, quantifies and prioritizes them through risk assessment methods in order to choose the proper mitigation policies while minimizing the total cost and maximizing the profit of the mitigation measures (minimize risk level) using a knapsack formulation. The proposed model is applied to a natural gas pipeline network example.

Keywords: Risk Assessment; Hazard analysis; Vulnerability analysis; Risk management; Natural Gas; Knapsack problem.

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INTRODUCTION

1.1 Presentation of the problem

The framework of the present work encompasses a primarily experience-based comparison of risk assessment methods associated with pipeline hazards carrying natural gas. The results of this research provide a broader perspective of the natural pipeline risk assessment and management method, as well as cost-benefit analysis by using a knapsack model. This information can be implemented not only by the natural gas industries' managers but also by other industries beyond the gas sector.

Natural gas is a clean energy source with increasing demand in Greece the last years and worldwide. The main uses of natural gas are for residential, commercial, industrial uses as well as for electricity production. Not only is natural gas cheap for the residential consumer, it also has a number of different uses.

The best known uses for natural gas around the home are natural gas heating and cooking. Also, natural gas space and water heating for commercial buildings is very similar to that found in residential houses. Natural gas is an extremely efficient, economical fuel for heating in all types of commercial buildings. Although space and water heating account for a great deal of natural gas use in commercial settings, non-space heating applications are expected to account for the majority of growth in natural gas use in the commercial sector. Moreover, industrial applications for natural gas are many, including the same uses found in residential and commercial settings; heating, cooling, and cooking. Natural gas is also used for waste treatment and incineration, metals preheating (particularly for iron and steel), drying and dehumidification, glass melting, food processing, and fuelling industrial boilers. Natural gas may also be used as a feedstock for the manufacturing of a number of chemicals and products. Gases such as butane, ethane, and propane may be extracted from natural gas to be used as a feedstock for such products as fertilizers and pharmaceutical products[1].Three types of companies comprise the natural gas industry: extraction companies, pipeline transportation companies and local distribution companies.

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[1] www.naturalgas.org/overview/uses.asp

Installing and operating a pipeline network that transfers big quantities of natural gas for residential, commercial and industrial applications, is a safe method of transportation and distribution considering the consequences to human factor, environment, and infrastructures of a region and to the industry's economic activity, when buildings, natural gas systems and appliances are constructed, installed and maintained properly. Although the use of natural gas, like any flammable fuel, carries some risk of fire or explosion. In particular, the major risk that involves a natural gas pipeline is a severe leakage or rupture of pipe that could cause fire or explosion. Natural gas is lighter than air, and so tends to escape into the atmosphere. But when natural gas is confined, such as within a house, gas concentrations can reach explosive mixtures and, if ignited, result in blasts that could destroy buildings. The methane, that is the basic ingredient of natural gas, is colourless, odourless and flavourless. It isn't toxic, but it is categorized to the asphyxiating gasses and involves only the danger of inhalation. Like all gases, if are inhaled in high concentration, could cause lack of oxygen and lead to suffocation, however the probability to be caused by leakage is minimal.

It must be underlined that distribution networks are designed with a degree of redundancy that ensures reliable supply of the product. In order to manage the operations of a pipeline network compressor, gas pressure is raised in order to offset pressure drops due to friction or to pack the lines. Pressure reduction units couple the various grade networks and manual or remotely operated valves isolate sub-networks. In addition meters at various points and on each service line, are required for charging customers and managing the network. All these devices have their own operational performance and safety characteristics, usually presented in detail in manufacturers' manuals. This research is concerned with the management of a technological accident in natural gas distribution networks that may have impacts on human factor, environment, infrastructures/installations and economic activity of the gas industry.

Several methods – qualitative, quantitative and semi-quantitative – have been developed in order to assess the risk of distributing natural gas via pipeline network. Qualitative risk index approaches assign subjective scores to different factors that are thought to influence the probability and consequences of a failure[2]. These scores are then combined using simple formulas to give an index representing the level of risk.

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[2] Muhlbauer, 1992; Cagno *et al*., 2000; Dey & Gupta, 2001

Risk index approaches provide a ranking of the different process components based on the perceived level of risk estimated. The ranking obtained by using these methods is highly subjective. In addition, these approaches do not provide any indication of whether the risk associated with a component is unacceptable and consequently no guidance is provided regarding whether any risk reduction action is necessary.

The index system scoring format suggested by Muhlbauer (1992) accounts for the use of in-line inspection tools to locate metal loss corrosion by awarding up to 8 points out of a maximum of 400 points representing resistance to failure (i.e., 2%). This underestimates the benefits of high-resolution pigging, which is known to result in significant reductions to the large percentage of failures that are attributable to corrosion (20–40% of all failures). Therefore, index systems provide at best an approximate risk-based ranking of process components, which has serious limitations when being used as a basis for integrity management decision making.

Moreover, current quantitative risk assessment approaches focus on a single aspect of the consequence associated with failure. Published studies deal with either loss of life risk or economic risk[3]. Integration of environmental damage, human factor safety, infrastructure and installations damage as well as economic activities risks has not been addressed adequately. Another limitation of quantitative risk assessment approaches is that they typically base the estimation of failure probability on historical failure rates.

Another approach to calculate failure probability is based on the concept of structural reliability that includes Markovian models and hot spots on a component-by-component basis[4]. The effect of the correlation from one hot spot to another has been investigated by Lotsberg et al. (1998), Faber et al. (1999), Brown and May (2000), and Montgomery et al. (2002). Faber et al. (2000, 2003) proposed an informal decision analysis where the number of considered elements is reduced in a consistent and systematic way. However, due to the numerical effort required and the stability of the method such an approach did not prove to be practical. Straub and Faber (2000) indicated that an integrated approach to the decision problem that is suitable for industrial purposes has not yet been developed.

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[3] Hill, 1992; Concord, 1993; Nessim & Stephens, 1995; Pandey, 1998; Nessim *et al*., 2000
[4] A number of interesting articles may be seen in *Journal of Infrastructure Systems*

Semi-quantitative approaches were also developed to provide a practical and easy tool to be used for designing maintenance programs that optimize the use of resources and in the meantime ensure effective and efficient asset management. These approaches use semi-quantitative models for consequence estimation as well as failure probability calculations. Examples of these approaches can be found in Khan and Haddara (2003a, 2003b), Khan and Haddara (2004), and Khan *et al.* (2004). It is easily employed in process plants and to components like pipelines or pressure components. These approaches provide a tool to ascertain that the estimated risk of failure satisfies a predetermined acceptance criterion[5].

During this research we tried to identify the hazard and vulnerability parameters in order to assess and prioritize the level of risk in a natural gas pipeline network and the better management of "potential disasters" that can be caused by natural gas pipelines failure, or in transfer stations of natural gas with the minimum possible cost (available financial resources) and the maximum profit by using the knapsack model.

1.2 Motivation

The increase in energy demand and the decrease of petroleum deposits lead to request of new energy sources. The most popular energy source during the last years, is natural gas; currently provides 23% of the European Union’s primary energy consumption and it is anticipated that this will grow to around 28% in 2020. As a consequence, gas industry owners and operators will experience considerable increases in the use of their distribution networks in the coming years. Even though the transportation of natural gas by pipelines is considered the safest method, historical evidence has shown that accidents due to hazardous releases during transportation can lead to severe consequences on the human factor (deaths, injuries), environment (forest fire due to the explosion, but this possibility is minor considering the pipeline routing concerns mostly urban areas), infrastructures of the region and the natural gas installations, and economic activity of the gas industry.

Several accidents have happened worldwide in natural gas pipelines with serious impacts to the safety of citizens. According to the EGIC report[6] of venturousness, regarding the length of pipelines and their operation age, is 2.77 millions/km per year in the European network of pipelines. The total frequency of accidents is 0.41

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[5] Khan *et al*., 2004; Willcocks&Bai, 2000; Dey, 2004

[6] 6th Report of EGIC - Base of Given Accidents European Network of Conductors of Transport of Gas

accidents/year/1000 km for the period 1974 - 2004, which however is decreased continuously with the passing of time and a tendency of stabilisation, is observed at the last years. The most striking example of accident in a natural gas pipeline distribution network that has been recorded in the recent years was the one in Japan in 1995, where the distribution system of natural gas failed due to an earthquake (magnitude of 7.2 R) and caused the death of 60.000 people.

A natural-gas pipeline is actually a system of equipments designed to allow gas flow from one location to another. The area of hazard associated with the damage will depend on the mode of pipeline failure, time to ignition, environmental conditions at failure point and meteorological conditions. The identification of the hazard zones and the calculation of individual and societal risk due to natural gas pipeline failure and the selection of prevention and mitigation measures can be achieved by applying a pipeline risk assessment methods. The failure of a natural gas pipeline may be time independent; such as third party damage, ground movements, overpressure or time dependent; such as material failure or corrosion. Therefore, regulatory authorities and pipeline managers is focused in improving the level of safety of the pipeline.

If a natural gas pipeline fails, then several severe consequences for individuals and society at large is possible to happen. Specifically, damage to natural gas network may cause gas leakage within customers’ facilities. The amount of leakage depends on the severity of damage and the operating pressure of the pipelines. In many cases for residential appliances, damage may include partial or complete fracture of threaded pipe connections, flexible tubing, pipe fittings, and damage to vent piping.

Also, the risk of a gas-related fire in residential structures following natural gas pipeline failure is generally very low because of the numerous conditions necessary for gas ignition[7]. The ignition of leaking gas requires an ignitable mixture of gas and oxygen between the approximate range of lower (5%) and upper (15%) explosive limits and an ignition source. This can occur in the presence of a pilot light or when a light switch is turned on or off. The likelihood of ignition is higher in conditions where poor air mixing allows formation of higher concentrations of gas.

Moreover, the most common consequence of severe pipeline failure to the natural gas systems is interruption in natural gas supply. Despite the fact that public service announcements consistently advise customers to shut off service only if they smell

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[7] see, for example, Williamson and Groner, 2000

gas, hear gas escaping, see a broken gas line, or observe structural damage to the building, customers continue to cut off their gas as a precaution.

For all the above reasons, risk management of natural gas pipelines is becoming more advanced, and many operating and inspection companies are following the trend of computerization to assist efforts of risk assessment and management. The main task however, before any risk assessment or management model can be implemented, is to identify the failure influencing mechanisms affecting a pipeline. Once the outline of the model is known it is recommended that further subdivisions be performed in order to arrive at a more accurate picture of the risks associated with the pipeline.

The proposed rules have been reviewed and the probable quantitative benefits may not outweigh the probable costs. Because it is difficult to attach financial figures to all benefits and values, the legislature has mandated that agencies consider both qualitative and quantitative benefits and costs when performing cost benefit analyses, as well as the specific directives of the statute being implemented.

However, there are important probable benefits to these rules that are qualitative rather than quantitative. The attached cost benefit analysis largely focuses on the probable quantitative benefits and costs of the contingency plan rules. While the rules' probable costs and expenditures are easily tabulated, converting subjective values into monetary equivalent is difficult and, in some cases, not possible. Probable qualitative benefits for which we have not assigned a monetary value include: effectively responding to a worst case spill scenario, preventing the ongoing detrimental impacts of a worst case spill scenario, protecting cultural and spiritual values of traditional tribal lands, decreasing impacts to endangered species, preserving recreational opportunities, creating a level playing field, and not rolling back contingency plan standards to where they were over twelve years ago.

1.3 Structure of the Postgraduate Thesis

In Chapter 2, we carry out a literature review of the risk assessment models and management methodologies that are applied around the world to prevent and response effectively to a natural gas pipeline failure. We present methods of pipeline management were summarised prevention and detection practises that are applied in natural gas pipelines networks globally, in order to assure the integrity of the pipeline regarding the existing circumstances.

In Chapter 3, we make an introduction of the natural gas distribution system basics and we present some of the accidents that have recorded to several natural gas pipelines globally and had led to a disaster with substantial consequences.Based on the literature, there is no unique definition of a severe accident. All definitions include various consequence (damage) types (evacuees, injured persons, fatalities or costs) and a minimum level for each damage type. The differences between the definitions concern both the set of specific consequence types considered and the damage threshold. Various types of consequences are covered to differing extents because of differences in availability and quality of information. The highest degree of completeness is available for fatalities and the economic damage in total.

In Chapter 4, we present the proposed risk management model that could be applied to pipelines networks carrying natural gas. By this model hazard and vulnerability factors of a natural gas pipeline failure are identified and the level of risk (risk indicator) is calculated for the main four categories of social and economic life of the area; human factor, environment, area's infrastructure and gas installations as well as the economic activity of the industry. The possible mitigation measures that can be taken in order to lower the risk indicator for one or multiple hazard and vulnerability parameters are also identified. Then these measures are prioritizing, based on the benefit (risk indicator before taking the mitigation measure – new risk indicator after the implementation of the mitigation measure), the cost of the mitigation measures and the available industry's financial capitals. This cost-benefit analysis is achieved through the application of the knapsack model.

In Chapter 5, the hazard parameters that can cause natural gas pipeline failure are identified and the method for calculating the possibility of a pipeline failure occurrence is presented. The hazard analysis includes a review of potential hazards sources associated with natural gas to be processed, used and handled at the peaking power plant and associated pipelines and facilities. The main hazard associated with the proposed development is related to a leak and ignition of flammable natural gas or to a lesser degree, to a leak of combustible liquids (distillate). The hazard identification includes a comprehensive identification of possible causes of potential incidents to pipeline distribution network and their consequences to human factor, environment, infrastructures within the surrounding area and the gas installations and the industry's economic activity.

In Chapter 6, we identify the vulnerability parameters that can increase the impact of a pipeline failure and we calculate the possibility of failure consequences to the following four (4) main categories: human factor, environment, infrastructure and installations and economic activity of the industry. Moreover we describe in detail the risk assessment method, which combines the possibility of pipeline failure occurrence (hazard, see Chapter 6) and the possibility of vulnerability to disasters considering that the failure has occured.

In Chapter 7, the proposed countermeasures for preventing and mitigating a potential accident or disaster that may occur at a pipeline network are presented in order to implement a cost – benefit analysis that can lead to the optimization of pipeline risk management with the minimum cost within the available amount of expenditures that the industry is willing to provide. For this purpose we introduce dynamic knapsack model.

Finally, in Chapter 8 the outcomes of the previous chapters are presented as well as some outline guidance regarding the risk management of a natural gas distribution network that can assist the gas industry managers to prioritize their needs and to allocate the available amount with the most appropriate way.

CHAPTER 2

LITERATURE REVIEW

This chapter begins by outlining some basic approaches used in the pipeline risk assessment and management research. We begin with a review of the basic methodologies used in the assessment of technological risk. According to this perspective, we classify the basic methods used in practise. The relevant literature mainly comprises phases in risk assessment and management approaches, qualitative approaches, quantitative and semi-quantitative models that represent the likelihood of risks on natural gas pipeline distribution system.

There are many economic actors interested in the assessment and management of technological risk of natural gas pipeline distribution network. A list includes natural gas production industries, owners and operators of distribution systems, insurance companies, safety technology manufacturers, regulatory agencies, applied technology research laboratories and institutions and concerned public.

The risk performance of a pipeline system is assessed by observing process details (manufacturing process diagrams), inputs (quality of raw material, level of expertise of inspection personnel) and outputs. Risk assessment may measure performance indicators directly of it may use estimated provided by experts. At the end, a risk indicator is produced that may be simple or complex. The risk indicator is contrasted to a comparison basis.

Moreover, risk assessment is a measuring process and a risk model is a measuring tool. The risk associated with pipeline failure doesn’t depend only on the “failure probability” but also from the “vulnerability and failure consequences” of all the potential risk scenarios. When it comes to basic pipeline risk assessment, the main consequences of concern are related to public health and safety (injuries and deaths), gas installations and infrastructure damage including environmental consideration.

Risk-based methods aim at identifying, characterizing, quantifying, and evaluating the likelihood of the loss caused as a result of the occurrence of a specific event. The use of risk-based methods for the management of the process components provides reliable quantification of potential risks. This provides an alternative strategy for the maintenance of assets instead of the use of simple ranking (prioritizing) based on reported failure occurrences.

It is important to make the distinction between a hazard and a risk because risk is changeable without changing a hazard. For example, ground movement is a hazard for a natural gas pipeline network that generates the risk of explosion or leakage. In addition, hazard is a characteristic or a group of characteristics that posse threat to pipeline integrity. Identified threats can be generally grouped into two categories: time-depended failure mechanisms and random failure mechanisms. Hazard analysis refers to identifying mechanisms that can lead to a pipeline failure with accompanying consequences.

2.1 Pipeline hazards identification literature

Several methodologies are available to identify hazards and threats varying in approach and degree of formality. Common hazard evaluation tools such as event trees, fault trees, "what-if" analysis and Hazard and Operability Studies (HAZOP) are used to identify all threats to pipeline integrity.

HAZOP: A hazard and operability study is a team technique that examines all possible failure events and operability issues through the use of keywords prompting the team for input in a very structured format. Scenarios and potential consequences are identified, but likelihood is usually not quantified in HAZOP. Strict discipline ensures that all possibilities are covered by the team. When done properly, the technique is very thorough but time consuming and costly in terms of person-hours expended. HAZOP and failure modes and effects analysis (FMEA) studies are especially useful tools when the risk assessments include complex facilities such as tank farms and pump/ compressor stations.

Fault-tree / event-tree analysis. Tracing the sequence of events backward from a failure yields a fault tree. In an event tree, the process begins from an event and progresses forward though all possible subsequent events to determine possible failures. Probabilities can be assigned to each branch and then combined to arrive at complete event probabilities.

2.2 Pipeline risk assessment problem.

First of all, risk is most commonly defined as the probability of an event that causes a loss and the potential magnitude of that loss. By this definition, the risk is increased when either probability of the event increases or when the magnitude of the potential loss increases. Transportation of products by pipelines includes risk because there is a probability of the pipeline failing, releasing its contents and causing damage.

Furthermore, in the most of the scientific researches, risk is referred as a measure of human loss and is translated in two quantities: the possibility of pipeline failure and the number of fatalities. Moreover, the impacts of a disaster or an accident are depending from the scenario parameters such as hole size, time of fire ignition, meteorological and environmental conditions at the location of the accident. Due to these parameters, the results of the risk assessment study could vary regarding the assumptions that have been done at the accident scenario. A great number of calculations are sometimes inevitable due to different scenarios and the distribution of the risk sources along the pipeline.

The most commonly accepted definition of risk is often expressed as a mathematical relationship:

$$Risk = \text{ event likelihood } \times \text{ event consequence}$$

The risk assessment models for the pipeline failure are divided in three main categories; (1) Qualitative, (2) Quantitative and (3) Semi Quantitative.

2.2.1 Qualitative Approaches

Qualitative methods may focus only on relative consequences or assess the probability and consequences in relative terms, such as high, medium and low. Qualitative approaches combining probability and consequences often use numerical scoring methods to generate a relative risk ranking of various pipeline segments and of various lengths along a pipeline route. Pipeline operators sometimes use these methods to set priorities for rehabilitation, repairs, inspection and testing of specific line segments. These methods define a number of risk factors, each of which is assigned a numerical value. The factors are mathematically combined, usually cumulative, to yield a numerical score value for each predefined segment length of the pipeline. In this way, segments can be ranked and grouped according to relative risk associated with a leak or spill.

In addition, qualitative approaches require expert opinions or a knowledgeable person's views. An expert can be the one who has extensive knowledge about the field related to project or who has worked on similar projects in the past. The major disadvantages of using qualitative approaches are the amount of subjectivity during the project, variation in human judgments, and lack of standardized approach. There have been numerous approaches suggested by Chapman (1998), like Delphi techniques and nominal group techniques to minimize the biasing, which exists, but still these approaches do not reduce the amount of subjectivity present in the process. Also, they are comparatively economical and readily applied but are unable to provide numerical estimates or relative rankings for the risks identified.

Qualitative risk index approaches assign subjective scores to the different factors that are thought to influence the probability and consequences of failure (Muhlbauer, (1992); Cagno et al. (2000); Dey et al. (2001)). These scores are then combined using simple formulas to give an index representing the level of risk. Risk index approaches provide a ranking of the different process components based on the perceived level of risk estimated. The ranking obtained by using these methods is highly subjective. In addition, these approaches do not provide any indication of whether the risk associated with a component is unacceptable and consequently no guidance is provided regarding whether any risk reduction action is necessary.

The index system scoring format suggested by Muhlbauer (1992) accounts for the use of in-line inspection tools to locate metal loss corrosion by awarding up to 8 points out of a maximum of 400 points representing resistance to failure (i.e., 2%). This underestimates the benefits of high-resolution pigging, which is known to result in significant reductions to the large percentage of failures that are attributable to corrosion (20–40% of all failures). Therefore, index systems provide at best an approximate risk-based ranking of process components, which has serious limitations when being used as a basis for integrity management decision making.

2.2.2 Quantitative Approaches

Quantitative Risk Assessment (QRA) tries to overcome the disadvantages of the qualitative risk assessment. Risk rankings, Risk Factors, Probabilistic Risk

Assessment (PRA), and Hierarchical Holographic Modeling (HHM) are popular approaches that have been successfully implemented in the past by several authors.

These methods seek to estimate numerical event frequencies or probabilities, for a specified time period, associated with specific, measurable consequences and determine the level of risk based on direct estimates of the probability and/or consequences of failure. For example, the risk of fatality from a pipeline accident can be expressed as the annual probability that a fatality might occur. This is the basis of the ***Individual Risk*** and ***Social Risk Analysis***.

The major advantages of quantifying the risks are providing an adequate understanding of failure, consequences and events, which are difficult to explain by a qualitative approach. In addition, it is easier to understand the overall process, reach the appropriate decision and allocate resources based on quantitative data rather than qualitative opinions.

Current quantitative risk assessment approaches focus on a single aspect of the consequence associated with failure. Published studies deal with either loss of life risk or economic risk (Hill (1992); Concord (1993); Nessim et al. (1995); Pandey (1998); Nessim et al. (2000)). Integration of environmental damage, life safety, and economic risks has not been addressed adequately. Another limitation of quantitative risk assessment approaches is that they typically base the failure probability estimates on historical failure rates.

Publicly available databases do not usually allow subdivision of the failure data according to the attributes of a specific process component and where adequate subdivision is possible, the amount of data associated with a particular attribute set is very limited because of the rarity of the failures. Failure probabilities are estimated from public data, therefore are not sufficiently specific to represent a given failure in a specific process component.

Another approach to calculate failure probability is based on the concept of structural reliability that includes Markovian models and hot spots on a component-by-component basis. The effect of the correlation from one hot spot to another has been investigated by Lotsberg et al. (1998), Faber et al. (1999), Brown et al. (2000), and Montgomery et al. (2002). Faber et al. (2000, 2003) proposed an informal decision analysis where the number of considered elements is reduced in a consistent and systematic way. However, due to the numerical effort required and the stability of the method such an approach did not prove to be practical. Straub et al. (2000)

indicated that an integrated approach to the decision problem that is suitable for industrial purposes has not yet been developed.

Jo et al. (2005) proposed a quantitative risk assessment for transmission pipeline carrying natural gas and introduce parameters for fatal length and cumulative fatal length that is defined as the integrated fatality along the pipeline associated with hypothetical accidents. Also, the cumulative fatal length is defined as the section of pipeline in which an accident leads to *N* or more fatalities. These parameters can be estimated easily by using the information of pipeline geometry and population density of a Geographic Information Systems (GIS). The model calculates individual risk in a seven step procedure and societal risk in a eight step procedure of natural gas pipeline. The main outcome of this method is that may be useful for risk management during the planning and building stages of a new pipeline and modification of a buried pipeline.In order to demonstrate and evaluate the proposed method, it was applied to a sample pipeline and the individual and societal risks have been estimated for the historical data of European Gas Pipeline Incident Data Group and BG Transco.

The Muhlbauer Model (1992) was adopted as the framework for the risk assessment process. As first published, the Muhlbauer Model was used to assign numerical scores to each of four hazard indices: Third Party Damage; Corrosion; Design, and Incorrect Operations. These factors were then numerically combined and a “Leak Impact Factor” (consequence factor) was applied to provide a relative measure of pipeline risk. The intent of the Muhlbauer Model was to provide a comprehensive framework for conducting pipeline risk assessments that could be modified to adequately account for unique situations, yet still provide a defensible system for relative comparisons between various pipelines or pipeline segments.

Another approach is the LOPA (layer of protection analysis) that is a simplified risk assessment used to identify safeguards to meet the risk acceptance criteria. Safety and protection measures in pipelines are formed into a multi-layer protection system which functions in a specified sequence. The LOPA assumes that no layer of protection is perfect; every layer has some probability failure on demand (PFD). Therefore, the risk of the occurrence of unwanted consequences depends on the failure of the safeguards. In the determination of the final risk level for a selected accident scenario, the event tree method is applied. The application of LOPA for pipelines risk assessment as a alternative method to QRA is given by Markowski (2003).

Risk Ranking

The most popular pipeline risk assessment technique in current use in the index model or some similar scoring technique. In this approach, numerical values (scores) are assigned to important conditions and activities on the pipeline system that contribute to the risk picture. This includes both risk – reducing and risk – increasing teams and variables. Weightings are assigned to each risk variable. The relative weight reflects the importance of the item in the risk assessment and is based on statistics were available and on engineering judgment where data are not available. Each pipeline section is scored based on all of its attributes. The various pipe segments may then be ranked according to their relative risk scores in order to prioritize repairs, inspections and other risk mitigating efforts. Among pipeline operators today, this technique is widely used and ranges from a simple one or two factor model (e.g. leak history and population density) to models with hundreds of factors considering virtually every item that impact risk.

The Decision – Analysis Matrix is one of the simplest risk assessment structures. It ranks pipeline risks according to the likelihood and the potential consequences of an event be a simple scale (high, medium or low) or a numerical scale (e.g. from 1 to 5). Each threat is assigned to a cell of the matrix based on its perceived likelihood and a high consequence appears higher in the resulting prioritized list. This approach may simply use expert opinion or a more complicated application might use quantitative information to rank risks. While this approach cannot consider all pertinent factors and their relationships, it does help to crystallize thinking by at least breaking one problem into 2 parts (probability and consequence) for separate examination

Risk ranking is the efficient way to set up risk priorities. Florig, et al. (2001) developed a method whereby risk experts categorize and define the risks to be ranked, identify the related risk attributes, and characterize the risk. This five-step approach starts with the iterative process of defining and categorizing the risks to be ranked and the set of attributes that describe those risks. Based on risk attributes, the next step is to create the risk summarization sheets. Then, participants are selected and risk rankings are prepared based on the risk summarization sheets. Finally, a description of issues identified and the resulting rankings are prepared.

The authors also suggested that risk ranking should be viewed as only one input to the decision-making process and not for the final recommendations for management decision-making priorities. Also, based on higher to lower ranking management can assign the controls and resources to mitigate the risk. Several authors (Webler, et al. (1995); Morgan, et al. (2000)) have suggested different risk ranking methodologies according to their respective fields.

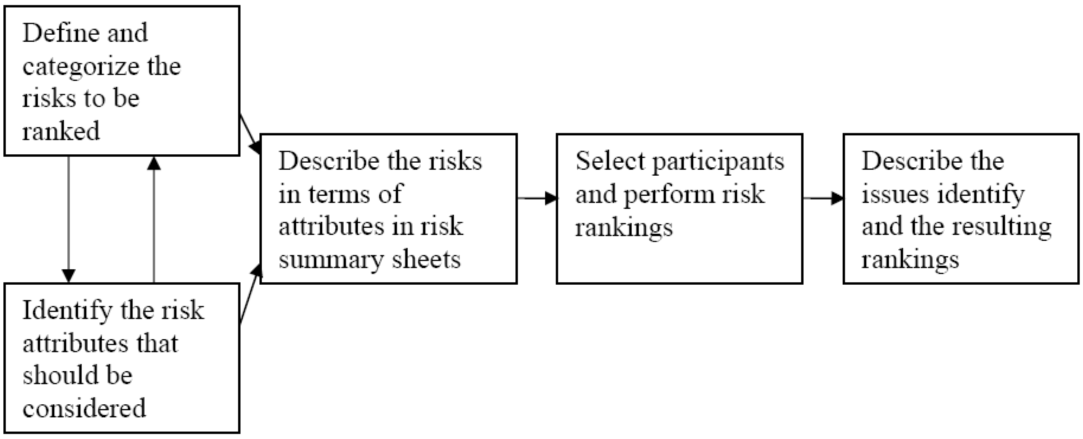


Figure 2.1 Steps in Risk-Ranking method

Henselwood et al. (2005) proposed a matrix-based approach of risk assessment that has been developed so as to determine the risks associated with high-vapor pressure liquids pipelines. The approach involved the development of a matrix representing each 100m section of the reviewed pipeline along with approximately 30 risk factors that describe that section of the pipeline. Further, a receptor matrix was constructed to account for each hectare of land within 1 km of the reviewed pipeline system. This approach has allowed the determination of risk as a function of location and separation from the pipeline and in turn has allowed for the determination of those areas where peak risks exist. In addition, this approach has ensured that the linear geometry related to pipeline risks has been accurately modeled.

One of the keys to the current risk assessment approach is that the length scale associated with major events (several 100 m) is significantly larger than the length scale associated with the receptor matrix (100m _ 100m units). Increasing the resolution of the receptor matrix and working with 1/9th of a hectare unit (same total land area covered) resulted in the average occupant vulnerability increasing by less than 1% for those events which resulted in the most significant outcomes (late ignition - rupture scenarios leading to fire and explosion). As such the selected receptor matrix is likely appropriately scaled and represents a balance between resolution and source data quality while ensuring calculation requirements are manageable.

The main advantages of indexing models are summarized as follows:

- Provide immediate answers
- Are a low-cost analysis (intuitive approach using available information)
- Are comprehensive (allow for incomplete knowledge and is easily modified as new information becomes available)
- Act as a decision support tool for resource allocation modeling
- Identify and place values on risk mitigation options

Risk Factors

Risk factorization is a method in which risk experts identify the risks, assign weights to those risks, and identify the total risk scores. Based on total risk scores, management sets their priorities to allocate the resources and design controls. Factorization of risk is a step-by-step approach toward quantifying the risk. Also, calculating the Risk factors is the most economical and effective way to identify the risk priorities. The risk factorization methodology is a very powerful decision-making tool to identify and prioritize the risk factors according to their order from highest to lowest, but the major disadvantage of this system is the amount of subjectivity within the method.

The major divisions into which risk factors can be divided are design, construction, operation, and maintenance. These four areas are associated with the lifecycle of most engineered systems. The design of the system is carried out first, and then the construction phase. Next, once the construction is finished, the system has to be operated and maintained. Errors in any of the four areas may lead to system’s failure, which may occur instantly or cause its slow degradation. Towards the end of the system’s life more and more failures start occurring, as it nears decommissioning.

The hazard function illustrates that the amount of risk is associated with an item at time t. In the case of manufactured items like pipelines the hazard function takes on a bathtub-shaped form, where the hazard function decreases initially and then increases as items age. Often manufacturing, design or component defects cause early failures. The period in which these failures occur is called the *burn-in period*. Once items pass through this early part of their lifetime, they have a fairly constant hazard function, and failures are equally likely to occur at any point of time. Finally, as items continue to age, the hazard function increases without limit, resulting in *wear-out* failures. For pipelines, the burn-in period is highly influenced by construction and design errors, while the wear-out period is dependent on maintenance, operation and again, design. The reliability of a pipeline is constantly dependent on how accurate the design is, therefore the greatest care should be practiced during the system design phase.

The failure of a high pressure gas pipeline is defined as a leak or rupture caused by damage such as external interference, corrosion, fatigue or ground movement. Leaks are defined as gas losses through a stable defect and ruptures are defined as gas losses through an unstable defect which extends during failure. The escaping gas may ignite, resulting in a fireball, crater or jet fire which can generate thermal radiation.

Probabilistic Risk Assessment (PRA)

The most rigorous and complex risk assessment model is a modeling approach commonly referred to as probabilistic risk assessment (PRA) and sometimes also called quantitative risk assessment (QRA) or numerical risk assessment (NRA). This technique is used in nuclear, chemical and aerospace industries and to some extent to petrochemical industry.

PRA is a rigorous mathematical and statistical technique that relies heavily on historical failure data and event-tree/fault-tree analyses. Initiating events such as equipment failure and safety system malfunction are flowcharted forward to all possible concluding events, with probabilities being assigned to each branch along the way. Failures are backward flowcharted to all possible initiating events, again with probabilities assigned to all branches. Final accident probabilities are achieved by chaining the estimated probabilities of individual events. This model needs extensive data and is considered one of the most expensive technique. Its output is usually a form whereby its results can be directly compared to other risks such as tornado damages. PRA – type techniques are required in order to obtain estimates of absolute risk values expressed in fatalities, injuries, property damages etc. per specific time period.

Hierarchical Holographic Modeling (HHM)

Haimes (1981) started his research in the field of HHM that addresses the issues related to hierarchical institutional, managerial, organizational or functional decision-making structures. Kaplan et al. (2001) suggested that HHM has been regarded as a general method for identifying the set of risk scenarios and could be viewed as one of the methods of Theory of Scenario Structuring (TSS), which is the part of QRA that is useful in identifying the set of risk scenario. HHM is particularly useful in modeling large-scale, complex, and hierarchical systems. Himes, et al. (2002) suggested that the nature and capability of HHM is to identify a comprehensive and large set of risk scenarios. To deal with this large set, a systematic process that filters and ranks these identified scenarios is needed so that risk mitigation activities can be prioritized.

The HHM methodology recognizes that most of the organizational as well as of the technology-based systems are hierarchical in structure, and thus the risk management of such systems must be driven by and responsive to this hierarchical structure. The risks associated with each subsystem within the hierarchical structure contribute to and ultimately determines the risks of the overall system.

The major advantage of the HHM framework for risk assessment and management is its ability to identify risk scenarios that result from and propagate through multiple overlapping hierarchies in real-life systems. In planning, design, or operational modes, the ability to model and quantify the risks is contributed by each subsystem and facilitates understanding, quantifying, and evaluating the risks of the whole system. In particular, the ability to model the intricate relations among the various subsystems and the ability to account for all relevant and important elements of risk and uncertainty renders this modeling process is more representative and encompassing.

Relative risk models Literature

Numerous factors affect the risks associated with pipeline failures. Information on all factors will typically be incomplete. Assumptions and default values will be required for some of the input data requirements. This necessarily limits the accuracy of the risk estimation for a specific length (segment) of a pipeline. It is very difficult to determine the probability associated with a specific short segment of pipe. The relationship among the factors that affect the probability of failure and the failure rate remains an area of ongoing industry interest and research. Relative risk models have been developed that can be used to adjust generic failure rate data to account for specific local attributes in a pipeline network.

An efficient way of evaluating risk along a pipeline is to divide it into segments with similar risk characteristics. The number of variables considered in the process determines the number of segments. Segmenting criteria include variables such as pipe specifications (diameter, wall thickness etc.), coating type, age and population density. There are several approaches of pipeline segmenting such as fixed-length method of sectioning, based on rules such as “every mile” or “between block valves”, or “between pump stations” is often proposed. While such an approach maybe initially appealing it will usually reduce accuracy and increase costs. Inappropriate and unnecessary break points that are chosen limit the model’s usefulness and hide risk hot spots if conditions are averaged in the section or risks will be exaggerated if worst case conditions are used for the entire length. It will also interfere with the efficient ability of the risk model to identify risk mitigation projects.

Another one is the dynamic segmentation that is the most appropriate method for sectioning the pipeline by inserting a break point wherever significant risk changes occur. A significant condition change must be determined by the evaluator with consideration given to data costs and desired accuracy. The idea is for each pipeline section to be unique, from risk perspective, from its neighbors. So, within a pipeline section we recognize no differences in risk, from beginning to end of the pipeline. The neighboring sections differ in at least one risk variable; it might be a change in pipe specification (wall thickness, diameter etc.), population or other factors. Section length is not important as long as the selected characteristics remain constant.

2.2.3 Semi - Quantitative Approaches

Semi-quantitative approaches were developed to provide a practical and easy tool to be used for designing maintenance programs that optimize the allocation of resources and in the meantime ensure effective and efficient asset management. These approaches use semi-quantitative models for consequence estimation as well as for failure probability calculations. Examples of these approaches can be found in Khan et al. (2003a, 2003b), Khan et al. (2004), and Khan et al. (2004). It is easily employed in process plants and to components like pipelines or pressure components. These approaches provide a tool to ascertain that the estimated risk of failure satisfies a predetermined acceptance criterion (Khan et al. (2004); Willcocks et al. (2000); Dey (2004)).

The risk-based inspection and maintenance approach was discussed by Willcocks et al. (2003) who introduces a failure modes effect analysis to identify the failure modes of system components and their consequences. Following, he introduces failure patterns and rates to calculate the probability of failure, and determines the risk to be used in inspection and maintenance planning. Depending on the level of risk for each mode and pattern of failure, the required analysis, inspection, maintenance, and repair tasks are selected. For example, a review of historical failure databases indicates that the major failure modes in a pipeline are internal corrosion and external impact. Thus, the main efforts (in terms of design, structural modeling, inspections, etc.) should be focused on these failure modes. Of course, this is a simple example of risk-based inspection and maintenance.

Dziubinski et al. (2006) presented a risk assessment methodology for dangerous substances transportation by long pipelines by combining qualitative (historical data analysis, conformance test and scoring system of hazard assessment) and quantitative techniques of pipeline safety assessment. This enabled a detailed analysis of risk associated with selected hazard sources by using quantitative techniques. The proposed methodology comprises a sequence of analyses and calculations used to determine basic reasons of pipeline failures and their probable consequences, taking individual and societal risk into account. To verify above methodology, complete risk analysis was performed for the long distance fuel pipeline in Poland.

A large number of articles were published on the subject of optimizing maintenance through the use of mathematical models (Montgomery et al. (2000); Khan (2003a, 2003b); Willcocks (2003); Dey (2004)). Most of the maintenance optimization models are based on lifetime distributions or Markovian deterioration models. It is often difficult to collect enough data for estimating the parameters of a lifetime distribution or the transition probabilities of a Markov chain. This presents an obstacle in the way of using these models to design practical maintenance programs. The combined use of the reliability index methods and the limit state approach may prove helpful in removing this drawback.

Kirkwood et al. (2006) presented a strategy to maintain and repair a pipeline using relative risk assessment and introduced a method that utilized qualitative data thus producing risk within pipeline segments relative to one another. Both quantitative and qualitative risks are defined. Risk is defined as the combination of the probability occurrence of a hazard and the magnitude of the consequences of the failure. Also is presented a detailed description of the pipeline hazards used in risk assessment that include internal corrosion, external corrosion, fatigue, stress-corrosion cracking, mechanical damage, third party intervention and loss of ground support. The total probability of failure (P_f) is given as the sum of each of the individual probability factors and the breaking down of the individual failure modes allows the model to identify the influence of each mode on the entire pipeline. Moreover the consequence of failure is the damage or cost incurred when a pipeline fails and defined as the sum of all the feasible consequence factors, that are defined as risk to life, damage to property, loss of service, cost of failure and environmental effects. These factors are not weighted against each other; rather weighting is decided for each factor by the pipeline operator.

Khan et al. (2006), proposed a risk-based methodology for integrity and inspection modeling (RBIIM) to ensure safe and fault-free operation of the facility. This methodology uses a gamma distribution to model the material degradation and a Bayesian updating method to improve the distribution based on actual inspection results. The method deals with the two cases of perfect and imperfect inspections. RBIIM aims at modeling inspection tasks to achieve safe operating conditions at minimum cost. This approach also provides a means for quantitatively establishing future reliability levels for the components. These levels can be used as a basis for optimizing re-inspection intervals. The uncertainties associated with the design and operation of process components have led to an increasing use of risk based approaches in making decisions regarding asset integrity management.

Semi-quantitative techniques allow some relative risk ranking, but these techniques are still unable to provide detailed assessments of large and complicated projects or systems.

2.3 Pipeline Risk Management Research

Risk management is the process of assessing risk and then designing strategies and procedures to mitigate the identified risk factors. Different methodologies have been suggested to develop solutions for managing risk. The major two concepts evolving in risk management are the use of qualitative approaches and quantitative approaches. Two basic classes of risk analysis methods are qualitative and quantitative methods.

The risk assessment is the core of risk management, the process of evaluating risks and allocating resources in a manner that controls risks and costs. As mentioned above, out of the three phases of risk management; Risk Identification, Risk Assessment, Risk Control and Mitigation, the quantification of risk lies under the risk assessment phase.

Due to the complexity of the large systems, such as a pipeline distribution system, the risk management process involves some uncertainty that should be addressed.

Many factors increase the uncertainty in the risk management process including the changing role of engineering and business processes, the rapid technology evolutions, and the global economy. One of the most efficient ways to address this uncertainty in the risk management process is through the study of probability concepts. This section presents strategies or formulation of risk management subjected to probabilities and uncertainty; Monte Carlo Simulation, Bayesian approach, and specialized approaches that use the probability concepts are considered.

In the past, several models have been proposed for the project risk management process. Miller et al. (2001) developed an approach that sketches out the various components of risks, outlines strategies for coping with risks, and suggests a dynamic layering model for managing and shaping the risks in large engineering projects. These authors dissected risks into categories such as market related, completion, and institutional. After the categorization of risk, they suggested four main risk-management techniques: shape and mitigate, shift and allocate, influence and transform institutions, and diversify through portfolios. Furthermore, after tracing risk management in 60 large engineering projects, they identified six primary layers of mechanisms used by management for coping with the risks: assess/understand, transfer/hedge, diversify/pool, create options/flexibility, transform risk, and embrace residual risks.

Chapman (1979) suggests SCERT (Synergistic Contingency Evaluation and Response Techniques), which provides a systematic approach to the planning and financial evaluation of large engineering projects involving significant risks. SCERT is a four-phase approach includes scope, structure, parameter, manipulation and interpretation. All four phases are then divided into specific steps. “Scope” is divided into activity identification, primary risk identification, primary response identification, secondary risk identification, and secondary response identification. The structure phase is composed of minor and major risk identification, specific and general response identification, simple and complex decision rule identification, and risk/response diagramming. The parameter phase contains desired parameter identification, scenario identification, probability estimation, and manipulation. The interpretation phase contains risk computation, risk efficiency decision rule assessment, risk balance decision rule assessment, and budget contingency sum assessment steps. PRA method that is described at the Risk Assessment Literatures supports management to improve the performance of the system as well as optimizes the decision-making.

Jo et al. (2003) presented a simplified equation that relates the diameter, the operating pressure and the length of pipeline to the size of the affected area in the event of a full-bore rupture. The equation is based on release rate, gas jet and heat flux from fire to estimate the hazard area. Hazard area is directly proportional to the operating pressure rise to a half power, and to the pipeline diameter rise to five-fourths power, but inversely proportional to the pipeline length raised to a quarter of power. This simplified equation is considered a useful tool for safety management of the high-pressure natural-gas pipelines. This research is focused to propose a simple and dependable approach for sizing the ground area potentially affected by the failure of a high-pressure pipeline carrying natural gas. Also, the hazard model is based on a consequence model which consists of three parts; 1) an effective release rate model at steady-state for high-pressure pipeline rupture, 2) a jet-dispersion model that relates the operating condition of the pipeline and the effective hole size to the contour of the lower flammable limit, and 3) a fire model that relates the rate of gas release to the heat intensity of the fire as a function of distance from the fire source.

2.3.1 Monte Carlo Simulation

Monte Carlo simulation is a useful method for PRA. Monte Carlo simulation is designed to propagate the variability and uncertainty associated with each individual exposure input parameter in PRA. Monte Carlo simulation draws random variables from a probability distribution and includes the observed values in risk analysis. Combined with the PRA, it provides risk managers with sufficient data to choose from quantile of risk. Several authors (Eschenroeder, et al. (1988), Haas (1997), and Binkowithz et al. (2002)) have suggested different Monte Carlo Simulation approaches within their respective fields.

Note that while this method is attractive to ensures, it does not take into account the cost of potential human suffering and should not be used as a primary decision criterion for safety and health related hazards. Similarly a cost benefit ratio greater than 1 is not a valid reason not to implement a safety related improvement. The cost benefit ration can at best be used as another tool to help rank priorities amongst a range of actions.

2.3.2 Bayesian Model

The Bayesian model allows computation of the posterior probability of an event given its prior probability. Bayesian model use the old concept of conditional probability. The Bayesian model states that posterior probability is proportional to the prior probability and current data, which allows computation of posterior probability because it allocates values to prior probability information with new data. Pate-Cornell et al., (1995) and Pate-Cornell (2002) have suggested Bayesian Model approaches. In addition, Greenland (2001) and Linville et al. (2001) have combined the Bayesian model and Monte Carlo simulation in the decision analysis.

2.3.3 Cost/Benefit Analysis Literature

Cost-benefit analysis is a powerful and flexible analytical tool that provides to pipeline managers a systematic way of organizing and viewing the advantages and costs of regulatory alternatives. *Risk/Cost Benefit Analysis* may also be part of a *Risk Assessment* Objective and is often used as a criterion to assist at the selection of the most effective control options to address an unacceptable risk.

If the consequences of the hazard can be meaningfully expressed in economic terms, then cost benefit analysis can be used to help set priorities and aid decision making. Both the capital cost and ongoing operating costs will need to be taken into account. The cost can then be annualized using, for example the remaining plant life. The benefit from a countermeasure selection is actually the reduction of the cost of the accident consequences and can be determined by computing the annual cost before and after. This will require some quantitative risk assessment work, although in simple cases estimation can give at least an indication.

The Potential Loss of Life (PLL) is the number of fatalities that can be expected to occur each year, averaged over a long period and is a measure of societal risk. The PLL is a useful basis for cost benefit analyses of risk reduction measures, via the “Implied Cost of a Fatality” (ICAF = cost of measure/(initial PLL-reduced PLL)). Such calculations are often controversial as they appear to require a value to be placed on human life, but these calculations are commonly used internationally, and may be suitable to aid decision making in regard to adopting control measures for major hazards. For example, a low ICAF for a proposed risk reduction measure implies that it is highly effective, because the cost is low compared to the risk reduction achieved.

Conversely, a high ICAF implies a relatively ineffective risk reduction measure, indicating that perhaps the money should be diverted to an alternate.

The Kiefner-NYGAS (2004) risk assessment model is designed to evaluate the relative risk of failure for each pipeline segment in a natural gas transmission system, determine the highest threat of failure on each segment, assess the most appropriate mitigative strategy for each segment by conducting cost/benefit analyses, and assist in prioritizing the order that baseline assessment should follow as well as when reassessment should occur. The model is capable of analyzing various scenarios of mitigating actions specific to each pipeline segment to reduce risk and bring the segments with “high” risk into a more acceptable risk range. Potential costs associated with each mitigation measure are also identified, cost benefits are calculated, and together with other operator knowledge, logical and specific solutions for each segment to improve pipeline integrity are established.

In spite of the advantages of cost-benefit analysis, it should never be the sole basis for decision making. Cost-benefit results are subject to uncertainty, and analyses rarely prove conclusively that the benefits of a program exceed the costs (or vice versa). Thus, decision makers should not interpret quantitative results too literally nor be bounded to a strict cost-benefit test. When used with other tools, however, results from cost benefit assessments will assist the decision makers to evaluate both the economic efficiency and overall effectiveness of existing and proposed programs and regulations.

Table 2.1 *Pipeline risk assessment and management areas addressed in the Literature*

	Risk Assessment			*Risk Management*
	Qualitative approach	Quantitative approach	Semi – quantitative approach	
Haas (1977)				+
Chapman (1979)				+
Haimes (1981)		+		
Chapman (1988)	+			
Eschenroeder et al. (1988)				+
Hill (1992)		+		
Muhlbauer (1992)	+	+		
Concord (1993)		+		
Nessim et al. (1995)		+		
Pate-Cornell (1995)				+
Webler et al. (1995)		+		
Lotsberg et al. (1998)		+		
Pandey (1998)		+		
Faber et. al (1999)		+		
Brown et al. (2000)		+		
Cagno et al. (2000)	+			
Faber et al. (2000)		+		
Morgan et al. (2000)		+		
Montgomery et al. (2000)			+	
Nessim et al. (2000)		+		
Straub et al. (2000)		+		
Dey et al. (2001)	+			
Florig et al. (2001)		+		
Greenland (2001)				+
Kaplan et al. (2001)		+		
Linville et al. (2001)				+
Miller et al. (2001)				+
Binkowithz et al. (2002)				+
Haimes (2002)		+		
Montgomery et al. (2002)		+		
Pate-Cornell (2002)				+
Faber et al. (2003)		+		
Jo et al. (2003)				+
Khan et al. (2003a, 2003b)			+	
Khan et al. (2004)			+	
Markowski (2003)		+		
Willcocks et al. (2003)			+	
Dey (2004)			+	
Kiefner et al. (2004)				+
Jo (2005)		+		
Henselwood et al. (2005)		+		
Dziubinski (2006)			+	
Kirkwood et al. (2006)			+	
Khan et al. (2006)			+	

2.4 Conclusions

In this chapter the basic concepts of risk assessment and management methods are introduced and discussed. As it is shown in Table 2.1 the pipeline risk assessment and management areas addressed in the Literature are divided in qualitative, quantitative, semi-quantitative, and risk management. The risk dimensions and methods were presented in order to shape an overall perception of the work needed to quantify the risk in order to use mathematical calculations and formatting.

CHAPTER 3

NATURAL GAS PIPELINE BASICS AND ACCIDENTS

This chapter refers to natural gas distribution network fundamental concepts and to the basic components that composes a pipeline network, as well as to the process and distribution of natural gas. Some of the most striking accidents that had happened to natural gas pipeline distribution networks worldwide are presented and their impacts to several areas of social and economical life of the affected areas are discussed.

3.1Natural gas basics

Natural gas is an extremely important source of energy for reducing pollution and maintaining a clean and healthy environment. In addition to being a domestically abundant and secure source of energy, the use of natural gas also offers a number of environmental benefits over other sources of energy.

Moreover, it is a fossil fuel extracted from deep underground wells. It is a physical mixture of various gases, typically containing 85 – 95% methane (CH_4), 7 – 12% ethane (C_2H_6) and small amounts of propane (C_3H_8), butane (C_4H_{10}), nitrogen and carbon dioxide (CO_2). The proportions vary from field to field and sometimes from well to well.

Furthermore, natural gas is odorless and colorless when it comes from the wellhead. As a safety measure, an odorant, which is a blend of organic chemicals containing sulfur (*mercaptans*), is added so natural gas leaks can be detected. Unlike propane, natural gas is lighter than air. Natural gas typically has a specific gravity of 0.6, meaning that it weighs about 0.6 times as much as air. The term *specific gravity* refers to the weight of the gas as compared to the weight of air. Not all mixtures of natural gas and air will burn. Some mixtures have too little quantity of gas, while others have so much quantity of gas that there is not enough air left to burn.

Table 3.1 *Fossil Fuel Emission Levels - Pounds per Billion Btu of Energy Input*

Pollutant	Natural Gas	Oil	Coal
Carbon Dioxide	117,000	164,000	208,000
Carbon Monoxide	40	33	208
Nitrogen Oxides	92	448	457
Sulfur Dioxide	1	1,122	2,591
Particulates	7	84	2,744
Mercury	0.000	0.007	0.016

Source*: EIA - Natural Gas Issues and Trends 1998*

The two cutoff points between combustible mixtures and non-combustible mixtures are called the Explosive Limits;

- The Lower Explosive Limit (LEL) for natural gas is approximately 5%. At concentrations below the LEL, there is insufficient gas to cause a fire or explosion.
- The Upper Explosive Limit (UEL) for natural gas is approximately 15%. At concentrations above the UEL, there is insufficient air to cause a fire or explosion.

The ideal mixture for combustion of natural gas is approximately 10% and the ignition point is 1208° F.

Table 3.2 *Fire and Explosion Hazards of Natural Gas*

Flash point	-300 deg F
Upper Flammable or Explosive Limit	15%
Lower Flammable or Explosive Limit	5%
Auto Ignition Temperature	1208° F
Extinguishing Media	Methane's flammability, wide flammable range, and very low flash point represent dangerous fire and explosion risks. Treat any fire situation involving rapidly escaping and burning methane gas as an emergency. Extinguish methane fires by shutting off the source of the gas. Use water sprays to cool fire-exposed containers and to protect the personnel attempting to seal the source of the escaping gas. Dry Chemical, CO_2 and Halon may also be used to extinguish fires.
Unusual Fire Hazards:	Methane gas is very flammable with a relatively wide flammable range (5% to 15%). The best fire-fighting technique may be simply to let the burning gas escape from the pressurized cylinder, tank car, or pipelines. Never extinguish the burning gas without first locating and sealing its source. Otherwise, the still leaking gas could explosively re-ignite without warning and cause more damage than if it burned itself out.
Route of Exposure	Primary Entry: Inhalation.
Potential Health Effects	Acute Effects: The initial symptoms of simple asphyxiant gases' effects are rapid respiration and air hunger, diminished mental alertness, and impaired muscular coordination. Continuing lack

	of oxygen causes faulty judgment, depression of all sensations, rapid fatigue, emotional instability, nausea, vomiting, prostration, unconsciousness, and finally, convulsions, coma, and death.
Summary of risks	As a simple asphyxiant gas, methane does not cause significant physiological responses, but it can displace the minimum required atmospheric oxygen level. Significant displacement results in an oxygen-deficient atmosphere with no adequate warning properties. Asphyxiation can occur especially in confined, poorly ventilated, undisturbed spaces infrequently entered by workers. Frostbite (cryogenic damage) can result from contact with liquid methane's extremely low temperature.

3.2 The natural gas distribution system

The transportation system of natural gas from its extraction to its end user is very complicated. The natural gas is pumped with great diameter pipelines and is transferred under high pressure (70 – 100 bar or 69 – 98,7 atm) to peripheral distribution stations. The pipelines operate at various pressures throughout the system. They are compressed higher when entering transmission pipelines and regulated lower when entering distribution pipelines and supplying customers. Under pressure that varies from 20mbar (0,0197atm) to 5bar (4,93atm), the natural gas is distributed to residential, commercial, industrial and agricultural customers. Depending on the operating pressure of the pipeline network, size of the pipe, year of installation and other factors, pipe material can be steel, plastic, cast iron or copper.

Pipelines do not experience many of the safety threats faced by other forms of freight transportation because they are mostly underground; but they are subject to failures that occur over time - such as leaks and ruptures resulting from corrosion or welding defects - and failures that are independent of time - such as damage from excavation, land movement, or incorrect operation.

The main two types of pipelines transport gas products are; (1) gas transmission pipelines and (2) local distribution pipelines. Gas transmission pipelines typically distribute gas products over long distances from sources to communities and they are primarily interstate. They typically operate at a higher stress level (higher operating pressure in relation to wall strength). By contrast, local distribution pipelines receive gas from the transmission pipelines and distribute it to commercial and residential end users. Local distribution pipeline networks, which are primarily intrastate, typically operate under lower-stress conditions. Local distribution companies may also operate small portions of transmission pipelines - typically under lower stress - and are therefore subjected to the international and national assessment and reassessment requirements.

Moreover, natural gas is delivered to a distribution service area or a local distribution company via a number of metering and/or pressure-regulating stations along the transmission pipeline. From there natural gas is supplied to customers through a grid of distribution pipes, valves and connections usually located underground with telecommunications, electricity, water, sewer and other utilities.

In addition, small-diameter gas service lines connect the gas distribution pipe to one or more customers at a gas meter is typically installed near the customer's facilities. The gas meter assembly has a manual gas service shutoff valve, a pressure regulator to reduce pressure from the gas main pipe to standard delivery pressure, a gas meter to measure the volume of gas, and a service tee that allows a utility to bypass other meters without entering the structure. Customer meters may not have a pressure regulator if they are fed from a low-pressure distribution system. The customer's natural gas houseline piping is attached to the service tee, which is typically considered the utility point of delivery and defines the physical boundary between utility and customer facilities.

The transportation of natural gas is shown to *figure 3.1*:

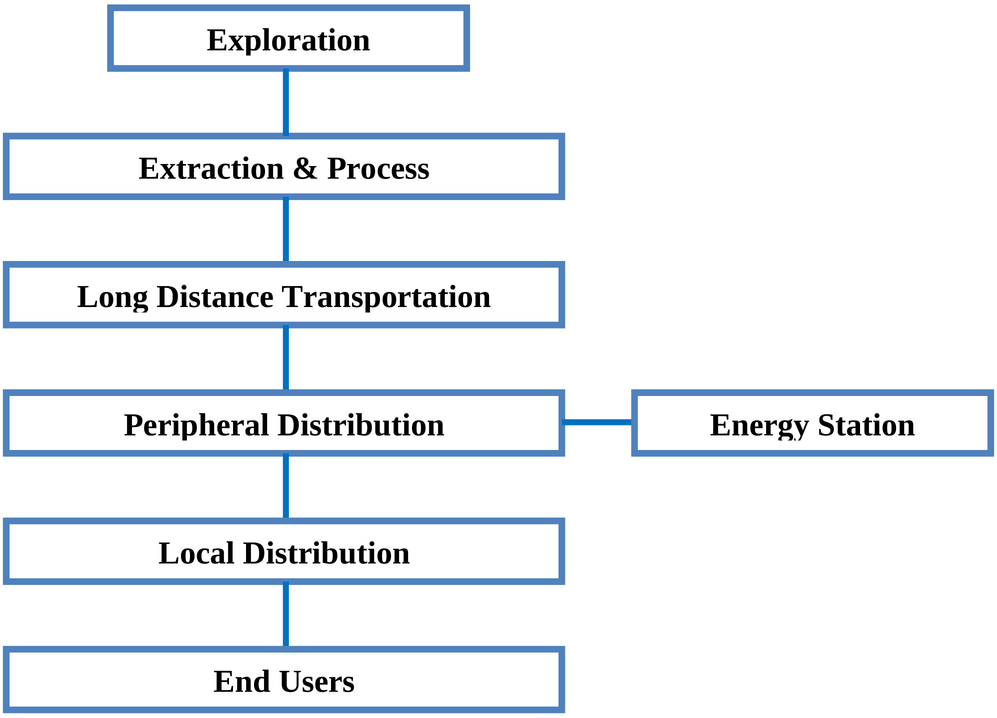
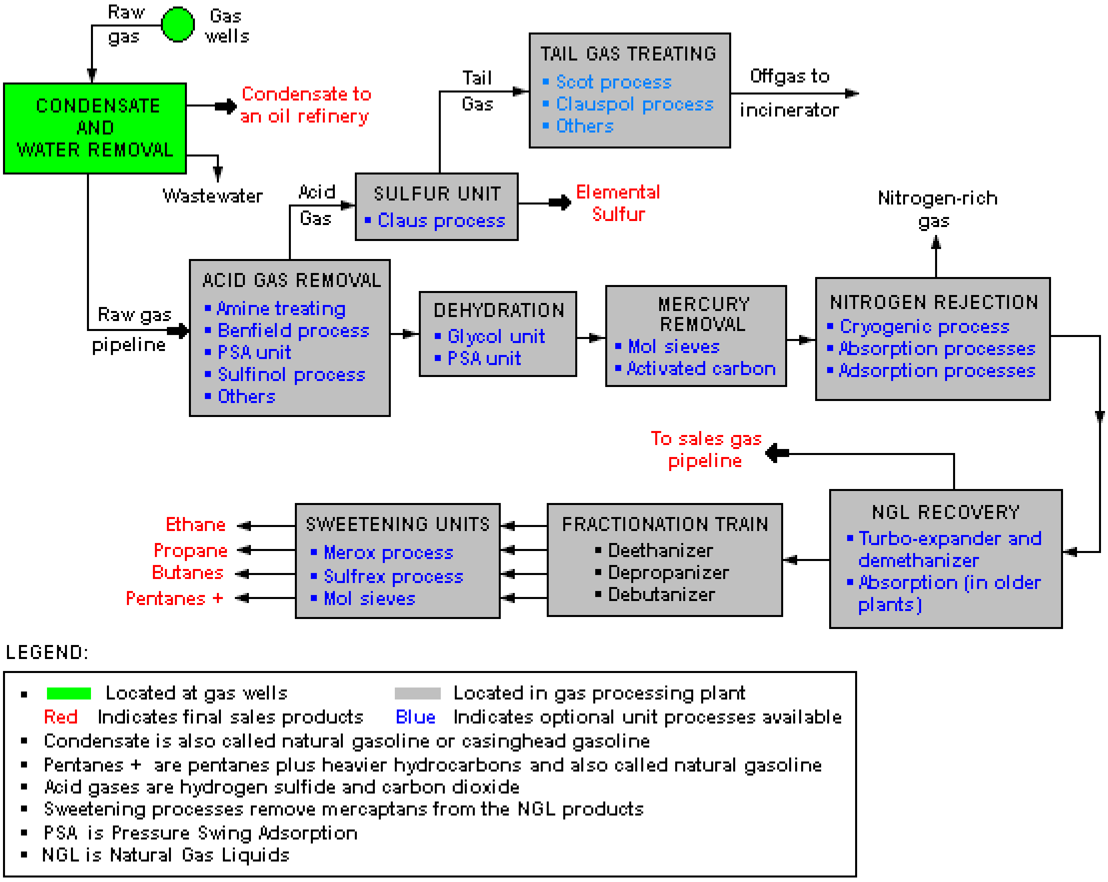


Figure 3.1 *Transportation of Natural Gas*

The image below is a schematic block flow diagram of a typical natural gas processing plant. It shows the various unit processes used to convert raw natural gas into sales gas pipelined to the end user markets.

The block flow diagram also shows how processing of the raw natural gas yields the byproduct sulfur, the byproduct ethane, and the natural gas liquids (NGL) propane, the butanes and the natural gasoline.



- Condensate is also called natural gasoline or casinghead gasoline
- Pentanes + are pentanes plus heavier hydrocarbons and also called natural gasoline
- Acid gases are hydrogen sulfide and carbon dioxide
- Sweetening processes remove mercaptans from the NGL products
- PSA is Pressure Swing Adsorption
- NGL is Natural Gas Liquids

Figure 3.2 *Schematic flow diagram of a typical natural gas processing plant*[8]

As far as the security of the pipeline is concerned, the national natural gas company that is responsible for the operation of the natural gas pipeline system is conducting patrols in regular basis at gas utilities in order to detect gas leaks. The magnitude of the leak is categorized in three (3) levels; Grade 1, Grade 2, or Grade 3. Grade 1 leak represents an existing or probable hazard and requires immediate action. Grade 2 leak is not hazardous to life or property at the time of detection but requires scheduled repair. Grade 3 leak is non-hazardous at the time of detection and is expected to remain so. For a large gas distribution system, several hundred Grade 2 or Grade 3 leaks may exist at any one time.

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[8] http://en.wikipedia.org/wiki/Natural_gas

3.3 Natural gas pipeline accidents

The use of natural gas, like all flammable fuels, involves the danger of fire or explosion that may cause severe impacts to pipeline system, infrastructure and property damage or cause fatalities and injuries. The background of natural gas use worldwide has proved that it is a safe gas for the consumer and the industrial applications if a proper construction, installation and maintenance of buildings, natural gas systems and appliances is present.

Nevertheless, several accidents have happened worldwide in natural gas pipelines with serious impacts to the citizens' safety. According to the EGIC report[9] of venturousness, the total frequency of accidents is 0.41 accidents/year/1000 km for the period 1974 - 2004, which however is decreased continuously with the passing of time and a tendency of stabilisation, is observed at the last years.

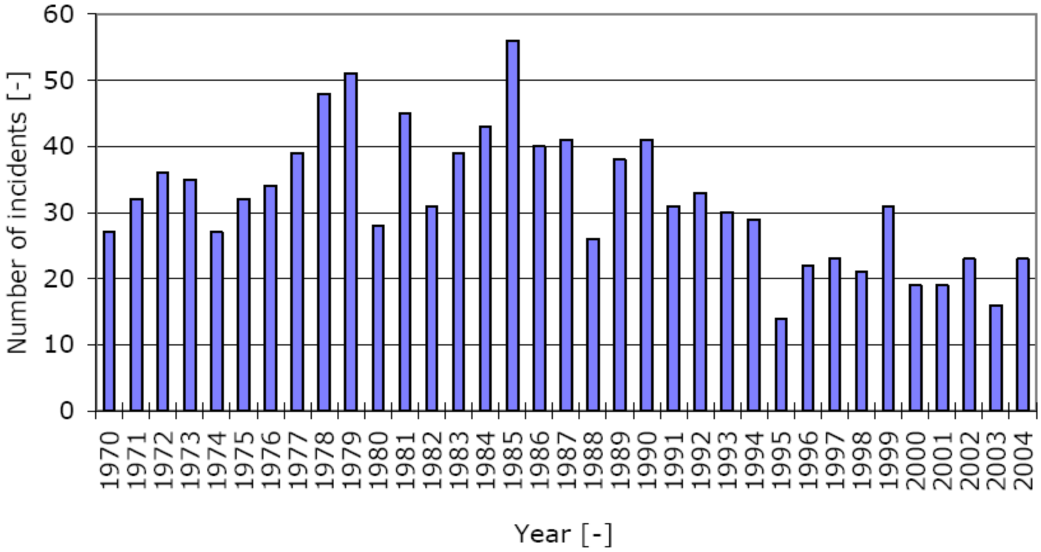

Figure 3.3 *Annual Number of Incidents in European natural gas pipeline network, based on EGIC data base*

The main causes of accidents in natural gas pipelines are: 50% due to exterior factors, 17% due to construction defect and material failure, 15% due to corrosion, 7% due to ground movement and 6.7% due to other and unknown factors. Also, the bigger leak sizes, such as holes and ruptures, are mainly caused by external interference while ground movements can also cause pipeline crack, formation of a hole or rupture but less frequent[10].

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[9] 6th Report of EGIC - Base of Given Accidents European Network of Conductors of Transport of Gas
[10] *6th EGIC Report of the European Gas Pipeline incident data group, 2005*

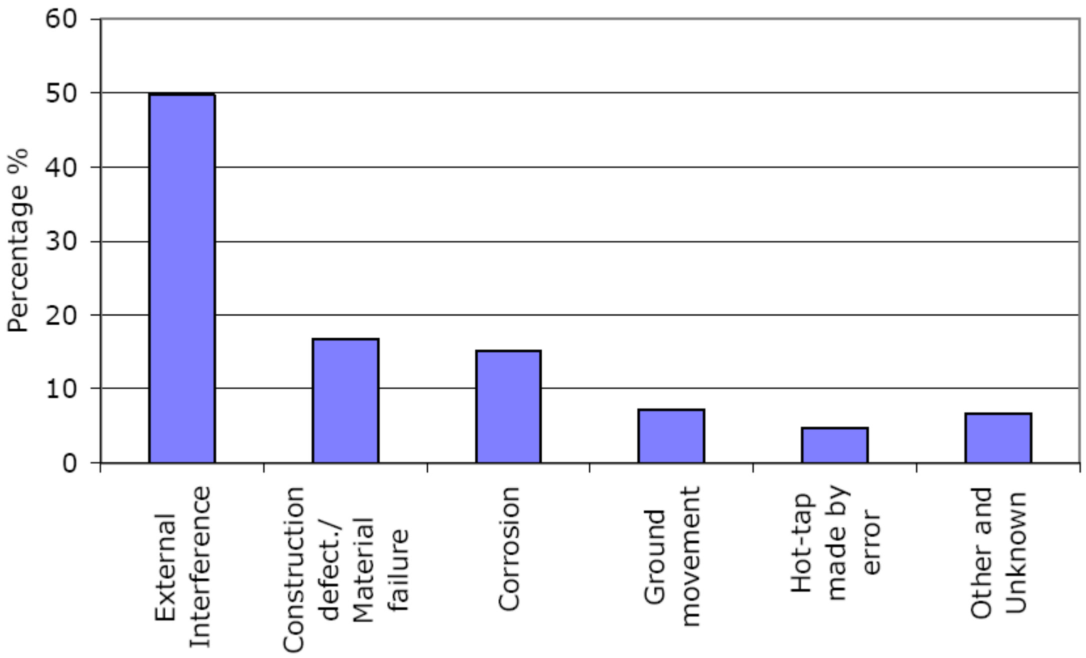

Figure 3.4 *Distribution of Incidents per Cause, based on EGIC data base*

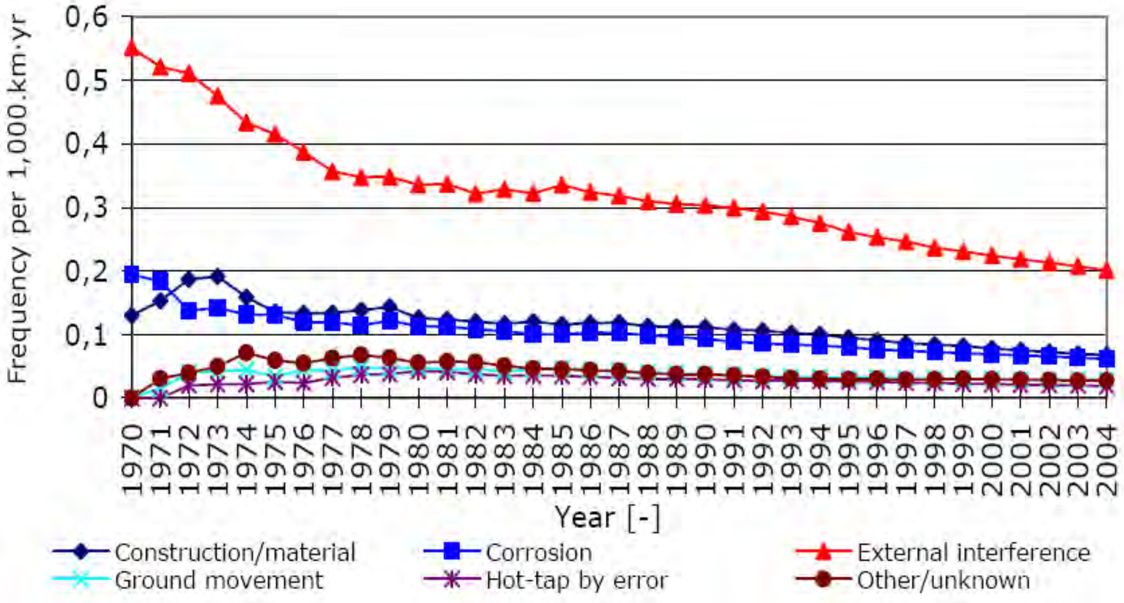

Figure 3.5 *Primary Failure Frequencies per cause (up to year), based on EGIC data base*

Based on the severity of the natural gas pipeline failure in terms of fatal accidents, based on data from DVGW (2004), the majority of accidents result in no deaths with corresponding shares of 73,8% at customer installations and with 90,4% at company installations. On the other hand, serious accidents of fatal incidents (≥5) contributes with a percentage less than 1% (0,7% in the United Kingdom and 0,4% in the European Union) to the total number of accidents. Nevertheless, the accidents of a smaller gravity are the major factor to total fatalities, where of accidents with one fatality and to a lesser extent with two fatalities account for most of the fatal incidents.

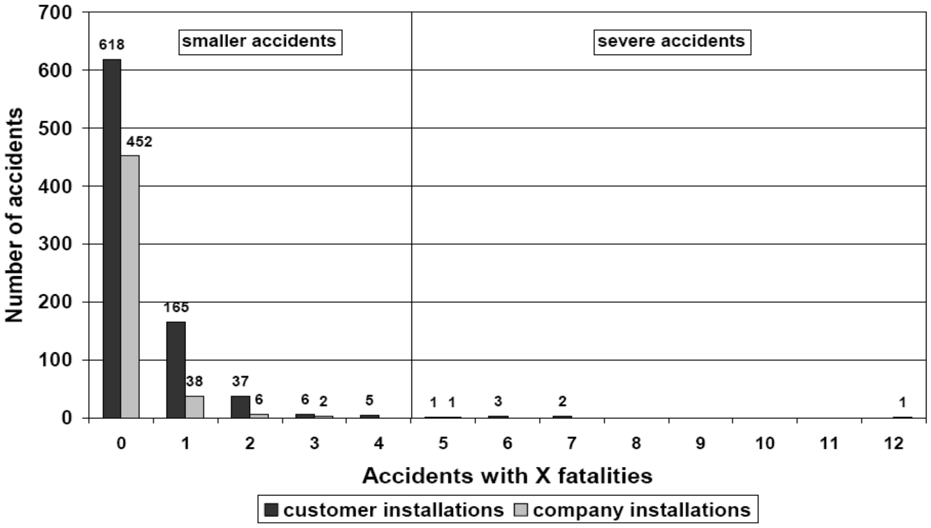

Figure 3.6 *The distribution of natural gas accidents, according to their severity in terms of fatalities for the period 1981-2002, based on data from DVGW(2004)* [6]

In *Table 3.3* are summarized the number of the accidents, fatalities and injuries for the period 1981-2002 at the customers' installations from a natural gas pipeline failure. The majority of the incidents were attributed to the type's explosion (27%), the deflagration (31%) and the exhaust fumes poisoning (29%). Similarly, the number of fatalities and injuries were higher for the types of explosions and exhaust fumes poisoning. On the contrary the deflagration caused high percentage of injuries and the number of fatalities is rather small. Also, the poisoning from the escaped fumes presented a continuous reduced tendency since the '90s that could indicate the technological progress and the security measures that are applied the last years.

Table 3.3 *Number of accidents, fatalities and injured for accident types, accident causes and installation types at customer installations for the period 1981-2002, based on data from DVGW(2004)*

Accident Type	# accidents	# fatalities	# injuries
Explosion	224	104	487
Fire	88	10	40
Deflagration	257	18	158
Asphyxiation	16	3	20
Exhaust fumes poisoning	240	179	233
Not specified	12	0	5
Total	*837*	*314*	*943*
Accident Cause	# accidents	# fatalities	# injuries
Technical Defects	220	44	152
Installation failures	123	39	173
Manipulation failures	175	84	143
Illegal changes of installation conditions of gas appliances	34	19	18
Intentional interventions at gas installations	202	101	386
Not specified	19	3	7
Total	*837*	*314*	*943*
Installation type	# accidents	# fatalities	# injuries
Pipes	144	45	187
Pipe joints	90	55	195
Valves	28	4	41
Gas appliances w/o exhaust fumes system	136	40	122
Gas appliances with exhaust fumes system	311	104	267
Installation type	# accidents	# fatalities	# injuries
Exhaust fumes system	55	35	63
Combustion air supply	3	0	1
Not specified	70	31	67
Total	*837*	*314*	*943*

Some of the most striking examples of natural gas pipeline accidents were related to earthquake disasters that stroke the United States of America and Japan. For example, the Whittier Narrows earthquake stroke on the morning of October 1st 1987, with a magnitude of 5.9R and followed by an earthquake of 5.3R on October 4th. Approximately 10,000 residential and commercial structures were damaged, including 123 single-family homes that were damaged beyond repair and another 513 that suffer major damage. Southern California Gas Company operates the natural gas distribution system in the region, received 20.600 customer calls for service restoration, of which about 16,500 were the result of customers shutting off their own gas service in response to media safety announcements immediately following the earthquake. The service was restored within 10 days by Southern California Gas Company personnel working 10hour days. Fortunately, the high pressure gas transmission network was not damaged. The distribution system was found to have 22 leaks with corrosion a factor in all but one case. Approximately 5,900 leaks were located after the earthquake 2,000 of which were attributed to the earthquake. The 75% of the damage was related to the connection gas appliances that had shifted during the earthquake. Among the low pressure natural gas pipeline network were found 300 leaks in service lines between the distribution mains and customer meters.

Table 3.4 *Summary of Repairs by Southern California Gas Company Following the Whittier Narrows Earthquake*

Damage	*Number*	*% of Total*
Appliance: Vent	40	2
Appliance: Miscellaneous	134	7
Appliance Connector: Range	90	5
Appliance Connector: Water Heater	385	20
Appliance Connector: Furnace	127	7
Appliance Connector: Dryer	46	2
Appliance Connector: Miscellaneous	97	5
Piping: Meter Set Assembly	376	20
Piping: Houseline	505	26
Piping: Yardline	120	6
TOTAL	1,920	

Another example is the earthquake that hit Loma Prieta in California that occurred on October 17th of 1989 at 5:04pm, approximately 97km south of San Francisco with magnitude 7.2R. The earthquake caused severe damages to 900 homes near the earthquake's epicenter and in the San Francisco Bay area. The damage at this area was caused by the amplification of the ground motions at the surface by soft soils and liquefaction of soils associated with land reclamation projects, some dating back to the 1800s. The victims were more than 60 and the electricity was cut off at the biggest area of the north San Francisco Peninsula. Nearly 160,000 natural gas consumers were without gas service following the earthquake, mostly due to customers shutting off their own service in response to media safety announcements immediately after the earthquake. Over a period of nine (9) days, personnel from Pacific Gas and Electric Company and six neighboring utilities and contract plumbers restored service to more than 156,000 individual customers. From these teams, an average of 1,000 personnel worked during five of the days. Not surprisingly, the locations of high concentrations of gas system repairs were found to coincide with locations of high building damage. Nevertheless, the earthquake caused fire ignitions near its epicenter and in San Francisco was observed the higher fire injection incidents following the earthquake.

The various causes for the fire ignitions in San Francisco, according to the fire incident reports, are shown at *Table 3.5*. Assuming equal possibility for gas or electricity as a cause for “stove” and “unknown,” natural gas could have been a factor in 34% of the fire ignitions, while electricity could have been a factor in 56%.

Table 3.5 *Causes of Fire Ignitions in San Francisco from the Loma Prieta Earthquake (17 October 1989)*

Cause	***Number***	***% of Total***
Electrical wiring	6	19
Electrical Equipment	8	26
Stove (Gas or Electric)	9	29
Water heater	1	3
Other gas appliances	2	6
Gas explosion	1	3
Miscellaneous	4	13
Unknown	1	3

Also, Northridge in California was hit by an earthquake with magnitude 6.7R in 17th January of 1994; the epicenter was located in the city Reseda, near the center of the San Fernando Valley. The earthquake caused total loss of electric power to the City of Los Angeles and to the adjacent areas. The damages to the gas piping system involved 35 failures of the older transmission lines, 123 failures of the steel distribution mains, and 117 failures in the service lines. An addition, 394 corrosion leaks were observed during the leak surveys following the earthquake. The total number of customers that their gas supply was cut off, immediately after the main shock and the aftershocks, exceeded the 150,000 homes, with approximately 133,000 of the service interruptions initiated by customers as a precautionary measure. Approximately 15,000 of the interrupted services were found to have leaks of unspecified severity when service was restored.

Table 3.6 *Northridge Earthquake Fire Statistics for Structures (17 January 1994)*

Fire Department	***Earthquake Fire Ignition***	***Gas-related Earthquake Fire Ignitions***
Beverly Hills	0	0
Burbank	0	0
City of Los Angeles	77	38
Costa Mesa	0	0
Covina	1	0
Glendale	0	0
El Monte	1	0
Fillmore	2	1
Inglewood	1	0
Long Beach	1	0
Newport Beach	0	0
Pasadena	1	?
Santa Monica	10	6
Santa Paula	0	0
South Pasadena	0	0
Los Angeles County	15	6
Ventura County	10	3
TOTAL	110	54

A recent accident that was recorded to a natural gas pipeline network happened in 1995. An earthquake with magnitude of 7.2 in Richter scale, stroke the city of Kobe in Japan. The earthquake caused severe impacts to city’s infrastructure, transportations systems and gas networks and more than 60,000 people died and 40,000 injured. The estimated damage was 200 billion dollars. In particular, 106 medium pressure gas mains were damaged and 26,459 low pressure gas service lines were damaged. It took 15 hours to shut – down the system that caused many fires and 85 days to restore the natural gas service.

3.4 Conclusions

Several accidents have happened worldwide in natural gas pipelines with serious impacts to the safety of citizens. According to the EGIC report (6th Report of EGIC - Base of Given Accidents European Network of Conductors of Transport of Gas) of venturousness, regarding the length of pipelines and their operation age is 2.77

millions/km per year in the European network of pipelines. The total frequency of accidents is 0.41 accidents/year/1000 km for the period 1974 - 2004, which however is decreased continuously with the passing of time and a tendency of stabilisation, is observed at the last years.

CHAPTER 4

PROPOSED RISK MANAGEMENT METHOD

In this chapter the proposed risk management method of pipelines networks carrying natural gas is introduced. The method involves the hazard and vulnerability analysis that compose the risk assessment of the pipeline failure in the selected area. After the analytical description of the stepwise risk management method follows the identification of the hazard and vulnerability factors of a natural gas pipeline failure and the calculation of the risk level (risk indicator) for the main four categories of social and economic life of the area, is discussed - human factor, environment, infrastructure on the area and gas installations and economic activity of the industry.

Furthermore, the possible mitigation measures that can be taken in order to lower the risk indicator for one or multiple hazard and vulnerability parameters will be introduced and discussed in order to prioritize them based on their benefit (risk indicator before taking the mitigation measure – new risk indicator after the implementation of the mitigation measure), their cost and the available industry's financial capitals. For this cost-benefit analysis the knapsack model is introduced.

4.1 Problem Definition

When it comes to risk management of a pipeline network, it is vital to allocate the available resources optimally by receiving mitigation measures and therefore reducing the hazard. The "Intelligent spending" practises are needed; that means sufficient minimum mitigation measures costs in order to achieve minimization of risk level. Determining the cost of risk factors, especially risk-reducing activities during the operation and maintenance of a pipeline must become a part of the management process.

The pipeline manager group performs a variety of activities that has an associated cost and is driven by initiatives such as ensuring contract obligations, compliance with the national and international initiatives and conformance with pipeline industry standards. Assigning a cost to pipeline accidents, sometimes a difficult task, and including this in the cost of operations, the optimum balance point is the lowest cost of operations[11]. The goal of the proposed natural gas pipeline management is the

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[11] Muhlbauer, 2003

achievement of a judicious balance between the risk of pipeline failure and financial gains.

The core of the risk management is the risk assessment of the pipeline failure. Ideally risk assessment specifies the probability of events of different intensities or magnitudes occurring and the impact of the direct and indirect impacts of these events on the affected interested parties. Societal conditions include the human settlement patterns, the built environment, the day-to-day activities and the institutions established to deal with natural hazards.

For the purposes of this research we try to link the risk assessment with risk management strategies for reducing the vulnerability of a city or a region where the pipeline runs through. In order to determine the vulnerability of such a city or a region, in a case of a pipeline failure, it is very important to be aware of the design of each structure (e.g. residential, commercial, public sector) and of the infrastructure, whether specific mitigation measures are in place or could be utilized, and their location in relation to the hazard. (e.g., distance from an earthquake fault line from a natural gas pipeline) as well as other risk-related factors.

Moreover, pipeline company owners/operators need a better understanding of the connection between risks to the production and distribution processes for natural gas and vulnerabilities inherent in the process control systems managing those processes, before they can make the commitment necessary to improve the security. However, the relationship is typically quite complex, especially for large and multi-faceted operations. As a consequence of this connection being difficult to understand, recommendations for mitigating vulnerabilities, or for applying sound design principles to architectures and pipeline systems, are frequently discounted, prioritized low, or even disregarded. Further, lack of an approach to detect cause-and-effect relationships, i.e., of exploited vulnerabilities and the resulting physical or business consequences, makes it more difficult for front line risk analysts to convey to corporate decision-makers risks to production and distribution operations in terms of their usefulness.

Summarizing, the proposed management method usually seeks to combine the qualitative and quantitative approaches to

- Input pipeline characteristics (diameter, operation pressure, wall thickness, location, natural gas characteristics)

- Identify hazard parameters (fault tree analyses)
- Identify consequences (event tree analyses)
- Calculate failure frequency of each parameter
- Predict pipeline failure consequences (release flow rate, ignition probability, thermal radiation)
- Calculate reduction factors of risk
- Calculate individual and societal risk (Young-Do Jo and Bum John Ahn, 2005)
- Calculate mitigation measures cost
- Prioritize mitigation measures according to the results of the cost – benefit analysis

4.2 Pipeline management – Proposed Methodology

Technological risk management involves the prevention of and response to unwanted or unexpected consequences arising from failure to sustain normal operation of a technological system. Risk management is the process of risk assessment and allocation of means and resources (countermeasures) that aim at the minimization of risk level and costs.

Typically incidents are directly caused by design error, operational error or natural disasters. In the case of a disaster related event we will assume that the system is at normal operational conditions (no simultaneous incident occurrence will be considered). The level of care to avoid losses and the level of acceptable risk management policies however ranges among people responsible for an incident are the ones suffering the heaviest toll of injuries and property losses (e.g. employees maintaining a pipeline or contractors digging near operating pipes). The main focus of technological risk for pipelines carrying natural gas is on understanding the main technical and organizational factors affecting the magnitude and likelihood of technological failures.

Risk reduction is rarely the single consideration in Risk Management. Cost effectiveness, corporate strategy, ethics, societal norms, defensibility of corporate actions in a court of law or in public meetings, conformance to regulatory rules and trends are some of the factors carrying decision weight and important in understanding the risk management decision context. Understanding technological risk is as fundamental a requirement for the natural gas industry as understanding operational efficiency. A company attains a good reputation for safe and reliable operation of a complex technological system after certain time of operation.

Various attributes of a distribution network, such as pipe material (steel, cast iron, plastic), pipe pressure (low, medium, high gas pressure), storage and compression technologies, and have significant effect on the nature of the risk a company is posing to its surroundings. The network industries and the natural gas distribution systems in particular, the technological base changes slowly by adding arcs to the existing network or by removing lines from service. Radical network changes tend to be prohibitively costly. Changes in the technological base have a significant impact on technological risk, but take a long time to implement. This makes maintenance and safety improvements to be more attractive risk reduction policies.

What constitutes risk reduction may vary drastically depending on point of view. The various stakeholders of the natural gas companies have different information needs and due to their differing skill sets, different verifiability requirements. The disaggregated measures of risk, if properly designed, may accommodate different point of view. The verifiability gaps, in turn may be reduced by using the least common denominator in verifiability requirements, or by bridging the gaps with help of third parties of guaranteed impartiality that can credibly attest to the quality of information available.

As we have already mentioned, the current research addresses at the risk management problem of a natural gas pipeline network and aims at the calculation of societal and individual risk as well as the allocation of the resources in order to minimize the risk level. The proposed method is using a combination of different qualitative and quantitative models. At this model the possible incidents of gas release are presented by an event tree analysis that defines events developed with time.

The calculation of societal and individual risk is based on the proposed method of quantitative risk assessment for transmission pipeline carrying natural gas by Jo and Ahn (2005). Furthermore the estimation of loss by calculating the cost of failure is based on the proposed by Park, et.al (2004) model, which expresses the risk for a gas pipeline in terms of cost; such as the cost of repair, of the supply interruption, of the material loss and of the damage to human and buildings.

The proposed steps in order to achieve the integrated risk management of the natural gas pipeline distribution network are summarized in stepwise manner as follows:

STEP 1: Identify and locate the potential risk sources inside the industry, based on:

a. Expertise: the kind of pipeline failure occurred in the past, it's intensity and location in the last 2, 4, 8, 10 or 20 years and if they are likely to occur in the next X years where X years is a proposed period of time and depends on the magnitude of the pipeline accident and the duration of implementing the countermeasures. In this case an expert group will be established and based on their experience and knowledge of the hazard sources will decide which categories of pipeline failures are crucial to be assessed.
b. Preliminary hazard analysis by scientific methods that are proposed in Chapter 5, where all the hazards with positive probability of occurrence the next X years are defined.

It is generally known that a pipeline usually does not have a constant hazard potential over its length, unlike the most other facilities assessed. Since the risk level is not uniform along the length of a pipeline; it is necessary to break it a long pipeline in shorter sections. The most appropriate method for sectioning the pipeline is to insert a break point wherever hazard sources are identified that cause differentiation to the risk level. A significant condition change must be determined by the evaluator with consideration given to the frequency of occurrence of accidents within the industry and along the pipeline that carries natural gas, data costs and desired accuracy. This type of sectioning is called ***dynamic segmentation***.

In addition, in most cases of accidents in the natural gas distribution network there are not any data base of past accidents, a reliable method for calculating the possibility of occurrence is to organize a expert team that based on their experience and knowledge will be able to assign a probability or rankings to the initial event (hazard) that may lead to a disaster.

The pipeline can be divided according to the following rules:

- Insert a section break each time the population density along a 1-mile section changes be more than 10%.
- Insert a section break each time the soil corrosivity changes by 30%.
- Insert a section break each time a difference in age of the pipeline is identified.
- Insert a section break each time an important infrastructure is been identified along the pipeline (for example a bridge, a highway or an industry area)

- Insert a section break each time the pipeline route a seismic zone is crossing.

STEP 2: Hazard analysis (see Chapt. 5) where the probability of occurrence of the accident is arising for the next X years, within the geographical bounds of the area that was defined in STEP 1 for a given magnitude (e.g. earthquake with magnitude 6-6.5 of Richter scale)

Hazard (H) refers to the probability of occurrence of any future natural event (e.g. earthquake) or manmade (explosion), with potential harmful effects on humans, environment, infrastructure / facilities and economic activities of the industry, and not at the results it could cause. The hazards may be unique, sequential or combined in their origin and consequences. The probability of occurrence is characterized by the location, intensity and frequency of the incident.

STEP 3: Estimate by performing vulnerability analysis (see Chapt.6) the probability of a unit impact of the disaster in four (4) areas: human factor, environment, structure and gas industry's economic activity, given that the possible occurrence in STEP 2 is becoming a certainty. Vulnerability as it is described in Chapter 6 is a function of how exposed are the correspondingly four aggregated areas and what are the capacity of the industry management at all levels.

Generally, vulnerability (V) is considering the circumstances that shape the probability for the four socio-economic parameters of the industry; i.e.,

- Human factor (fatalities, injuries)
- Environment (per hectare for the soil, per m^3 for water supplies and the atmosphere)
- Infrastructures/ installations (per block or installation)
- Financial activity (percentage (%) of economical activity reduction of the industry) given that the event has occurred (natural or manmade accident).

During the vulnerability analysis is essential to take into account the existing countermeasures and prevention measures (such as early warning systems) that are located in the area/ industry for the response of risks, because they reduce the vulnerability of the industry and the affected areas and consequently its risk.

STEP 4: Perform risk assessment of the natural gas pipeline failure

Specifically Risk (R) is the possibility of the harmful impacts or anticipated losses that arising from a specific event in the above mentioned areas. The risk of pipeline failure due to the various hazard zones can be estimated with the following function:

Risk = Hazard * Vulnerability (given that the disaster has occurred)

R = H * (V/H)

At this stage in accordance with risk assessment results we define the level of risk that are concerned negligible, small, medium, significant and high.

STEP 5: Quantify the impacts to the human factor, to the environment, to the structure and to gas installations as well as to the gas industry's economic activity based on the quantified data of the exposed systems.

Based on the consequences at the four (4) above systems, a quantitative indicator from 1 to 100 at the level of the industry is assigned, which characterizes the overall risk of the industry. The following table summarizes the disaster impacts as well as the units of measurement.

Table 4.1 *Measurement units per impact category*

Category impact	**Unit Measurement**
Human factor	(Number of fatalities) * (cost of human life) (€) (Number of injured) * (hospitalization cost) (€) Number of homeless (qualitative analysis)
Environment	Soil: (hectares that have been damaged) * (cost per hectare) (€)
	Water resources: (m^3 of water resources that have been polluted) * (cleaning cost of water resources per m^3) (€)
	Atmosphere: (m^3 of atmosphere that have been polluted) * (cleaning cost of atmosphere per m^3) (€)
Infrastructures/ installations	(building blocks for infrastructures or installations that have been damaged) * (cost per building block) (€)
Financial activity	% of Reduction of the financial profit of the industry

In this research we consider that the natural gas pipeline failure has a minor impact on the environment due to natural gas physical and chemical properties.

STEP 6: Estimate benefit and calculate the new risk indicator that emerges from implementing each countermeasure, (e.g. what is the reduction of total risk of the industry if an early warning system of gas leakage is established).This process consists of the following actions: In the beginning the management of the industry propose potential countermeasures for the industry vulnerability reduction.

Countermeasures are all the response measures and risk reduction measures that refers to building measures or tools that are planned and implemented for the avoidance or limitation of the disaster impacts. Benefits are studied and defined that comes from the countermeasures implementation during the prevention phase for each hazard.

In order to calculate the benefit of the countermeasures STEP 3 should be repeated ("Vulnerability analysis") but this time the countermeasures will be added and then the new Risk indicator is calculated. According to the new Risk indicator the responsible for taking decisions will decide which countermeasures will select in order to implement to the pipeline network.

The following table shows indicative benefits that will rise if the countermeasures will be taken for the reduction of impacts.

Table 4.2 *Indicative benefits of countermeasures implementation per areas*

Impacts	Benefits
Human factor • death • injuries • homeless • hospitalization	Reduction of human losses
Environment • Soil pollution • Water resources pollution • Forest land reduction	Environmental degradation reduction (soil, water or forest)
Damages to infrastructure/installations • buildings • properties • installation	Damage reduction to the installations and the infrastructures
Financial impacts • Income loss • Industry profit reduction	Cost reduction that is caused by the disturbance of services.

• Camp costs that will be set up for the homeless needs • Disturbances to the natural gas network services	

STEP 7: Estimate the cost of each countermeasure

When the countermeasures are defined in order to prevent or/and minimize the impacts of potential disasters, based on the new risk indicator, their cost will be estimated and a cost – benefit analysis (based on a knapsack model) will be performed. This method is implemented in order to collect and decide the countermeasures to be implemented, balancing the cost of each measure with the benefit that arises from it. Generally, the risk management cost must be equal with the benefits that are gained from the selected measures.

Advantage of this method is that it ensures that the industry's investment for the prevention and risk management will gain greater benefit with the available resources. The limitations of the method are the lack of data and methods that are required in order to estimate the indirect benefits and costs.

STEP 8: Priorities based on the combined cost/benefit analysis. The managers categorize the potential hazards according with the effectiveness of the potential investment at countermeasures in order to achieve the best possible risk management within the available investment.

STEP 9: Resources for each production procedure for the pipeline network based on the risk indicator for each segment.

STEP 10: Finance the countermeasures that gas managers selected for each pipeline segment based on the available resources in order to minimize the total risk index of the pipeline industry.

In the following figure the proposed general method for risk management is shown.

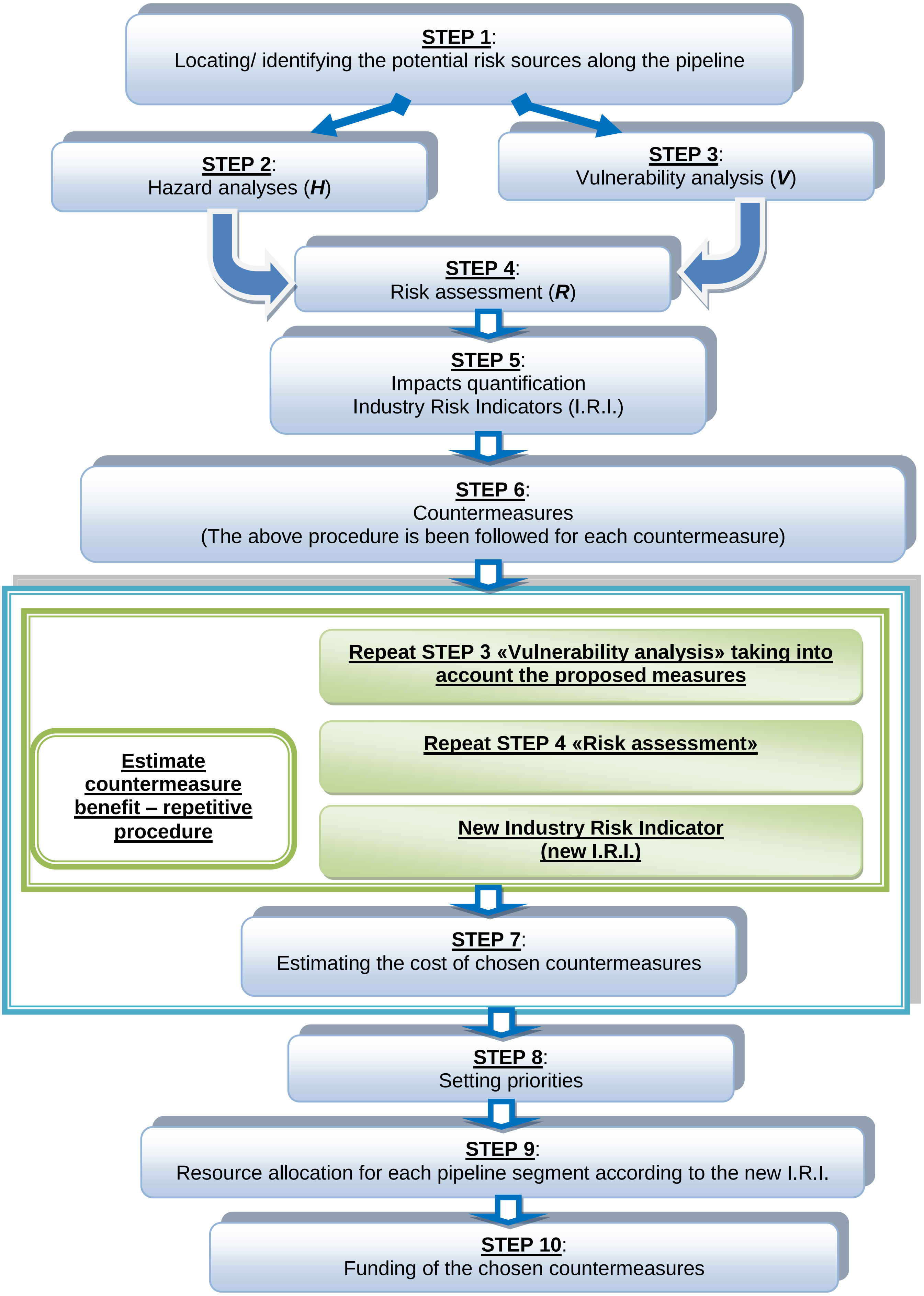

Figure 4.1 *Proposed risk management frame*

4.3 Conclusions

The above proposed Risk Management method for potential natural gas pipeline network failures combines the hazard and vulnerability analysis in order to calculate and assess the risk of pipeline failure to the four (4) main areas; human factor, environment, infrastructure that is within the hazard area and the gas installation as well as to the economic activity of the industry. In addition the proposed cost – benefit analysis (based on a knapsack problem) can help the industry’s decision makers to choose the suitable countermeasures with the most benefit and the less cost in order to minimize the risk indicator of the pipeline failure.

CHAPTER 5

HAZARD ANALYSIS

The hazard analysis involves a review of potential hazards sources associated with natural gas to be processed, used and handled at the peaking power plant and the associated distribution pipelines and facilities. The hazard analysis aims to a comprehensive identification of possible causes of potential incidents to pipeline distribution networks and their consequences to human factor, environment, infrastructures within the surrounding area and the gas installations and the industry's economic activity as well as outline of the proposed operational and organisational safety control required to mitigate the likelihood of the hazardous events from occurring.

Generally, the main hazard associated with the proposed development is related to a leak and ignition of flammable natural gas or to a lesser degree, to a leak of combustible liquids (distillate). A leak of flammable natural gas would generally only have the potential to cause injury or damage if there is an ignition that results in a fire or (in case of confinement) an explosion incident.

The factors involved are:

- The pipelines, vessel or equipment must fail in a particular mode causing a release. There are several possible causes of failure, with the main ones being corrosion and damage by external agencies
- The released material must come into contact with a source of ignition. In some cases this may be heat or sparks generated by mechanical damage while in others, the possible ignition source could include non-flame proof equipment, vehicles or flames some distance from the release
- Depending on the release conditions, including the mass of flammable material involved and how rapidly it is ignited the results may be a localised fire (jet fire), a flash fire or an explosion of the vapour cloud formed through the release
- Finally, for there to be a risk, people must be present within the harmful range (consequence distance) of the fire or explosion. How close the people are, will determine whether are injuries or fatalities as a result of the pipeline failure. Environmental damage from gas fire incidents are generally associated with a failure to control fire that resulted from the explosion

In more detailed, natural gas pipeline failure constitutes a fire and explosion hazard. Natural gas pipeline failures may result in fatalities, injuries and significant monetary losses in terms of property damages and lost fuel value. The natural gas industry has aggressively persuaded the development of risk reduction practices and technologies, in order for the risk of these failures to be minimized.

Natural gas is a buoyant, flammable gas which is lighter than air (relative density 0.6). On release into the open the non-ignited gas tends to disperse rapidly at altitude. Ignition at the point of release is possible, in which case the gas would burn as a jet (or torch) flame. Also, release of natural gas in an enclosed area, an explosion or a flash fire is possible. Moreover, the gas is non-toxic, posing only an asphyxiation hazard. Due to buoyancy any release of credible proportions from operations of this scale, in the open, would not present and asphyxiation hazard. With standard confined space entry procedures and appropriate security arrangements to prevent unauthorized access to any of the facilities the risk associated with asphyxiation from natural gas should be minimal.

Locally the pressure of the compressed natural gas may be hazardous in case of an uncontrolled release. These hazards, while of importance for people working at the site, do not have implications beyond the immediate location of the release unless the released gas is ignited. Therefore, the risk associated with of non-ignited compressed gas does not form part of the scope of the present risk assessment.

5.1 Identification of Hazard Factors

The most common hazard factors that influence the pipeline’s integrity and may cause natural gas leakage and consequently explosion or fire are (Fig. 5.1):

1. Third – party damage
2. Corrosion
3. Design
4. Natural hazards (e.g. earthquakes)
5. Others (e.g. human error)

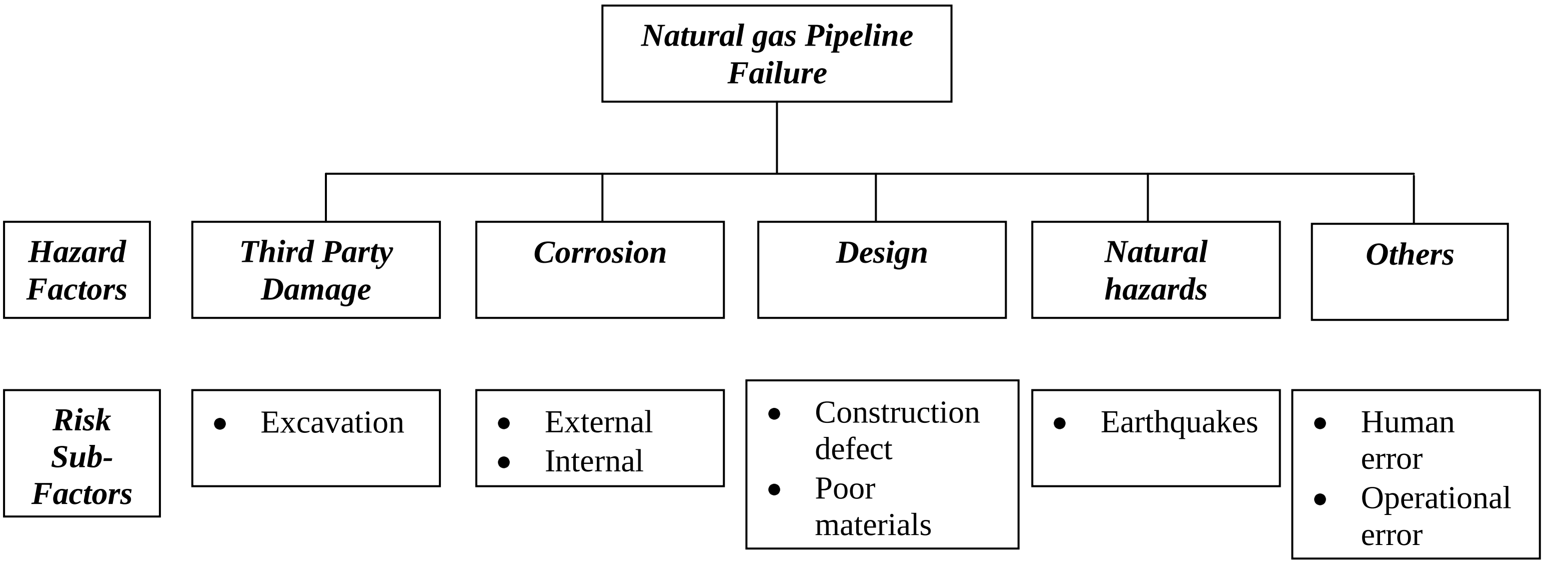

Figure 5.1 *Hazard parameters of pipeline failure mechanism*

Following each hazard factor is being discussed (see §5.1.1 - §5.1.5). and the probability of failure for each parameter is calculated (see §5.2).

5.1.1 Third party damage

Third party damage refers to incidents caused by crews digging near or into the pipeline inducing loss of gas containment to a safe pipeline. Damage to a pipeline, due to third party activities, can cause punctures, ruptures or breaks depending on its size, material and condition. The result will be massive release of natural gas to the open air, accompanied possibly by jet fire. The effects of a blow can be immediate or delayed, causing corrosion nucleus or a decrease in pipe thickness.

5.1.2 Corrosion

The probability for pipeline failure caused by corrosion is perhaps the most familiar hazard associated with steel pipelines. Corrosion focuses mainly in the loss of metal from pipes and is a main concern because any loss of pipe wall thickness leads to a reduction of structural pipeline integrity and an increase of failure probability.

Non-steel pipeline materials are sometime susceptible to other forms of environmental degradation. Some plastics degrade when exposed to sunlight, polyethylene, that is a common material in natural gas pipelines, can be vulnerable to hydrocarbons. Also, polyvinyl chloride (PVC) pipe can be attacked by rodents that actually gnaw through the pipe wall. In general, pipe materials can be internally degraded when transporting an incompatible product.

5.1.3 Design

Construction and material defects have been primarily associated with the quality of the welding process and joints linking pipe segments to form a line. Additionally, defects in the quality of a pipe material may form a default that will cause immediate after construction or delayed incidents. Pipeline support depends also on construction procedures and the quality of the materials that are used.

5.1.4 Natural hazards

Soil subsidence and earth movement are considered significant hazard sub-factors for the transportation pipeline networks. For distribution pipelines (particularly cast iron mains) soil movement at a smaller scale resulting to loss of pipe support is enough to cause a break. All corrosion types are depending on the pipe material. Earthquakes can produce ground shaking and permanent ground displacements. The severity of hazards at a particular location depends on the magnitude of the earthquake, the distance from the earthquake source, and the soil characteristics of the concerned area.

The size of an earthquake is usually expressed in term of magnitude. Among several different magnitude scales, moment magnitude is the current standard used to measure of the size of an earthquake for engineering and risk management purposes. Also, the level of ground shaking is normally expressed in terms of acceleration that a rigid object located on the ground surface would experience. Acceleration is often expressed as a percentage of gravity (g). A peak horizontal acceleration of 0.4 g on an object corresponds to a peak horizontal force of 40% of the weight of the object. The ground shaking produced by earthquakes moves in horizontal and vertical directions.

Earthquakes can also cause permanent ground displacement; abrupt surface ground movements along the fault are perhaps the most striking examples. Instability caused by the ground shaking typically causes other types of permanent ground displacement. Ground settlement, down slope movement of large areas of soil (similar to landslides), and sloughing of soil or rock from steep hillsides are other common types of permanent ground displacement. Damage from surface faulting is typically limited to a zone within a few tens of meters from the fault. Other forms of permanent ground displacement, especially those associated with landslide-like movements, can take dimensions of hundreds of meters.

The ground movement is responsible for the 7% of the total accidents that have been recorded to the EGIC data base. The following Graph presents the relation among earthquake magnitude, leak size and diameter class. An earthquake is possible to cause leakage nonetheless smaller pipe diameter are more prone to ground shaking rather than big pipe diameter.

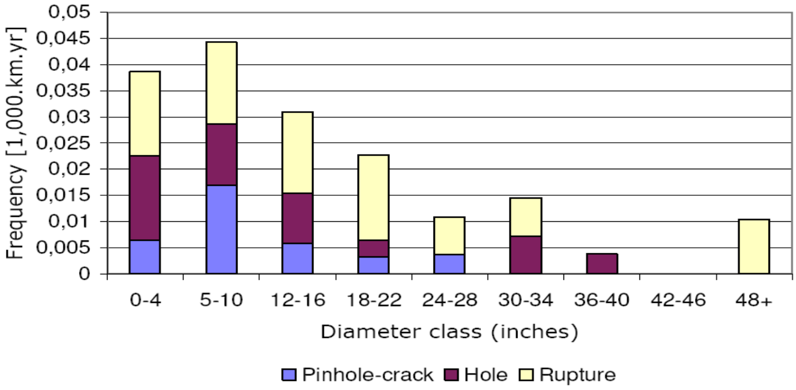

Figure 5.2 *Relate earthquake – leakage size and diameter class (EGIC data base)*[12]

The most common earthquake damage to gas systems results from construction defects to the buildings in which the gas system is placed and the equipment to which gas lines are connected. Earthquakes can produce ground displacements that can also damage natural gas systems directly. Additionally, the most important factor contributing to earthquake damage to customer gas installations is the poor performance of buildings, other structures, and the gas-fired equipment. As demonstrated by recent earthquake experience, shifting or toppling of gas appliances such as water heaters, boilers, furnaces, dryers and stoves is the principal cause of most gas-related, post-earthquake fire ignitions (e.g. 71% in the Northridge earthquake).

Gas meters are also susceptible to indirect earthquake damage caused by debris falling from customer facilities. Potential hazard sources involve unreinforced masonry chimneys or facades, falling masonry from damaged walls, falling parapets and other architectural features, and falling blocks used to construct residential fences.

These modes of damage are less frequently observed and pose a lesser risk because they cause release and dispersion of natural gas to the atmosphere.

Ground shaking is hazardous to aboveground components of the natural gas distribution system, which typically include gas measurement and pressure regulation facilities. Damage to aboveground components of the natural gas system is rare because of the ruggedness typically incorporated into their construction.Ground shaking has also been associated with some damage to buried pipelines. Although the precise mechanism of the damage is not well understood, it is generally believed that soil constraints on a buried pipeline force the pipeline to experience the same ground deformations associated with ground shaking. Damage from ground shaking is a concern for older pipelines that may have been weakened by corrosion, prior damage, or mechanical failures, or were constructed using outdated methods or materials. The pipelines that are more susceptible to damage due to ground shaking are made of cast iron, aging bare steel pipe, and pipe with threaded connections.

5.1.5 Others

Operator errors may take many forms. An example is to load the medium of low pressure network in pressure mixing stations with high pressure gas. The same category includes other “causes”, among them sabotage. In distribution networks tampering with residential meters is not rare and can be the cause of serious accidents, especially when it causes leaks that are not discovered timely.

5.2 Calculation of the probability of failure (P_f) for each risk factor

The probability of failure is expressed in terms of loss. An event tree analyses (ETA) illustrates the possible incidents of a gas release developed with time, for example leakage, ignition or delayed ignition. The frequency of incidents is estimated in terms of the major identified hazard factors of impact, e.g. corrosion, excavation, ground movement. The natural gas is lighter than the air so when it is released seldom forms clouds to cause a flash fire or a jet fire. So, natural gas pipeline failure can cause fatality, injury, and building damage and long term reduction of the economical activity of the natural gas industry. The relative probabilities are provided by the European Gas Pipeline Incident Data (EGIC).

- Probability of failure due to third party damage $P_{f_i\ 3rd\ party\ activity}$

To calculate the probability of pipeline damage due to third-party activity is necessary to identify and measure the variables that play a critical role in the threat of third-party damages according to the location and type of the pipeline. This could be achieved by using scoring algorithms.

Table 5.1 *Third Party Index*[12]

Parameter	% Contribution
Depth of cover	20
Activity level	20
Patrol	15
One-call	15
Public education	15
Aboveground exposures	10
ROW conditions	5
Third Party Index	**100**

- Probability of failure due to corrosion $P_{f_i\ corrosion}$

The corrosion index assesses three general types: atmospheric, internal and subsurface corrosion. This reflects three general environment types to which the pipe wall is exposed. The probability of pipeline damage due to corrosion is time dependent, its probability is estimated by manipulating data obtained by the direct current voltage gradient (DCVG) method. If the inspection data are not sufficient historical failure data analysis (HFDA) is applied[13].

Table 5.2 *Corrosion Index Scores* [14]

Parameter	% Contribution
Atmospheric corrosion	10
Internal corrosion	20
Buried pipe corrosion	10
Coating condition	15
Cathodic protection	15
Interference	15
Mechanical corrosion	5
Corrosion Index	**100**

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[12] Muhlbauer W. K. *Pipeline Risk Management Manual. Ideas, Techniques and Resources* (3rd Ed.). Houston: Gulf Professional Publishing, 2004

[13] Park, Lee and Jo, 2004

[14] Muhlbauer W. K. *Pipeline Risk Management Manual. Ideas, Techniques and Resources* (3rd Ed.). Houston: Gulf Professional Publishing, 2004

- Probability of failure due to design $P_{f_i \; design}$

  A significant element in the risk picture is the relationship between how a pipeline was originally designed and how it is presently being operated. The design related parameters are:

  - Safety factor (e.g. pipe diameter and wall thickness, maximum and normal pressure, material strength)
  - Fatigue (e.g. diameter/wall thickness ratio, pressure cycle magnitude)
  - Surge potential (e.g. flow rates)
  - Integrity verifications (e.g. pressure test level, in-line inspection technique)
  - Land movements (e.g. seismic shaking, landslide)

Table 5.3 Design Index Scores [15]

Parameter	% Contribution
Pipe strength	20
System safety factor	10
Fatigue potential	15
Surge potential	15
Integrity tests	20
Earth movements	20
Design Index	**100**

- Probability of failure due to seismic activity $P_{f_i \; geohazards}$

In this section, the formulation to compute the probability of failure due to ground movement that may affect the pipeline integrity of a structure due to seismic events is presented. The probability of failure of a pipeline due to seismic events can be computed using the total probability rule as follows:

$$P_f = \int_{S_a} F(S_a) f(S_a) dS_a,$$ [16]

where

$f(S_a)$: annual probability density of S_a at building site

$F(S_a)$: seismic structural fragility defined as the conditional probability of attaining or exceeding a specified performance level for a given S_a.

S_a: spectral acceleration

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[15] Muhlbauer W. K. *Pipeline Risk Management Manual. Ideas, Techniques and Resources* (3rd Ed.). Houston: Gulf Professional Publishing, 2004

[16] **Williams et al.,** *Decision analysis for seismic retrofit of structures*, Structural Safety (2008)

- Probability of failure due to incorrect operations $P_{f_i\ error}$

The assessment of human error involves many variables and it is difficult to quantify it. The index assesses the potential for pipeline failure caused by errors committed by the pipeline personnel in designing, building, operating and maintaining a pipeline.

Table 5.4 *Incorrect Operations Index Score* [17]

Parameter	% Contribution
Construction/Design	10
Training	20
Procedures	15
Maps and records	5
Overpressure potential	10
Safety systems	10
Maintenance	10
Communications	10
Mechanical errors preventers	5
Risk Assessment	5
Incorrect Operations Index	**100**

The likelihood of all the hazard sources occurring [$P_{(occurrence)}$] can be calculating by implementing the reliability theory, under the assumption that each threat is relatively independent and that the pipeline could be modeled as a series system, using:

$$P_{total\ of\ occurance} = 1 - \left[1 - P_{f\ 3rd\ party} \cdot 1 - P_{f\ corrosion} \cdot 1 - P_{f\ design} \cdot 1 - P_{f\ nat.hazards} \cdot 1 - P_{f\ others} \right]$$

The assumption of independence between hazards located in close proximity to each other generally provides conservative results, especially if the hazards share a common triggering event.

5.3 Conclusions

The hazard parameters that can cause natural gas pipeline failure are identified and the method for calculating the possibility of a pipeline failure occurrence is discussed. This analysis reviews the potential hazards sources associated with natural gas

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[17] Muhlbauer W. K. *Pipeline Risk Management Manual. Ideas, Techniques and Resources* (3rd Ed.). Houston: Gulf Professional Publishing, 2004

pipeline distribution networks. The hazard parameters of pipeline failure that was selected are; third party damage, corrosion, design, natural phenomena, others. The main impacts associated with the occurrence of hazard sources are related to leak and ignition of the natural gas or to a lesser degree, to a leak of combustible liquids (distillate).

CHAPTER 6

VULNERABILITY ANALYSIS AND CONSEQUENCES

This chapter aims to identify the selected area’s vulnerability, where the natural gas distribution network passes through. This means that the percentage of the effected people, infrastructure, environment and economical activity are rated and it includes anyone who enters the area of concern; employees, commuters, visitors, shoppers, transient or seasonal workers, inhabitants, forests, protected areas, monuments, households, commercial buildings, bridges and others. The population with special needs such as hospitals or areas with large non country’s speaking population can be considered because they can be more vulnerable to a disaster. Also, inventorying the area’s assets to determine the number of buildings, their value and population or human capacity, in hazard zones will be helpful to determine the vulnerability. Another vital task is to identify the critical facilities and installations of the natural gas distribution industry because survival of these facilities is essential for the distribution of the natural gas. Other items to define include economic elements of the industry’s activity.

The above vulnerability parameters that can increase the impact of a pipeline failure will be identified and discussed in this chapter. Also will be analysed the method for calculating the probability of unit impact of the accident to the pipeline network given that the hazard has occurred. The vulnerability analysis will involve the impacts to the following four (4) main areas: human factor, environment, infrastructure and installations and economic activity of the industry. Moreover a detailed description of risk assessment method follows, which combines the possibility of pipeline failure occurrence (hazard, see Chapt. 5) and the vulnerability to disasters considering that the failure of the pipeline has occurred.

6.1 Vulnerability parameters

The results of a vulnerability analysis should take into account all feasible events, in terms of effect distance (radius) over which people are likely to become casualties, the likely degradation of the environment, the anticipated damaged infrastructures and gas installations and the reduction of the industry’s economic activity. This should take into account people and installations both outdoors and indoors. Pipelines present a linear risk so where a length of pipeline over which a location-specific accident scenario can affect the population, the environment and the infrastructure associated with the specific development, the full length over which a pipeline failure could affect the above four areas should be considered in the vulnerability analysis.

The outcome of a natural gas pipeline failure is considered a leak or rupture caused by damage such as external interference, corrosion, fatigue or ground movement. Leaks are defined as gas lost through a stable defect; ruptures are defined as gas lost through an unstable defect which extends during failure. The escaping gas may ignite, resulting in a fireball, crater or jet fire which generates thermal radiation. In the following figure is shown the event tree of a pipeline failure.

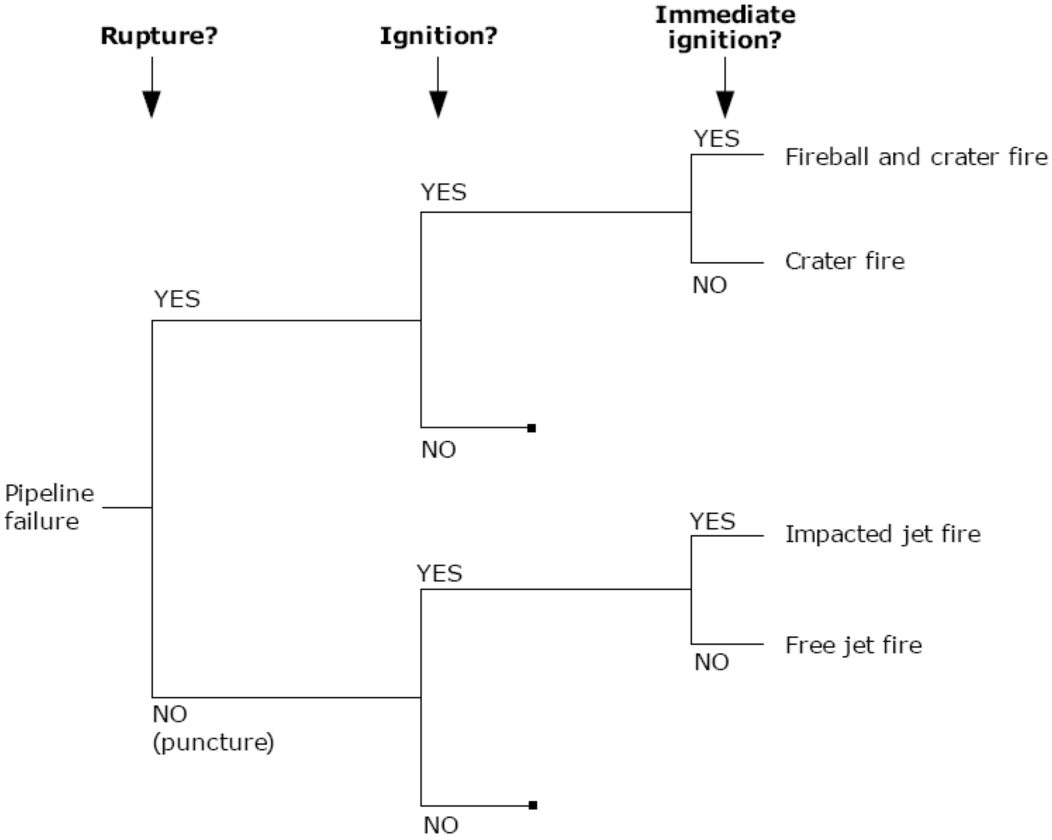


Figure 6.1 *Event Tree for a pipeline failure*

The main parameters that increase the vulnerability of the pipeline distribution network can be summarized as follow:

- Pipe characteristics:
  - Wall thickness
  - Length
  - Diameter (e.g. data from previous earthquakes indicates that larger diameter pipes are more prone to failure)

  - Material
  - Age of pipe; considering that age relates to the level of risk, older networks have reduced resistance to material degradation, so they are more vulnerable to accidents
  - Pipeline joints; networks with steel welding, have better performance in a case of a disaster compared to connections formed by flanges or links
  - Crossings; presence of connections and ramifications are presenting concentration of stress that may lead to a greater percentage of failures
  - Depth of coverage
  - Operating pressure (low, medium, high pressure network)
- ➢ Area characteristics:
  - Land use
  - Population density
  - Infrastructures that are intersected by the pipeline network
- ➢ Existing prevention and mitigation measures:
  - Frequency of maintenance
  - Systems of leakage detection
  - Monitoring methods and early warning systems that are applied by the industry along the pipeline length
- ➢ Environmental characteristics
  - frequency of construction activity
  - frequency of drainage, pile driving, deep plowing, placing dam walls
  - percent of pipe under water table
  - percent of pipe exposed to fluctuating water table
  - percent of pipe exposed to heavy root growth
  - percent of pipe exposed to chemical contamination
  - soil type (sand, clay, peat)
  - pH value of soil
  - resistivity of soil
  - presence of cathodic protection

6.2 Consequences of Natural Gas Pipeline Failure

A natural gas pipeline hazard failure, as it was noted in Chapter 5 can cause leakage, ignition and fire. The consequences of these disasters are studied for the following four areas:

1. Human factor. Refers to the number of deaths and injuries of the natural gas industries personnel as well as the citizens of the surrounding areas. The cost of human factor - includes cost of fatalities, injuries - refers to the case of ignition and can be estimated by the Hoffman method, considering age distribution within the hazard area of the pipeline
2. Environment. This involves the degradation of soil, forest and water environment. Natural gas is an environmentally friendly fuel and compared to other fossil fuels it has a very good performance in terms of pollutants criteria of the lower atmosphere (NO_x, Ozone, Carbon monoxide). It is also the fossil fuel with the highest hydrogen content so its combustion produces the least CO_2, which is a primary greenhouse gas. The various processes of natural gas distribution systems have some adverse effects on the environment. In general, these effects are not severe and often do not exceed EPA thresholds. So, in our case due to the fact that natural gas is not a toxic gas we suppose that the environment impact is minor.
3. Infrastructure/ gas installations. The consequences in this category involves the cost of buildings and other facilities damage within the potential hazard zone of the pipeline failure, as well as the cost of repair of the natural gas installations.
4. Gas industry’s economic activity. This category refers to the cost of natural gas supply interruption that was caused from the pipeline failure and reduced the natural gas industry profit to 10% of the yearly profit of the industry.

6.3 Vulnerability analysis

In the context of pipeline networks carrying natural gas it is the ignited releases that are of real concern. A vulnerability analysis for calculating consequences should model and predict the gas release rate, the characteristics of the resulting fire, the radiation field produced and the effects of the radiation on people and buildings nearby. Fires which may occur as a result of ignition of a large gas release caused by a rupture are defined as follows:

- fireball, which occurs in the event of immediate ignition of a large gas release

- crater fire, which occurs in the event of delayed ignition of the gas flow released when this is obstructed in the crater formed by the immediate release, or following the immediate ignition fireball
- jet fire, which occurs in the event of delayed ignition of the gas flow released when this is unobstructed in the crater formed by the immediate release.

The probability of occurrence of a crater or jet fire is dependent on assumptions made about sources of delayed ignition close to the release point. Typical assumptions result in crater fire probabilities for natural gas is between 0.15 and 0.3. Generally, natural gas is lighter than air, even at the low temperatures that would apply after a pressurized release, so ingress of gas into buildings is not expected to occur. Fatal injury effects are assumed for cases where people are in the open air or in buildings are located within the flame envelope from a fireball, crater fire or jet fire. Outside the flame envelope, the effects are dependent on direct thermal radiation from the flame to the exposed people or buildings.

As it was described above (see Chapt. 5) probability of failure occurrence are determined based on reliability models using fault and event tree analysis. It requires number of frequency data for initiating events which are very difficult to establish for pipelines. Each failure scenario must take into account protection layers and specified conditions, mainly environmental ones that would determine further development of the scenario. It is worth noting that real hazard zones caused by overpressure (explosion) and thermal radiation (fire) are circular areas of a radius equal to the assumed threshold value.

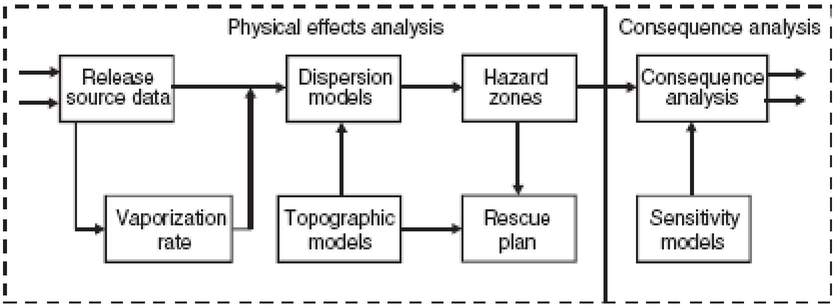


Figure 6.2 *Structure of model for calculation of potential consequences of a pipeline failure*

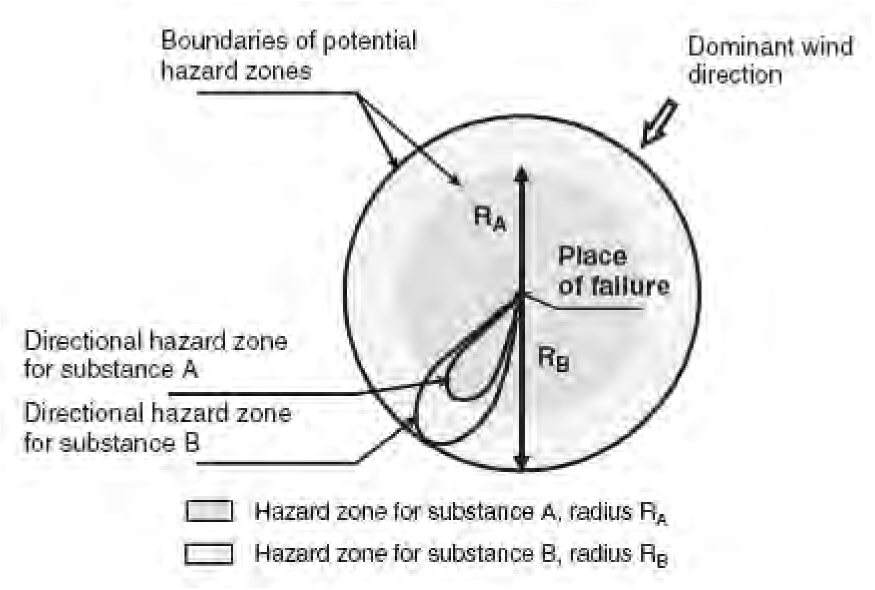


Figure 6.3 *Potential hazard zones for accidental release of natural gas to the air.*

6.4 Risk assessment

Risk assessment is a comprehensive process, which needs to be thoroughly understood both at operative and planning level of natural gas distribution, in order to generate and implement efficient risk reduction policies. Risk assessment includes both quantitative and qualitative information, which has been collected through understanding the concept of risk and its physical, social, economic and environmental factors and consequences. The identification of hazards and vulnerability/ capacity assessments together constitute risk assessment.

The calculation of risk at a particular location from an extended pipeline source is complicated by the fact that the failure position is unknown in advance. It is necessary to consider the effects from the predicted pipeline fire along the interaction length, which is the length of pipeline that could pose a hazard to the development or point of interest. Individual risk is calculated at specified locations and distances from the pipeline, and societal risk can either be calculated generically, based on estimates of population density, or in a site-specific manner, taking account of the precise locations of buildings, gas installations and people.

As it was noted to Chapter 3, Risk (R) is the possibility of the harmful impacts or anticipated losses that arising from a specific event. The risk of pipeline failure due to the various hazard zones can be estimated with the following function:

Risk = Hazard * Vulnerability (given that the disaster has occurred)

$$R = H * V$$

So in accordance with the risk assessment results the level of risk that are concerned negligible, small, medium, important, high is calculated. Following, we describe the way of estimating individual and societal risk based on the quantitative risk assessment method that was developed by Jo and Ahn [Jo et al., 2005] for transmission pipeline carrying natural gas.

Input Data

We consider a pipeline that carries natural gas and runs through a populated area - it could be rural, R or suburb, B - with length L, diameter d, wall thickness s and functions under pressure P.

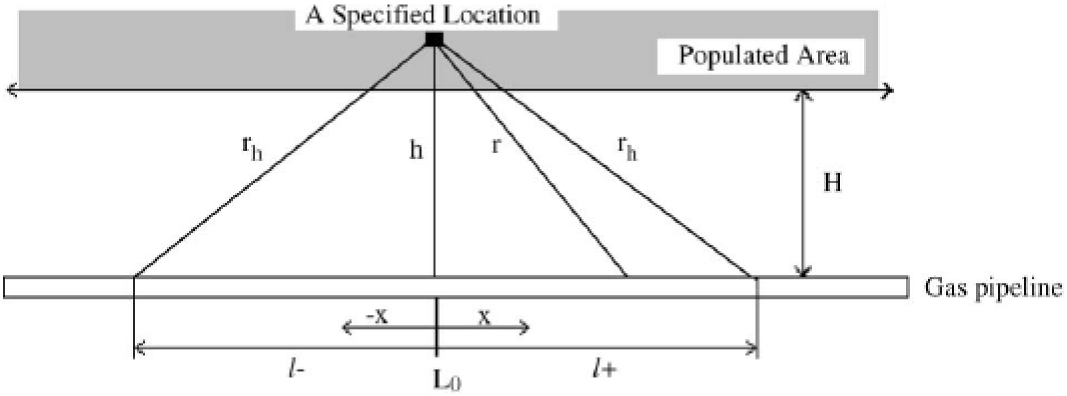


Figure 6.4 *The relation of variables*

r_h = hazard distance (m)

h = distance from pipeline to a specified point scaled by square root of effective rate gas release $(m/kg \cdot s)^{1/2}$

$l_\pm$ = ends of interacting section (m)

H = distance from gas pipeline to populated area (m)

L_0 = leak point

- ***Calculation of Individual risk***

The individual risk is defined as the probability of death at any particular location due to an accident. It can be expressed as the probability of a person at a specific location becoming a casualty within a year. The procedure to calculate the individual risk of natural gas pipeline is shown at the following diagram:

STEP 1: Calculating the effective rate of gas release

$$Q_{eff,i} = 1.783 \cdot 10^{-3} A_p \cdot a_i \cdot p_0 \cdot \max\left[0.3, \frac{1}{\sqrt{1 + 4.196 \cdot 10^{-3} \cdot a_i^2 \cdot \; L_0 + x \; / d}}\right]$$

Where:

$Q_{eff,i}$ = effective rate of gas release from a hole on the pipeline

A_p = cross-section area of pipeline (m)

a_i = dimensionless size of small, medium and great hole resulted from the failure of the pipeline, the i denotes the accident scenarios such as small, medium and great hole on the pipeline

p_0 = stagnation pressure at operating condition (N/m^2)

L_0 = pipe length from gas supply station to leak point (m)

x = distance from L_0 as shown to the following figure

d = pipe diameter (m)

STEP 2: Calculating the radii of 99%, 50% and 1% fatality

$$r_{i,99} = \sqrt{15.3 \cdot Q_{eff,i}}$$

$$r_{i,50} = \sqrt{30,4 \cdot Q_{eff,i}}$$

$$r_{i,1} = \sqrt{60.3 \cdot Q_{eff,i}}$$

where:

$r_{i,99}$ = radius of fatality 99% (m)

$r_{i,50}$ = radius of fatality 50% (m)

$r_{i,1}$ = radius of fatality 1% (m)

$Q_{eff,i}$ = effective rate of gas release from a hole on the pipeline

STEP 3: Drawing circles of radii of 99%, 50% and 1% fatality with a specified location as origin

STEP 4: Measuring the length of pipeline within the zones of 100%-99%, 99%-50% and 50%-1% lethality

For a straight gas pipeline, the length in each zone can be estimated by using the operator, Re, which represents the value of real part in the complex number.

$$l_{i,100-99} = 2 \cdot \sqrt{Q_{eff,i}} \cdot \mathrm{Re} \cdot \left[\sqrt{15.3 - \bar{h}_i^2} \right]$$

$$l_{i,99-50} = 2 \cdot \sqrt{Q_{eff,i}} \cdot \mathrm{Re} \cdot \left[\sqrt{30.4 - \bar{h}_i^2} - \sqrt{15.3 - \bar{h}_i^2} \right]$$

$$l_{i,50-1} = 2 \cdot \sqrt{Q_{eff,i}} \cdot \mathrm{Re} \cdot \left[\sqrt{60.3 - \bar{h}_i^2} - \sqrt{30.4 - \bar{h}_i^2} \right]$$

where:

$l_{i,a-b}$ = length of pipeline within the range from a to b% fatality (m)

$Q_{eff,i}$ = effective rate of gas release from a hole on the pipeline

Re = operator of complex number

$\bar{h}_i^2$ = distance scaled by the square root of the effective rate of gas release, $\bar{h}_i = h \big/ \sqrt{Q_{eff,i}}$, where h is the distance from the pipeline to a specified location of interest

STEP 5: Estimating the fatal length of pipeline

$$L_{FL,i} = \int_0^L P_i \cdot dL \approx l_{i,100-99} + 0.86 \cdot l_{i,99-50} + 0.156 \cdot l_{i,50-1}$$

where:

$L_{FL,i}$ = fatal length scaled by square root of effective rate of gas release $m \big/ \ kg \cdot s \ ^{1/2}$

STEP 6: Estimating failure rate

$$\phi_{i,EI} = \phi_{i,EI,d} \cdot K_{DC} \cdot K_{WT} \cdot K_{PD} \cdot K_{PM}$$

where:

$\phi_{i,EI}$ = failure rate caused by third party activity

$\phi_{i,EI,d}$ = failure rate varying with pipe diameter due to external interference

K_{DC} = correction factor of depth of cover

K_{WT} = correction factor of wall thickness

K_{PD} = correction factor of population density

K_{PM} = correction factor of prevention method

STEP 7: Estimating the individual risk

$$IR = \sum_i L_{FL,i} \cdot \phi_i$$

where:

IR = Individual risk

$L_{FL,i}$ = fatal length associated with accident scenario i

ϕ_i = expected failure rate per unit pipe length (1/year km) associated with accident scenario i

- ***SOCIETAL RISK***

With the risk of multiple fatalities being concerned, the societal risk is defined as the relationship between the frequency of an incident and the number of resulting casualties. It is usually expressed in the form of graph if cumulative frequency (*F*) of

N or more casualties plotted against *N* (an "*F-N*" curve). In the case of hazardous pipelines, which have the potential to cause multiple fatalities, the societal risk is considered usually more important than the individual risk. The procedure to calculate the societal risk of natural gas pipeline is described at the following steps. The STEPS 1 to 3 are the same as those followed for the calculation of individual risk, as well as STEP 7 (societal risk) with STEP 6 (individual risk):

STEP 1: Calculating the effective rate of gas release

$$Q_{eff,i} = 1.783 \cdot 10^{-3} A_p \cdot a_i \cdot p_0 \cdot \max\left[0.3, \frac{1}{\sqrt{1 + 4.196 \cdot 10^{-3} \cdot a_i^2 \cdot \ \ L_0 + x \ \ /d}}\right]$$

STEP 2: Calculating the radii of 99%, 50% and 1% fatality

$$r_{i,99} = \sqrt{15.3 \cdot Q_{eff,i}}$$

$$r_{i,50} = \sqrt{30,4 \cdot Q_{eff,i}}$$

$$r_{i,1} = \sqrt{60.3 \cdot Q_{eff,i}}$$

STEP 3: Drawing circles of radii of 99%, 50% and 1% fatality with a specified location as origin

STEP 4: Counting the number of people within the zones of 100%-99%, 99%-50% and 50%-1% lethality

STEP 5: Estimating number of fatalities

$$N_i = N_{i,100-99} + 0.802 \cdot N_{i,99-50} + 0.142 \cdot N_{i,50-1}$$

where:

N_i = number of fatalities from an accident (persons)
$N_{i,a-b}$ = number of people within the range from a to b% fatalities
i = denotes the small, medium and great hole on the pipeline

STEP 5: Drawing the number of fatalities over the pipeline

STEP 6: Estimating the cumulative fatal length of pipeline

$$L_{CFL,i} \ \ N_i \geq N \ \ = \int_0^L u \cdot \ \ N_i \geq N \ \ \cdot dL$$

where:

$L_{CFL,i}$ = cumulative fatal length of pipeline (m)

N_i = number of fatalities from an accident scenario (persons)
N = number of fatalities
u = unit function
L = pipe length from gas supply station to leak point (m)

STEP 7: Estimating failure rate

$$\phi_{i,EI} = \phi_{i,EI,d} \cdot K_{DC} \cdot K_{WT} \cdot K_{PD} \cdot K_{PM}$$

STEP 8: Construction of the societal risk curve of natural gas pipeline

$$F = \sum_i \phi_i \cdot L_{CFL,i} \quad N_i \geq N$$

The cumulative fatal length $L_{CFL,i}$ means a length within which an accident leads to N or more fatalities.

Quantified risk assessment (QRA) applied to a pipeline involves the calculation of risk resulting from the frequencies and consequences of a complete and representative set of credible accident scenarios.

6.5 Conclusions

In this chapter the methodology for analysing vulnerability of areas nearby the natural gas pipeline network was presented. After the pipeline failure, the scenario occurring in the case of rupture, ignition or immediate ignition of the gas is the development of a jet-fire, a fireball and crater fire. Whether the impacts of the pipeline failure will be significant for the human factor, the environment, infrastructure and installations and the economic activity of the industry, depends from the various vulnerability factors that were presented in this chapter.

Moreover the risk assessment method was presented, which combines the possibility of pipeline failure occurrence (*hazard analysis*, see Chapt. 5) and the possibility of vulnerability to disasters considering that the failure has happened (*vulnerability analysis,* see Chapt. 6). The assessment of the consequences of releases of natural gas is a fundamental requirement for the safe design and operation of industrial installations, plants and pipe distribution networks.

CHAPTER 7

MITIGATION MEASURES – COST BENEFIT ANALYSIS

To mitigate pipe failures, there is a series of possible mitigation measures that can be considered on a site by site basis. This chapter refers to the available prevention and mitigation measures that are applied worldwide by the natural gas pipeline industries in order to manage a potential accident or disaster that may occur at the network. Each of these countermeasures will be discussed and their usability concerning the reduction of pipeline failure risk will be analysed.

Moreover a cost –benefit analysis is introduced that aims to the optimization of pipeline risk management with the minimum cost within the available amount of available financial capital that the industry is willing to provide. For this purpose we introduce a dynamic knapsack model is introduced where benefit is considered the reduction of the risk indicator due to the implementation of the selected countermeasure and cost is considered the cost of the countermeasures.

7.1 Available mitigation measures

The safety technologies and practices can be divided into two categories: passive and active safety systems. Passive safety systems attempt to minimize damages after a failure has occurred. Active safety systems attempt to minimize the probability of a failure occurring in the first place. The latter are preventive approaches. As far as passive safety practices are concerned, the best known are; increasing pipe wall thickness and using casings. In general, the larger pipe diameter, the stronger a pipe is and consequently, the more difficult for it to be accidentally severed by farming or construction equipment. A smaller diameter pipe needs more upgrading of its nominal thickness to sustain external forces. Casings are either in the form of a larger diameter pipe surrounding the gas carrying pipe or in the form of concrete walls covering the top and possibly the sides of the pipeline.

An impressive active safety approach is the one-call system, where contractors can learn from a call to the gas utility or transportation company whether the site they are about to start construction on is at a the top or near a pipeline. Another practice is regular aerial supervision of the pipeline network by pipeline company personnel. It is anticipated that in the future satellite supervision will substitute the present day aerial patrols. Today foot patrols are the most common supervision practice.

Seismic resistant design of pipelines at fault crossings may be the most effective compared to landslide and liquefaction areas because fault (particularly strike-slip faults) locations can be determined with reasonable accuracy. The same mitigation measures can be employed for areas with high susceptibility to landslides or liquefaction/lateral spreading except that the locations of block interfaces may be less certain. There may be an opportunity to avoid landslide and liquefaction zones when selecting the alignment of new pipelines. Selection of pipe joint design is important in mitigating pipe damage due to wave propagation. To mitigate damage due to permanent ground deformation (fault movement, landslide, liquefaction) use modern welded steel pipe with butt electric arc welded joints. Replace old pipe that has oxy acetylene welded joints within the fault zones and several thousand feet beyond.

Moreover, to avoid corrosion a number of active safety systems are considered a standard practice:

- Lining the pipeline with a coating externally or internally
- Cathodic protection of pipes by charging them with a constant electric field
- Inspecting the interior of the pipeline with a pig travelling inside the pipeline by the force of the gas behind it. This technique does not require service interruption. Technologies are improving, producing faster and more reliable intelligent pigs.
- Quality control of transported natural gas to avoid sour gas corrosion.

Also another typical preventive approach is quality control of pipe material, welds, joints, valves and other equipment during construction. Regular pipeline integrity assessment is also possible through use of hydrostatic testing. The pipe is filled up with water slightly over the design pressure. If a leak is observed, the pipeline part it was found on is repaired by techniques of varying complexity, from fillings to sleeves to complete rehabilitation of the pipe. Leaks and ruptures due to a number of predisposing factors, are forced to occur, so the technique of hydrostatic testing, manages many failure causes simultaneously.

Moreover, the primary method of reducing operator error is good training and sound management systems. Today, human factor analysis can help task design so that safety is maximized. Heavy use of information technology appears to be an attractive safety improvement direction to a number of practitioners.

Finally, emergency response plans are crucial to minimize damages in the event of an accident. Drills on emergency response plans and training help reduce the probability of operator error in the difficult to cope with situations that arise after an accident. Regional variations in either failure risk or risk of high damage are typically managed through different design factors. In areas of higher population density medium to low pressure pipelines operate only and is required a lower design factor (or higher safety factor) for pipe wall thickness. Similarly, in areas where the soil is more corrosive, the design factor decreases. The risk of excessively stressing a pipeline during an earthquake increases mainly in areas with certain geological characteristics only.

7.1.1 Technology tools for preventing corrosion

- **Development of Coupons to Read Off-Potentials of Pipelines**

Since 1992, the pipeline industry has devoted a large effort to investigate the effectiveness of using steel coupons buried on the outside of the pipeline to monitor the effectiveness of cathodic protection. The coupon technology has introduced superior methods to measure the adequacy of cathodic protection systems without the inefficient interruption of CP current protecting the pipelines. The coupons have also proved a valuable tool for investigation of many other CP problems including interference stray direct currents (DC) from mining and railways, telluric currents, AC interference, and long line detection currents encountered in the depolarization of pipeline systems.

- **Alternating Current (AC) Prediction & Mitigation Techniques**

AC mitigation is becoming a major problem as pipeline right-of-way (ROW) is harder to acquire, and pipelines are subsequently forced to share power corridors with high voltage AC transmission lines. This has created incidences where significant voltages have been observed on pipelines in the ROW, raising concerns for both personal safety and system integrity. The pipeline industry through collaborative work completed development of a user friendly software package in 1997 to assist the pipeline operators in resolving two-thirds of the situations while sharing the ROW with AC voltage lines.

- **Assuring the integrity of corroded pipe**

The RSTRENG assessment methodology, which was recognized in the federal pipeline safety regulations in 1996, has been the primary means for determining the remaining strength of corroded pipe, and as such is critical for pipe repair and remediation decisions made both within and without a risk assessment program. This has already been incorporated in ASME's B31G code and referenced in 49 CFR 192 and 195.

- **Cathodic Protection (CP)**

There have been major accomplishments in the area of cathodic protection, including: CP Criteria - The pipeline industry devoted over $1 million and thousands of hours of research to investigate the CP Criteria to assist NACE (National Association of Corrosion Engineers) with the rewrite of RP0169. All of the changes are already incorporated in NACE standards and many of the changes were written into the Department of Transportation (DOT) code 49 CFR 192 in 19996, to ensure pipeline integrity for the pipeline systems.

- **Internal Corrosion Models**

Some of the major results of the work on internal corrosion are: Models to estimate the corrosion rates with normal pipeline gas and liquid contaminants and expected operating conditions; A Risk Assessment Program to assist pipeline operators to choose the most effective internal corrosion mitigation action plans; A major study on the Management of Microbiologically Induced Corrosion (MIC). This research has been the basis for on-going studies on detection, identification, and mitigation of corrosive environments caused by MIC.

- **Pipeline Current Mapper/Stray Current Mapper**

The Pipeline Current Mapper (PCM) and the pending Stray Current Mapper (SCM) were developed to overcome some of the limitations and complexity of existing CP survey techniques. Limitations of existing CP system troubleshooting techniques include:

1. Labor intensive (multiple connections to pipeline)
2. Requires highly trained/skilled operator
3. Subject to user interpretation and error

The PCM has been implemented by over 20 US operators since its introduction in 1997.

7.1.2 Technology tools for preventing external forces and loads

- **External Force**

External force which includes 3 rd party damage, incorrect operations, and "acts-of-God", like floods and landslides, are the most prevalent root cause in the pipeline incidents reported to DOT. Studies of the One Call System, sources of External Force Damage and methodologies to prevent Excavation Damage have recently been completed to identify gaps in the systems that thereby minimize the incident rate. In 1997, spacing of mainline valves was found to have no effect on improving safety even if the valve was closed at the time of a line break A variety of remote monitoring systems have been evaluated and some are promising to become commercial services.

- **On-bottom Stability of Off-shore Pipelines**

The latest version of the definitive design reference manual for assuring the stability of pipelines laid in the subsea environment is presented in a user-friendly, state-of-the-art software that addresses all design considerations, including: coatings; soil characteristics; and pipe-to-soil interactions.

- **Transportation Crossings**

PC-Pisces, an engineering analysis program, predicts the safe maximum vehicle loading when traversing buried pipelines. PC-Pisces has been used to minimize the problem of casing shorts and the associated accelerated corrosion by establishing safe installation of uncased crossings. PC-Pisces has been adopted in 1993 by the American Railway Engineering Association and by the American Petroleum Institute. This methodology is being updated.

A total of 38 leading practices included in the prevention and detection group that are being used by pipeline operators are provided in the following Table:

Table 7.1 *Prevention/Detection Practice*

Prevention/Detection Practice	**Description**
Visual Examination	Includes all visual determinations and measurements of pipe and components
Surface Nondestructive Testing	Includes techniques such as magnetic particle and shear wave ultrasonic testing to assess external anomalies
Surveillance/Patrol	Aerial or foot patrol of ROW, detailed visual inspection
Coating Condition Evaluation	All inspections associated with field coating evaluation of exposed buried or above ground pipe sections.
Close Interval Survey (CIS)	Aboveground potential measurement at close intervals.
Direct Current Voltage Gradient (DCVG)	Aboveground coating integrity assessment.
Bellhop Inspection	Exposure of a pipe section for examination. Usually includes visual and other NDE methods
Compliance Audit	Audit conducted by operator personnel to assure compliance with regulatory and Company procedures
CP Test Points.	Required measurement of CP current at fixed test points
Leak Survey	Required evaluation for pipeline leaks.
Geometry Tool Inspection	Inline inspection of pipe to detect obstructions, dents, pipe ovality, evaluation of clearances for inline inspection, etc.
Inline Inspection Tool (Baseline)	Inline inspection tool run in newly constructed pipe to establish initial pipe condition and detect construction damage.
Inline Inspection Tool (In-service)	Periodic inline inspection tool runs for pipeline integrity assessment
Preservice Hydrotest	Initial hydrostatic test to validate initial integrity and detect construction and defective materials
Construction Inspection	Inspection effort during pipeline construction to assure regulatory and specification compliance.
Manufacturer Inspection	Active QA/QC during pipe and component manufacture to assure initial product quality
Transportation	Inspection Inspection during pipe/component loading to assure proper methods that minimize transportation related damage.
Hydrostatic Retest	Periodic retesting to assure continued integrity or for up rating purposes
Strain Monitoring	Installation and monitoring of the deformation extent of pipe or components as a method to assure integrity.

Table 7.1 *Prevention/Detection Practice (continue)*

Prevention/Detection Practice	**Description**
Ground Displacement Survey	Use of survey methods to detect and monitor the extent of pipe deformation due to unstable soil or subsidence.
Soil Corrosivity Evaluation	Laboratory evaluation of soil samples removed from a bellhole to evaluate potential corrosivity
Resistivity Survey	Over-the-line determination of soil resistivity to estimate corrosive potential.
Rate Predictive Methods	Use of corrosion rate data to predict the time required for excessive metal loss and maintenance interval estimates.
External Coupon Monitoring	Installation and monitoring of buried coupons adjacent to pipe for corrosion monitoring and IR drop estimates.
Internal Coupon Monitoring	Installation and monitoring of coupons inside a pipeline to detect and monitor internal corrosive conditions.
Gas Analysis	Analytic determination of natural gas composition and potentially corrosive components.
Microbiological Corrosion Monitoring	Process of determining the contribution of microbiological organisms to either external or internal corrosion.
Surface Ultrasonic Inspection (B-scan)	Inspection to determine the extent and severity of internal corrosion from the outside pipe surface.
Iron Analysis	Determination of iron quantities in the gas stream as indicator of internal corrosion at upstream location(s).
Surface Radiography	Radiography to determine the presence of internal corrosion pitting damage (also pipe construction NDE).
Proper Materials Specifications	Specifications establishing required pipe/material quality for the facility design conditions.
Proper Design Specifications	Pipeline and facility design specifications that are suitable for the intended purpose.
Effective Public Education	A primary tool for third party damage prevention.
Effective Operator Personnel Training	Formal and on-the-job training processes that produce well qualified operations/ maintenance personnel.
Comprehensive Construction Procedures	Complete written methods and procedures to assure high quality pipeline construction.
Comprehensive Emergency Procedures	Complete written procedures covering pipeline and facility emergency measures
Comprehensive Operations and Maintenance Procedures	Complete documented procedures for all pipeline operations and remediation.
One Call System	Centralized state operated locations for construction activity notification and erosion and washout monitoring.

The following table summarises how to assure the integrity of a natural gas transmission line regarding the existing conditions.

Table 7.2 *Assuring Integrity of Natural Gas Transmission Lines*

	R-O-W Patrol		***Corrosion Control***			***In-Line Inspection***				***Bellholes***		***Tests***
Practices / ***Conditions***	***Aerial Patrols***	***Ground Surveys***	***CP Measurements***	***Close Interval Survey***	***Coupons/Monitors***	***MFL Pigs***	***Geometry Pigs***	***Mapping Pigs***	***Cameras***	***Visual Inspections***	***NDE Examinations (d)***	***Hydrostatic Retesting***
Outside Forces												
3rd party damage	X	X					Xa		Xc	X		
Earth movements	Xb	Xb					X	X				
Metal Loss												
External Corrosion			X	Xf		X				Xd	X	X
Internal corrosion					X	X	X					X
Gouges						X				Xd	X	X
Gas Leakage	X	X								X		
Coatings			X	X						X		
Cracks												
Seam weld										Xe	X	X
Girth weld										Xe	X	X
Stress corrosion											X	X
Fatigue										Xe		
Selective corrosion										Xe	X	X
Geometry												
Ovality, buckles							X		X	X		
Obstructions, dents							X		X	X		
Ovality, wrinkles							X		X	X		
Bend radius							X	X				
Pipeline movement								X				
Metallurgical												
Inclusions						X					X	X
Hard spots						X					X	X
Laminations											X	

Source: GRI-91/0366

Where

(a) Geometry Pigs are designed to detect dents and ovality

(b) Effective for landslides but not for differential settlement
(c) Designed to detect dents and wall protrusions
(d) Assumes coating has been removed
(e) Generally cannot detect without using NDT methods
(f) Locates possible corrosion resulting from inadequate CP

7.2 Cost – benefit analysis. Implementation of “0 – 1” knapsack problem

Cost – benefit analysis is a systematic procedure for evaluating decisions that have an impact on the social and economic life of a region. There are different ways to conduct a valid cost – benefit analysis, depending on the available information and the nature of the problem. A 0 - 1 knapsack problem is introduced in order to illustrate this approach. This approach involves the following elements; defining the nature of the problem, including the alternative options and interested parties, determining the direct cost of the mitigation alternatives; determining the benefits of mitigation, via the difference between the risk indicators with and without the countermeasures; and finally choosing the best alternatives without exceeding the available industry’s budget.

Moreover, benefit – cost analysis has traditionally required measures of benefits and costs of candidate projects. The knapsack optimization is used to formulate problems in which a number of projects might be implemented by judicious distribution of resources available. For many applications one seeks to maximize a function of benefit, subjected only to the constraints imposed by resource limitations. For several years, benefit – cost analysis has been the method of choice for allocation of resources to projects in such fashion as to maximize total benefits subjected to constraints. The method typically requires a common currency for the measurement of benefits and costs. We are interested in the application of benefit – cost analysis to guide the simultaneous allocation of a number of resources to a set of mitigation actions in several realistic situations, in order to:

1. Maximize benefit given resource constraints in the form of a budget. It is often possible to vary proportions of inputs to obtain the maximum benefit from the output

2. Decide whether or not to undertake a particular activity, by comparing its costs with its benefits.
3. Select the most productive set of activities with the highest benefit-to-cost ratios. This set might be composed of entirely separate activities or they might be interdependent in complicated ways.

The problem of allocating available budget for implementing mitigation measures to natural gas distribution networks is not a problem of selecting a unique countermeasure but a combination of countermeasures which is optimal. One optimum way of selecting the best mix of mitigation measures is using techniques based on a 0 - 1 knapsack formulation. The mitigation measures (items) are considered indivisible; you either take a mitigation measure or not, so the problem is solved with dynamic programming. The basic idea of the knapsack problem is that given some items, pack the knapsack to get the maximum total value. Each item has some weight (cost) and some value (profit). Total weight is in no more than some fixed number W (available budget). So we must consider weights (costs) of items as well as their value (profit).

For each mitigation alternative, one needs to specify the direct cost to implement the countermeasure. For the natural gas pipeline network, its owner and operator incurs the costs of mitigation. Once the costs are estimated for each mitigation measure alternative, the next step is to specify the potential benefits that impact each of the interested parties. The benefits, in the case of the pipeline network, will be estimated from the reduction of the risk indicator for the pipeline network before and after the implementation of the selected countermeasure. In order to calculate the attractiveness of mitigation, the nature of the benefits to each of the interested parties is estimated and compared to the upfront costs of mitigation.

Summarizing, the knapsack problem is one that appears to be appropriate for this application in combinatorial optimization. In our case the decision management problem for allocating the available capital for mitigation strategies introduces the knapsack problem in which each variable must equal 0 or 1. The “0-1” knapsack problem for our application is formulated as follows:

$$\max \sum_{i=1}^{N} b_i \cdot x_i$$

subjected to $\sum_{i=1}^{N} x_i \cdot w_i \le W$ and $x_i \in \ 0,1$

where:

b_i is the benefit from implementing countermeasure i

w_i is the cost of countermeasure i

W is the available budget

N is the total number of available countermeasure

The *Dynamic Programming* (DP) model is constructed considering the following elements:

1. STAGE i is represented by countermeasure i
2. STATE y_i at Stage i is the total cost of the stages $i, i+1, ...N$

   $y_1 = W$ and $y_i = 0,1,...W$ for $i = 2,3,...N$

3. ALTERNATIVE x_i at STAGE i is 0 if the countermeasure is not selected and 1 otherwise.

We want to select a certain number of each measure in the knapsack so that:

- The knapsack weight capacity (total available budget) is not exceeded
- The total benefit is maximal

Let $f_i \ \ y_i$ the optimal value at STAGES $i, i+1, ...N$ given the STATE y_i

The backward recursive equation is thus given as:

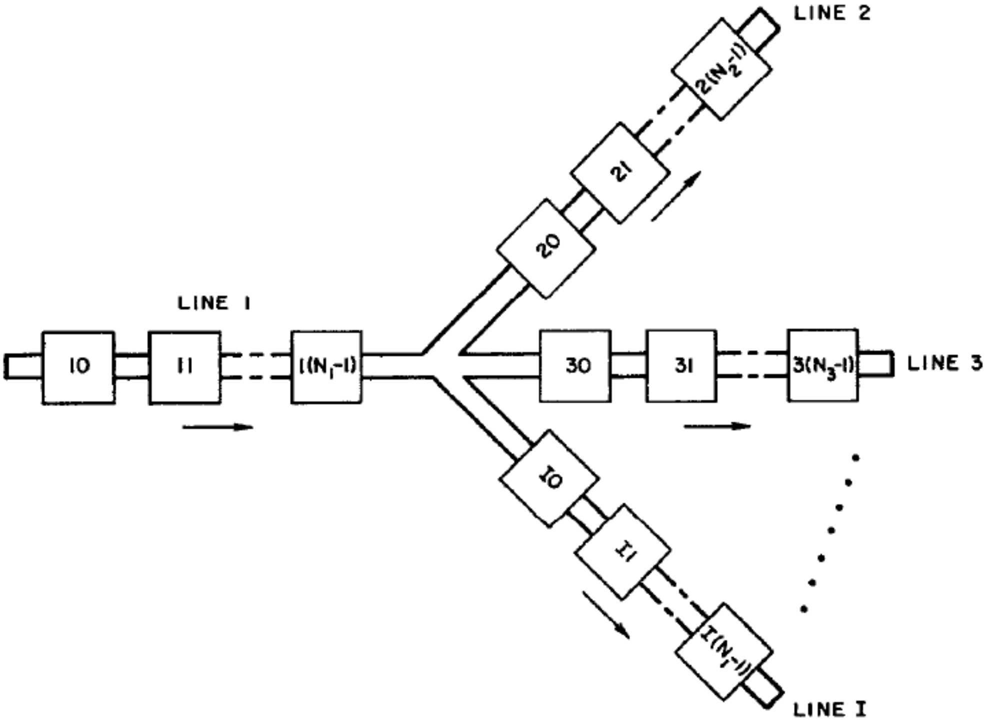
$$f_N \ \ y_N \ = \max_{\substack{x_N = \ 0,1 \\ y_N = 0,1,...W}} \ b_n \cdot x_n$$

$$f_i \ \ y_i \ = \max_{\substack{x_i = \ 0,1 \\ y_i = 0,1,...W}} \ b_i \cdot x_i + f_{i+1} \ \ y_i - w_i \cdot x_i \quad , \ i = 1, 2...N-1$$

By solving the 0 – 1 knapsack problem we manage to optimize the allocation of resources for mitigation in a case of pipeline failure with the maximum benefit within the limits of the available budget that the gas industry is willing to spend for the effective minimization of risk level along its pipeline network.

7.3 Example

Consider a pipeline network in an imaginary city with diameter 500mm, operating pressure 0.3MPa, cover-depth 100 mm passing through an area with population density 2500 persons/km^2. The network is shown in the following image. The natural gas industry wants to spend the amount of 50,000€ for choosing and implementing some of the available mitigation measures. In the Table 7.3 is summarized the alternatives mitigation measures, their cost and their benefit to the reduction of risk indicator in a case of pipeline failure. We suppose that after the pipeline failure a jet fire and an explosion occurred.



n = 4 (number of mitigation measures - items)

W = 50,000€ (available industry's budget)

Table 7.3 *Costs and benefits of the mitigation measures*

Available mitigation measures	***j***	***w (*10^4 €)*** ***direct cost of its mitigation measure***	***b*** *(risk indicator after– risk indicator before) the implementation of the mitigation measure*
Aerial Patrols	*1*	*4*	*2*
SCADA system	*2*	*3*	*4*
Leak detection system	*3*	*2*	*3*
Mapping pig	*4*	*1*	*1*

Solution

Item	Weight (*10^4)	Benefit
1	4	2
2	3	4
3	2	3
4	1	1

- STAGE 4

$$f_4 \quad y_4 \;=\; \max_{\substack{x_4 = \; 0,1 \\ y_4 = 0,1,...4}} \quad x_4 \quad , W = 0.1,2,3,4,5$$

y_4	x_4		Optimum solution	
	0	1	$f_4 \quad y_4$	x_4
0	0	-	0	1
1	0	1	1	1
2	0	1	1	1
3	0	1	1	1
4	0	1	1	1
5	0	1	1	1

- STAGE 3

$$f_3 \;\; y_3 \;\; = \max_{x_3 = \; 0,1} \;\; 3x_3 + f_4 \;\; y_3 - 2x_3 \quad , W = 0.1, 2, 3, 4, 5$$

y_3	x_3		**Optimum solution**	
	0	1	$f_3 \;\; y_3$	x_2
0	0 + 0	-	0	0
1	0 + 1	-	1	0
2	0 + 1	3 + 0	3	1
3	0 + 1	3 + 1	4	1
4	0 + 1	3 + 1	4	1
5	0 + 1	3 + 1	4	1

- STAGE 2

$$f_2 \;\; y_2 \;\; = \max_{x_2 = \; 0,1} \;\; 4x_2 + f_3 \;\; y_2 - 3x_2 \quad , W = 5$$

y_2	x_2		**Optimum solution**	
	0	1	$f_2 \;\; y_2$	x_2
0	0 + 0	-	0	0
1	0 + 1	-	1	0
2	0 + 3	-	3	1
3	0 + 4	4	4	(0,1)
4	0 + 4	4 + 1	5	1
5	0 + 4	4 + 3	7	1

- STAGE 1

$$f_1 \;\; y_1 \;\; = \max_{x_1 = \; 0,1} \;\; 2x_1 + f_2 \;\; y_1 - 2x_1 \quad , W = 0.1, 2, 3, 4, 5$$

y_1	x_1		**Optimum solution**	
	0	1	$f_1 \;\; y_1$	x_1
5	0 + 7	2 + 4	7	0

The results are shown to the following table:

	COST (€)	BENEFIT
$x_1 = 0$	0	-
$x_2 = 1$	30,000	4
$x_3 = 1$	20,000	3
$x_4 = 0$	0	-

Result

- The *maximal possible benefit* is 7.
- Two possible optimal solutions:
  - Choose item 2; SCADA system, during computation of f(3) in Stage 3 . Choose item 3; Leak detection system, in computation of f(2) in Stage 2.
  - Choose item 3; Leak detection system, during computation of f(2) in Stage 2. Choose item 2; SCADA system, during computation of f(3) in Stage 3.
- Both solutions coincide. The natural gas industry in order to achieve the maximum possible benefit – with other words the effective reduction of the risk level – within the available budget should invest on buying a SCADA system and a leak detection system.

7.4 Conclusions

In this chapter, the proposed countermeasures for preventing and mitigating a potential accident or disaster that may occur at a pipeline network were summarized and discussed. Also the 0-1 knapsack problem was introduced in order to perform a cost –benefit analysis that can help the natural gas industries to allocate their available budget to the countermeasure alternatives that produce the maximum reduction of the risk level (benefit). The cost to mitigate is primarily undertaken by owners, but everyone in a region benefits from reducing the risk of a pipeline network, from uninterrupted or faster restoration of the supply distribution networks after a disaster. Therefore, the primary users of this research are owners and operators of the natural gas networks; the operators could be government agencies or private sector organizations who fund the cost of implementing countermeasures.

CHAPTER 8

CONCLUSIONS

Many algorithms have been developed in the field of risk assessment aiming at calculating individual and societal risk as well as estimating of hazard zones. Most of them are based at the Muhlabauer model and guidelines that evaluate various aspects of pipeline risk by using risk models that calculate the probability of a pipeline failure occurrence as well as the extent of theirs consequences.

Also for risk assessment is used the Analytic Hierarchy Model (AHP), that was developed by Saaty (1980) and is a multiple attribute decision – making technique to identify the factors that influence failure on specific segments and analyzes their effects be determining probability of risk factors. This technique allows subjective and objective factors to be considered in risk analysis and also provide a flexible and easily understood way to analyze subjective risk factors.

Summarizing, a combination of qualitative and quantitative risk assessment is beneficial to successfully identifying the risks associated with the process, while controlling the cost, time, and resources. Qualitative risk analysis helps with understanding the process, and it is highly recommended as first step of the risk management process irrespective of the fact that quantitative risk analysis is going to be performed.

The outcome of literature review was that little work has been done on the field of estimating cost – risk relationships and even less on models that optimize cost while minimizing risk. The proposed Risk Management Method for potential natural gas failures combines the hazard and vulnerability analysis in order to calculate and assess the risk of pipeline failure to human factors, environment, infrastructure that is within the hazard area and the gas installations and to the economic activity of the industry.

The likelihood of all the hazard sources occurring [$P_{(occurrence)}$] is calculating by implementing the reliability theory, under the assumption that each threat is relatively independent and that the pipeline could be modeled as a series system. Through vulnerability analysis the possibility of an impact of the pipeline failure on four (4) systems: human factor, environment, structure and gas industry’s economic activity, is calculated.

Finally, we use a “0-1” knapsack formulation to optimize budget allocation to countermeasures with the maximum benefit (reduction of risk level). An example of the knapsack problem for a natural gas pipeline network illustrated the applicability of the model. This research contributes to the ability to make strategic allocation decision – where the diversity of benefits and costs demands inclusive measurement and where optimal resource allocation is demanded in the importance of the decisions.

For future research the proposed risk management method is capable of considerable improvement and extension as aspects of pipeline risk are considered; for example the effects of additional mitigation measures and operating procedures. Also, the estimation of probabilities for the hazard analyses when sufficient historical data for statistical analyses are not available, may make its application difficult for natural gas companies. The method should be considered more as the basis for developing system than a finished product. Although the “0-1” knapsack formulation that we are proposing can allocate the budget to mitigation measures by a reliable and effective way, it can be revised further to situations when the budget is not defined as a single value, but as a range of parallel projects.

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APPENDICES

APPENDIX A

TERMINOLOGY

A

Acute Hazard: A potential threat whose consequences occur immediately after initiation of an event, e.g. fire, explosion.

Alternatives: In this context, alternatives refer to any regulatory or non-regulatory OPS programs or policies that address pipeline safety.

B

Backfill: The soil that is placed over a pipe as one of the final steps in pipeline installation. Sand is often used as a backfill material because of the uniform support it provides and because it does not damage the pipe coating during installation.

Baseline: The condition or set of conditions that would exist but for the outcomes associated with an alternative or program. In the context of OPS cost-benefit analysis, baseline would account for the absence of OPS alternatives designed to improve or enhance safety of the interstate natural gas and liquids pipeline system. The baseline is rarely static; rather, it is usually characterized by conditions that are either improving (i.e., a “rising” baseline) or deteriorating (i.e., a “falling” baseline).

Benefits: Positive incremental effects that result from the implementation of alternatives. Benefits can take the form of avoided costs, i.e., costs that would have taken place otherwise but are prevented by an alternative. For cost-benefit analyses, benefits are often organized into *safety, environmental,* and *economic/commercial* categories.

Benefits transfer: The application of economic data, functions, or models collected or defined in one benefit valuation setting, to the valuation of benefits in another, similar setting.

Bounding analysis: A way of interpreting results of cost-benefit analysis that defines the lower and upper boundaries of a range of values that represent a cost-beneficial outcome.

C

Casing: A pipe completely surrounding the pipeline to provide protection and act as a conduit for potential product leaks. These have historically been used primarily where a pipeline crosses under a road or railroad.

Cathodic protection (CP): Method of protection against galvanic corrosion of a buried or submerged pipeline. In the CP method, a low-voltage charge is impressed on a metal in order to protect it from corrosion. Essentially, the pipeline is turned into a cathode by application of protective currents, which prevents the loss of metal. The CP system is general comprised of anodes, rectifiers, electrical connections and monitoring points.

Chronic hazard: A potential threat that can continue to cause harm long after the initial event, e.g. carcinogenicity, ground water contamination, long term health problems.

Control valves: These valves are designed to operate in the full range of positions from closed to fully open. The function of control valves is to control fluid flow rates be operating in partially open positions.

Corrosion: The wearing away of a material, usually by a chemical reaction.

Costs: Unfavorable effects associated with an alternative or policy change. Stated another way, costs are incremental resources used by entities, such as private sector firms, government agencies, or the public, in response to alternatives.

Cost-beneficial: An evaluation criterion describing the net difference between costs and benefits (i.e., net social welfare) associated with alternative courses of action.

Cost-effective: A term used to describe the lower cost of two or more alternative courses of action that provide identical benefits.

Cost-benefit analysis An analytical tool used to define, quantitatively and qualitatively, the net change in social welfare resulting from alternatives and policy changes, based on the value of their beneficial and unfavorable impacts (i.e., benefits and costs). A primary goal of cost-benefit analysis is to inform regulatory decision makers about the relative merits of alternative approaches to solving problems.

D

Discount rate: The rate at which past or future resource flows are converted to present values. For cost-benefit analyses, discount rates reflect either public or private valuation tradeoffs (i.e., the value of forgoing future consumption for present consumption of public or private resources, respectively).

Distributional equity: The concept that alternatives may create groups that benefit disproportionately as a result of an alternative's impacts, and others that suffer adverse impacts due to an alternative's influence.

DOT: Department of Transportation. The regulatory agency of the U.S. government that is charged with regulating aspects of pipeline design, construction and operation. The Office of Pipeline Safety (OPS) is the department within DOT charged with ensuring pipeline safety.

E

EPA: Environmental Protection Agency. The regulatory agency of the U.S. government that is charged with regulating activities that may be harmful to the environment.

Economic efficiency: The concept that, for a given alternative or change, the value of incremental social welfare benefits must equal or exceed that of the incremental social welfare costs created.

F

Failure: The point at which a structure is no longer capable of serving its intended purpose. Although a pipeline that is actually leaking product is the most obvious indication of failure, failure is often also defined as the point at which the material is stressed beyond its elastic or yield point – it does not return to its original shape.

Fatigue: The process of repeated application and removal of stress level, materials that must resist such cycles of stress must be specially designed for this service.

Flaw: A defect in the pipe wall that could be a threat to pipeline integrity, e.g. cracks, gouges and metal loss.

Fracture toughness: The ability of a material to resist cracking. Materials that are more ductile can absorb larger amounts of energy before cracks spread.

G

General equilibrium models: Models that account for dynamic linkages and interrelationships between sectors in the economy, and thus can be used to predict indirect impacts associated with alternatives (i.e., changes in prices, outputs, income, and employment).

H

HAZ: Heat affected zone. The area of metal around a weld that has been metallurgically altered by the heat of the welding process. This area is often more susceptible to cracking than the parent metal.

Hazard: A potential event that can lead to a loss of life, property, income, e.t.c.

I

Index: One of four general categories to which pipeline accidents can be attributed. Aspects of pipeline design, operation and environment are scored to arrive at numerical values for the third-party index, corrosion index, design index and incorrect operations index.

Index Sum: A summary number from the risk model that represents an assessment of all variables that affect spill probability. Index sums vary between a theoretical low of zero (extremely high probability of failure) to a theoretical high of 400 (virtually no chance of failure).

In-line inspection (ILI): The use of an electronically instrumented device, travelling inside the pipeline, to measure characteristics of a pipe wall, especially the detection of anomalies such as metal loss, due to corrosion, dents, gouges and cracks. Several ILI tool technologies are available, each with relative strengths in terms of types of anomalies detected, ability to characterize the anomaly and accuracy.

Incremental (cost or benefit): Denotes an additional change in the value of a variable, such as costs or benefits, attributable to an alternative (*also known as marginal*).

L

Leak: Loss of containment from a pipeline component; the unintentional release of product from the pipeline. Although the terms leak and spill are used interchangeably, a distinction could be that a leak is any amount of product escaping a pipeline, whereas a spill refers to the results of a leak – the final leaked volume and accumulation point, for instance.

Leak impact factor: A number that represents the overall consequence of a pipeline failure in the risk assessment. This factor is a score based on the product hazard and the dispersion factor. The leak impact factor is divided into the sum of the four index values to arrive at the relative risk score.

M

MAOP: Maximum allowable operating pressure; also called MAWP for maximum allowable working pressure. The highest internal pressure to which the pipeline may be subjected based on engineering calculations, proven material properties and governing regulations.

N

Non-use value: The component of a natural resource that is valued by individuals apart from any past, present, or anticipated future use of the resource in question.

P

Product Hazard: A numerical score that reflects the relative danger of the material being transported through the pipeline. The relative ranking of the product characteristics considers acute and chronic hazards such as flammability and toxicity.

psi, psig, psia: Pounds per square inch, pounds per square gauge or pounds per square absolute (normal unit of pressure measurement in USA). Zero psig is equal to about 14.7 psia, depending on the exact atmospheric pressure of the area.

Public education: The program sponsored by pipeline companies to teach the general public about the pipeline industry. The emphasis is usually on how to avoid and report threats to the pipeline and what precautions to take should a leak be observed.

Pipeline: As defined in 49 CFR Part 192 and Part 195, interstate natural gas and hazardous liquids pipelines regulated by the U.S. Department of Transportation’s Office of Pipeline Safety.

Present value: The current, discounted value of a past or future resource flow.

Primary research: The process of conducting basic research tasks, such as quantitative risk modeling or contingent valuation surveys, to answer specific research questions. Research methods that rely on values derived from primary research studies (e.g., benefits transfer) are referred to as ***secondary research***.

Q

Qualitative analysis: Use of qualitative research methods to answer specific research questions; use of these methods provides qualitative rather than quantified descriptions of variables, parameters, or relationships of interest

Quantitative analysis: Use of quantitative techniques (or groups of techniques) to generate estimates of the actual value of specific variables, parameters, or relationships, and to express them in quantified terms (e.g., units of product, euro).

Examples of quantitative techniques include, but are not limited to, probabilistic risk assessment, decision analysis, and Monte Carlo analysis.

R

Risk / Benefit Analysis (RBA): To identify the most cost effective controls for an unacceptable risk

Rectifier: A device that converts AC electricity into DC electricity and delivers the current onto the pipeline for purposes of cathodic protection.

Relative risk value or score: This number represents the relative risk of a section of pipeline in the environment and operating climate considered during the evaluation.

Risk: The probability and consequences of a damaging event.

ROW: Right of way. The land above the buried pipeline (or below the aboveground pipeline), that is under the control of the pipeline owner. This is usually a strip of land several yards wide that has been leased or purchased by the pipeline company.

S

Safety device: A pneumatic, mechanical ore electrical device that is designed to prevent a hazard from occurring or to reduce the consequences of the hazard (e.g. pressure relief valves, pressure switches)

SCADA: Supervisory control and data acquisition. A SCADA system allows conditions along the pipeline to be from a central location. This is a system to gather information such as pressures and flows from remote field locations and regularly transmit this information to a central facility where the data can be monitored and analyzed.

Sensitivity analysis: An approach to characterizing the uncertainty associated with estimates of unknown values, based on analysis of the sensitivity of such estimates to changes in underlying parameters. Performing sensitivity analysis provides a range of plausible values that describe to decision makers the overall influence of specific sources of uncertainty on the expected outcome.

Social welfare A term used by economists that refers to a change in the economic well-being of society; social welfare is measured by net changes in producer or consumer surplus*)*.

T

Third party: Any individual or group not employed by the pipeline owner or contracting with the pipeline owner. Third-party damages occur when an individual not associated with the pipeline in any way accidentally strikes the pipeline while performing some nonrelated activity.

U

Uncertainty: The extent to which the estimated value of a variable, relationship, or parameter may differ from its true value. Because the true values of many economic and environmental variables (e.g., rate of future climate change) are inherently unknowable, results of cost-benefit analyses and other economic analyses are generally subject to some uncertainty.

Use value: The component of value of a natural resource associated with any direct past, present, or anticipated future use of, or contact with, that resource.

W

Wall thickness: The dimension measurement between a point on the inside surface of the pipe and the closest point on the outside surface of the pipe. This is the thickness of the pipe material.

Willingness-to-pay The concept that the value of goods and services not typically traded in markets, such as environmental amenities, is equal to what consumers are willing to forgo to acquire such goods and services. Willingness-to-pay is a measure of a given consumer's willingness to incur opportunity costs in order to acquire goods or services.

Y

Yield point: This is a point, defined in terms of an amount of stress, at which inelastic deformation takes place. Up to this point, the material will return to its original shape when the stress is removed; past this point, the stress has permanently deformed the material.

APPENDIX B

TABLES

Table B.1 Failure frequencies based on failure causes and hole size (EGIC, 1993)

Failure causes	*Failure frequency (1/year km)*	*Percentage of total failure rate (%)*	*Percentage of different hole size (%)*		
			Small	Medium	Great
External interference	3.0×10^{-4}	51	25	56	19
Construction defects	1.1×10^{-4}	19	69	25	6
Corrosion	8.1×10^{-5}	14	97	3	<1
Ground movement	3.6×10^{-5}	6	29	31	40
Others/unknown	5.4×10^{-5}	10	74	25	<1
Total failure rate	5.75×10^{-4}	100	48	39	13

*The hole sizes are defined as follows: small hole, hole size is lower than 2 cm; medium hole, hole size ranges from 2 cm up to the pipe diameter; great hole, full bore rupture or hole size is greater than the pipe diameter.

Table B.2 Correction values of failure frequencies caused by third party activity

Factors	*Correction value*	*Conditions*
Depth of cover	2.54	dc<0.91 m
	0.78	0.91m ≤ dc ≤ 1.22 m
	0.54	dc > 1.22 m
Wall thickness	1	$t = t_{\min}$ or d > 0.9m
	0.4	6.4mm < t ≤ 7.9mm and 0.15m < d ≤ 0.45m
	0.2	$t > t_{\min}$
Population Density	18.77	Town
	3.16	Suburban
	0.81	Rural
Prevention Methods	1.03	Market posts only
	0.91	All other methods

Table B.3 Minimum Wall Thickness with pipeline diameter

d (mm)	-150	150-450	450-600	600-900	900-1050	1050
$t_{\min}$ (mm)	4.8	6.4	7.9	9.5	11.9	12.7

* dc: depth cover, t: wall thickness of pipeline, d : diameter of pipeline; rural: a population density not exceeding 2.5 persons/ha; town: central areas of towns or cities; suburb: area immediate in character between rural and town; $t_{\min}$: minimum wall thickness

Table B.4 Probit Models for Injury by Thermal Radiation (TNO, 1992)

Probit Equation	***Effects***
$\mathrm{Pr} = -39.83 + 3.0186 \ln\left(tI^{\frac{4}{3}}\right)$	First – degree burns
$\mathrm{Pr} = -43.14 + 3.0186 \ln\left(tI^{\frac{4}{3}}\right)$	Second – degree burns