A Cost-Benefit Analysis of Investing in Safety and Risk Engineering: The Case of Oil & Gas Transportation Services by Pipelines

Alexander Guzman, Behrooz Asgari,
Graduate School of Management, Ritsumeikan Asia Pacific University, Japan

***Abstract*--Most decision frameworks regarding the implementation of activities to mitigate the risk of failure in pipelines are based on a screening process under a considerable degree of uncertainty, which is generally derived from a subjective judgment or lack of sufficient information.**

Since the screening process is designed mainly to prioritize the risk mitigation activities according to an acceptable level of risk, the risk index cannot be used to perform a cost benefit analysis.

Therefore, the current challenge to pipeline operators concerning pipeline sustainability is implementing risk mitigation activities, such as environment protection initiatives or safety measures.

This study attempts to introduce a framework to measure the benefits of the investment in safety measures for pipelines using fuzzy logic as a tool for dealing with uncertainty. Thus, this paper provides a way to determine the surplus between the value of mitigated risk and the costs of the activities associated with such mitigation, using the possibility theory from the fuzzy logic to determine the values of the risk. Therefore, it is possible to determine if the costs associated with these risk management activities are reasonable or not, dealing with a degree of uncertainty of the data.

The proposed framework is considering variables such as threat and consequence scenarios, probability of adverse events, vulnerability, failure modes, percentages of risk reduction and mitigation costs.

I. INTRODUCTION

During the last couple of decades, as the world's energy consumption has increased, the number of serious accidents related with the failure of energy infrastructure has significantly risen and most of them have had large impact on people and the environment.

Those serious accidents have increased the public awareness about the risk of failure of certain energy infrastructure, and have also increased the concern about the risk acceptability by governments, regulatory bodies and operators. According to [1], the accidents have also had a strong influence on the development of engineering standards and safety legislation, which is often updated in reaction to the serious accidents.

One of the well known large accidents related to the failure of energy infrastructure is the large oil spill in the Gulf of Mexico in April 2010 caused by a failure in the offshore oil drilling rig known as Deepwater Horizon, which claimed eleven lives and was responsible for a large oil discharge to the ocean covering an estimated area of 62,159 Km^2 [2].

For the case of linear energy infrastructure such as oil pipelines, although the trend of the number of incidents tends to decrease and stabilize according to the databases of the European Gas Incident Group EGIG (2011) and US Department of Transportation USDOT (2013), the consequences caused by the failure of pipelines remain high in terms of affecting people, environment and property. Only in the United States, according to the Pipeline & Hazardous Materials Safety Administration PHMSA of the USDOT (2013), for the last two decades (1993-2012) the records indicate that the total number of significant incidents in pipelines were 5,612; with a total number of fatalities of 367; a total property damage of 6.6 billion dollars; and a total quantity of 2.3 million of spilled barrels.

Regarding the concern over the safety of energy infrastructure, operators have been performing risk assessments in attempt to identify and evaluate accurately the probability of failure of the infrastructure as well as the consequences related with that failure. For the case of pipelines, safety is one of the priority interests to regulatory bodies, governments, operators, investors and society because of the potential impact in case of a failure. According to [3], the risk can never be fully avoided, however, the overall risk of failure can be reduced to a tolerable level by opting efficient risk management measures.

II. PROBLEM STATEMENT

Growing in a sustainable way represent one of the most important challenges that currently energy companies, especially pipeline operators are facing. In addition, continuing operations in areas where the surrounding environment has changed (e.g., adverse weather or high population density), brings a new concern to the commitment to sustainability. According to this concern and due to the aging of pipelines, changing the public awareness about risk placing emphasis on public health and safety, and increased requirements set by regulating bodies [4], pipeline operators should re-build their risk assessment and decision making methodologies.

Decreasing the risk of failure in pipelines involves a substantial operational expenditure. That is why it is necessary to evaluate the effectiveness of the measures applied.

However, most decision frameworks regarding the implementation of activities to mitigate the risk of failure in pipelines are based on a screening process under a considerable degree of uncertainty, which is generally derived from a subjective judgment or lack of sufficient information. Since the screening processes are designed mainly to prioritize the risk mitigation activities according to an acceptable level of risk, the risk index cannot be used for cost benefit analysis.

Thus, according to [5], the main argument which is still unresolved is the quantification of the probability of failure, the risk reduction and the cost of mitigating measures to predict expected losses or benefits.

> "*Due to lack of applicable safety related data or the high level of uncertainty involved in the safety data available. Novel safety methods are therefore required to identify major hazards and assess the associated risk in an acceptable way in various environments where the mature tools cannot efficiently applied"* [6].

III. THE SAFETY MANAGEMENT OF PIPELINES

To start describing the management approaches for Safety and Risk management of industrial infrastructure is important to note their interrelation, commonalities and differences. Since those approaches are focused mainly in preventing releases of hazardous materials, it could result in confusion during the simultaneous implementation of both approaches, and could even create conflicts between functional departments within the company due to the overlapping of functions.

One of the most relevant management approaches regarding industrial safety was issued in 1992 by the Occupational Health and Safety Administration of the United States (OSHA). This management approach was focused in Process Safety Management (PSM), and was designed to prevent accidental realizes of substances and enhance awareness of dangers associated with handling and storing highly hazardous chemicals [7].

Later, in 1996 the environmental protection agency of the United States (EPA) issued the Risk Management Plan (RMP), intended to prevent accidental releases to the environment by focusing on prevention measures on substances with a high potential threat to the environment.

Although [7] argues about the consistency between the requirements of the PSM and RMP approaches for the implementation in off-site risk facilities, for the case of pipelines there is an overlap and repetition of activities due to its dual on-site/off-site configuration. Therefore, some pipeline operators tend to invest a high effort trying to simultaneously implement the PSM and RMP approaches causing an inefficient expenditure in safety management.

Thus, it is important to note that the main difference between the PSM and RMP approaches is that the PSM is concerned about the potential hazards and protection of employees within a specific area, while the RMP is concerned with incidents that could occur outside of the facility [7].

In response to the necessity of a consistent safety management approach for pipelines, in 2000 the Federal Office of Pipeline Safety of the United States issued new regulations for pipeline integrity management in high consequence areas (HCAs) that establish requirements for integrity management programs (IMP) for pipelines transporting hazardous liquids [8].

According to [8], the IMP establish an efficient solution due to the combination of the common framework of operational risk management of the PSM and RMP, addressing the protection of employees from the PSM approach and the protection of the community safety from the RMP approach. Figure 1 shows the generic PSM/RMP process framework and its implicit risk assessment core.

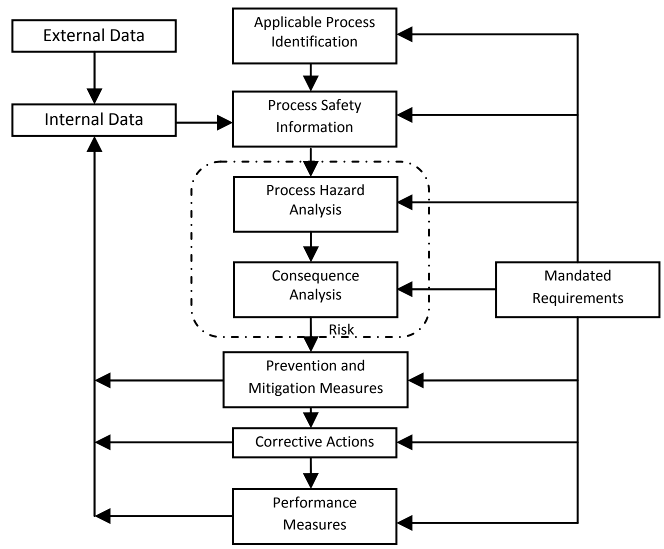

Figure 1. Generic PSM/RMP process framework [8]

A. The Pipeline IMP Framework

The relevance of the IMP in this study has to do with the issue that the pipeline IMP framework highlights the risk assessment as the central part of the prevention and mitigation decision process, which also represents the main common point of the safety management approaches.

> *"The IMP defines a risk-based approach for classifying the pipeline segments for inspection, testing, prevention and mitigation measures based on their proximity to and potential effects on HCAs. The IMP mandates a formal process for risk-based decision making to control risks through enhanced pipeline risk management"*[8].

Although the concept of HCAs is particular to US regulation, similar regulatory documents were issued in Canada, Europe, UK and Australia regarding the IMP implementation framework. Table 1 shows the most relevant documents issued in order to promote or regulate the implementation of the IMP of pipelines.

Although the structure of the IMP in literature seems to be the evolution of the previous safety management approaches as is stated by [8], all of the frameworks tend to follow a generic structure of risk management and could be synthesized comprehensively using the process presented in the risk management standard of the International Organization for Standardization issued in 2009, titled: "Risk management – Principles and guidelines" (ISO 31000). The figure 4 shows the comprehensive pipeline IMP framework based on the guidelines of the ISO 31000.

TABLE 1 RELEVANT PIPELINE IMP DOCUMENTATION

Institution / Regulatory Body	Code	Year of Issue	Title
The Code of Federal Regulations of the United States of America (CFR)	CFR 49.195.452	2000	“Pipeline integrity management in high consequence areas ”
The American Petroleum Institute (API)	API-RP1160	2001	“Managing System Integrity for Hazardous Liquid Pipelines”
American Society of Mechanical Engineers (ASME)	ASME/ANSI B31.8S	2002	“Managing System Integrity of Gas Pipelines”
The Code of Federal Regulations of the United States of America (CFR)	CFR 49.192.O	2003	“Gas Transmission Integrity Management”

The comprehensive pipeline IMP framework described in figure 2 establishes the context of the methodology for the benefit analysis of the investment in pipeline safety measures.

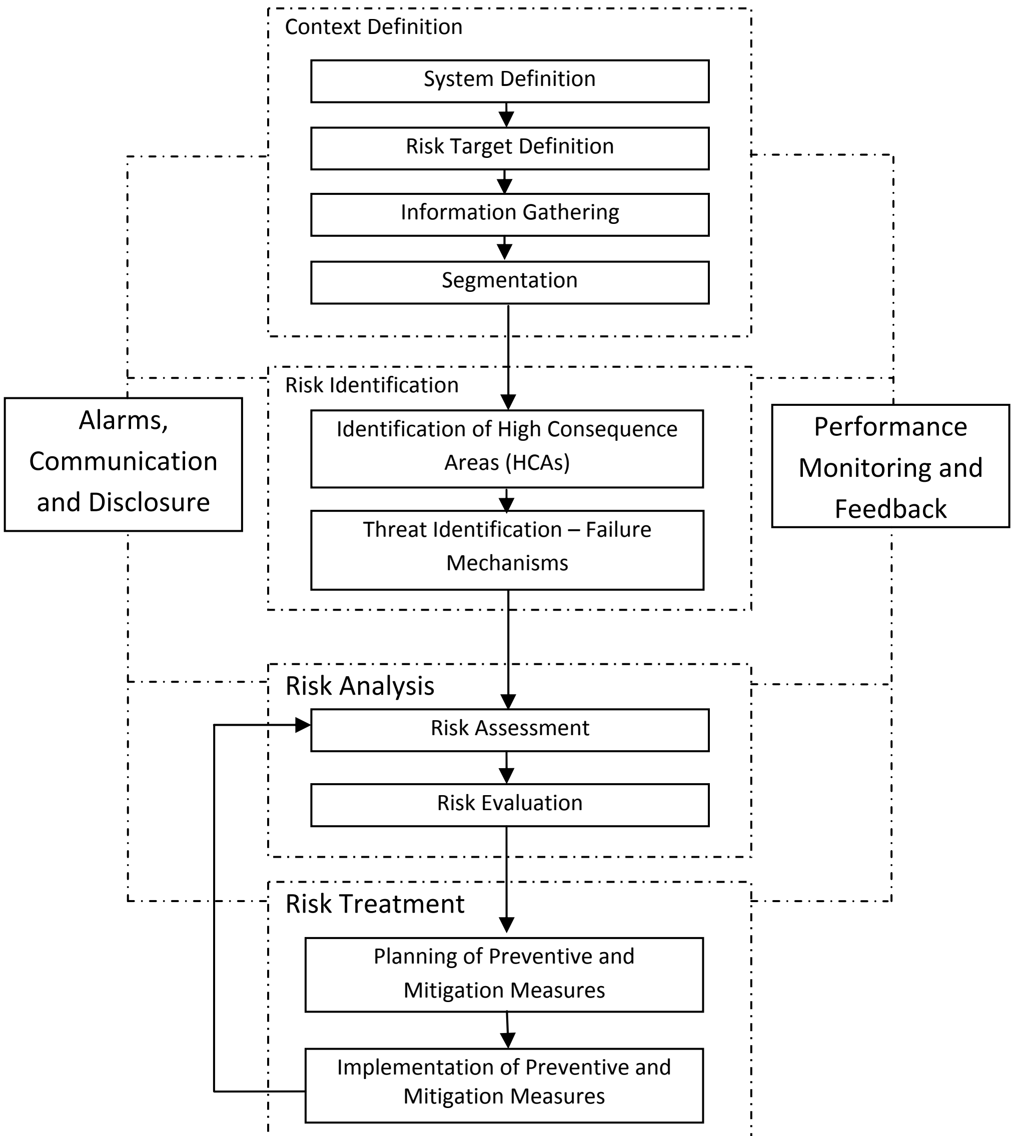

Figure 2. Comprehensive Pipeline IMP framework.*3.2.1 Risk Identification*

Since the risk of failure for pipelines can be defined as the combination of the probability of a failure event and its consequences [9], during the risk identification stage the main objective is to identify the sources of the risk components mentioned in its definition, the probability of failure (Threats) and the consequences. The Risk Identification comprises:

1) The Identification of High Consequence Areas (HCAs), which basically are specific zones where a product release could have the most significant adverse consequences. According to [10], those areas are defined by the inference of pipelines in populated areas, sensitive environment and commercial navigation routes.
   Figure 3 shows the diagram of a potential impact area of a pipeline crossing near to a school, which is defined as an example of HCA.

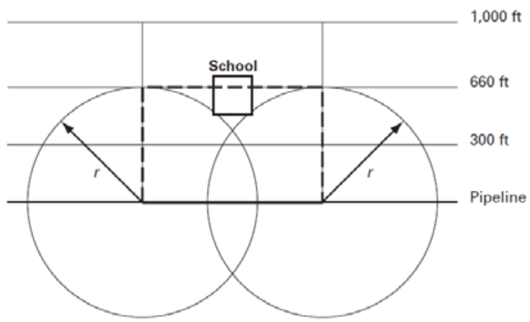

Figure 3. Diagram of a potential impact area for a 30 inches pipe and 1,000 psig [11].

2) The Identification of threats against the integrity of the pipeline. As stated by [11], the identification of potential threats should be the first step managing integrity of pipelines, and all known threats should be considered for the risk analysis. Also, according to [11] threats are classified into nine categories according to the failure mechanisms. Table 2 shows the classification of the threats according to the time frame and failure mechanisms.

TABLE 2 PIPELINE THREATS CLASSIFICATION [11]

Time frame	Threat
Time-Dependent	External corrosion
	Internal corrosion
	Stress corrosion cracking
Stable	Manufacturing related defects
	Welding / Fabrication related
	Equipment failure
Time-Independent	Third party / Mechanical damage
	Incorrect operational procedure
	Weather related and outside force

Although the grouping presented in the standard [11] is based on an extensive database of pipeline incidents, the definition of the applicable threats depends on the particularity of the environment and the operating characteristics of the pipeline. In some cases it may be very inefficient to try to evaluate the probability of failure of the threats that are not applicable to the actual conditions of the pipeline.

B. Risk Analysis and Evaluation

Risk analysis and evaluation provides an input for decision-making regarding the safety measures related to threats and consequences, as well as provides the best strategy for risk treatment, such as inspection, maintenance or replacement. Thus, risk analysis enables minimizing risk to people and the environment of an unintentional release together with lowering the probability of failure [12].

For this step, it is important to have a clear policy on risk tolerance, since the purpose of risk evaluation is also to provide support in making decisions about the priority for risk treatment according to the risk criteria established by the safety policy of the operator. Risk analysis and evaluation comprises of:

1) The risk assessment of the pipeline, in which the methods are based on a classic definition of risk as the product of the probability of occurrence of an adverse threat (P_i) and the consequence of the related adverse threat (L_i):
   $$R_i = P_i \times L_i \quad (1)$$
   The risk assessment can be applied using a quantitative approach, a qualitative approach or by using aspects of both approaches as a semi-quantitative approach. According to [8], the pipeline operators tend to use the quantitative and qualitative approaches to organize large amounts of information before making pipeline rehabilitation and repair decisions, however in the practice the quantitative risk assessment approach (QRA) is used mainly for construction licensing and public acceptance. [12].
   While the qualitative approach is focused on assessing the threats and consequences on a relative scale (e.g., low, medium, high and very high), quantitative methods are focused on assessing the threats and consequences using probabilistic methods, such fault tree, event tree and failure frequency analysis.
2) The Risk Evaluation, which considers the results of the risk assessment values and tolerable level set by the operator or the regulator. According to [13], the Risk evaluation involves the comparison of the level of risk found during the assessment process with the risk criteria established when the context was considered. Based on this comparison, the need for treatment can be considered. Although most of the IMP frameworks have this evaluation step implicit in their risk assessment approaches, it is important to highlight the importance of analyze the distribution of the risk assessment results between the areas of intolerable risks and broadly accepted risks as is shown in the figure 4.

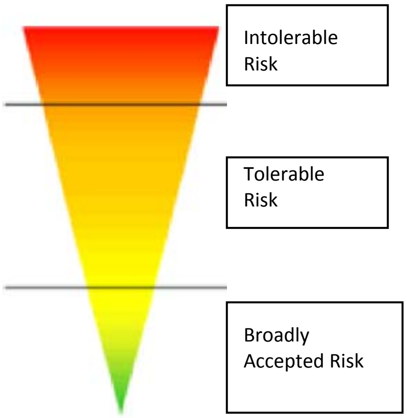

Figure 4. Tolerable risk area [14].

C. Risk Treatment

As is stated by [8], the IMP approach establishes a particular emphasis on the selection process for the prevention and mitigation measures, and specifies some required safety measures rather than leaving their selection to the operator. Moreover, the risk treatment stage includes a cyclical process that contains aspects of planning and implementation of safety measures, updating information of threats and consequences, reassessment of the residual risk, and adjustment to the plan of activities. Thus, the particular elements of risk treatment comprise:

1) The Planning and Implementation of the preventive and mitigation measures, which according to [13] are mainly designed for:
   - Avoid the risk by deciding not to start or continue the operation.
   - Eliminate the source of risk.
   - Reduce the probability or uncertainty by pipeline inspections.
   - Modification of consequences.
   - Sharing the risk with other parties by the insurance option.

Table 3 shows an example of grouping for some safety measures established by [10].

Since the safety measures of the IMP framework represent important amounts of operational expenditure, there is a necessity to establish a new stage in order to evaluate the benefits achieved to the organization. This new step of benefit measurement will be discussed in the following section of this paper.

Summarizing the safety management approach for pipelines presented in this section, it is important to highlight that the IMP was established as an efficient solution to cope with the conflicts between the previous safety approaches by sharing the same operational framework, which could be synthesized using a comprehensive risk management framework.

TABLE 3 GROUPING OF PIPELINE SAFETY MEASURES [10]

Group of Activities	Safety Measure
Prevention Third Party Damage	One-call utility location systems
	Improved line marking
	Optical or ground intrusion electronic detection
	Mechanical pipe protection
	Additional pipe wall thickness
	Pipeline marker tape
Control of Corrosion	Monitor and maintain cathodic protection
	Rehabilitation of pipeline coatings
	Pipeline maintenance cleaning
	In line inspection
Detecting and Minimizing the consequences of unintended releases	Reducing volumes lost
	Install release detection systems
	Improving emergency response
	Control of the released product
Operating pressure reduction	Pipeline operating pressure reduction

IV. RISK-COST BENEFIT ANALYSIS

A. Introduction to Cost Benefit Analysis

As mentioned in the previous section, there is a gap in the common pipeline integrity frameworks regarding the decision making process for the benefit evaluation of implementing safety measures. Although the operators certainly perform cost-benefit measurement of their expenditure in safety, the risk assessment is not commonly taken in account.

The main concept of Cost Benefit Analysis (CBA) establishes the evaluation of the monetary difference between the pros (benefit) and cons (costs) of the implementation of projects or activities, and then determines the net benefits to the status quo [15]. Thus, the net benefit achieved by the organization regarding the implementation of an N number of measures, could be expressed as the sum of the benefits minus their costs as:

$$NB = \sum_{i=1}^{N} B_i - C_i \tag{2}$$

Where:

NB: $Net\ Benefit\ Achieved\ by\ the\ organization$
B_i: $Particular\ benefit\ \ for\ the\ measure\ i$
C_i: $Particular\ Cost\ \ for\ the\ measure\ i$

As is stated by [15], the main purpose of CBA is to help in decision making in any field, and more specifically the objective is to facilitate efficient allocation of society's resources. Also, according to the timeframe of the CBA evaluation, it could be classified in two major types. *Ex ante* CBA, which is evaluated while the activities or measures are under consideration before they are implemented and *Ex post* CBA, which is evaluated after the implementation of the activities or measures [15]. Therefore, in relation with the decision making for safety issues, the *Ex ante* CBA approach is the most useful in deciding whether the investment should be made in a particular safety measure.

In order to illustrate the aid of the CBA evaluations for decision making, table 4 shows the values of each type, and also introduces a third CBA type which is evaluated during the course of the implementation of the measure known as *in media res*.

TABLE 4 VALUE OF THE CBA EVALUATION

Class of Analysis	Value
Ex Ante CBA	Resource allocation decision for the project or activity, helping to make “go” versus “no-go” decisions or select the best option, if accurate.
In Media Res CBA	Contributing to learning about actual value of similar activities or measures, with less uncertainty about future benefits and costs.
Ex Post CBA	Learning about actual value of specific activities or measures implemented.

Source: [15]

B. Risk Cost-Benefit Analysis and its implication in safety

Since the concept of Risk CBA involves the use of the models for combining probabilities and consequences in order to estimate benefits or costs, one of the novel techniques of Risk CBA for safety management is related to the decision making for the implementation of risk treatment measures.

According to the need to evaluate the effectiveness of safety measures in terms of benefits achieved by the organizations, and also considering that the common relative risk values cannot be used to perform a cost benefit analysis, the novel techniques of Risk CBA in decision-making implement models to determine the monetary surplus between the benefits and costs of safety measures using risk assessment.

According to [5], the cost benefit analysis provides a way to estimate the cost associated with reducing, avoiding or transferring risks, allowing to the managers to make decisions about whether such cost is excessive, thus promoting a productive allocation of resources. Therefore, [5] presents a model to determine the net benefit of counter-terrorism protective measures for critical infrastructure; describing a probabilistic risk assessment considering multiple threat scenarios and likelihoods; the value of averting a loss of human life, physical damage, risk reduction and protective measure costs for critical infrastructure. Next, the model proposed by [5] is as follows:

$$E_b = E(C_B) + P_{attack} \sum_{i=1}^{M} \sum_{j=1}^{N} \Pr(\theta_i \parallel attack) \Pr(L_j \parallel \theta_i) L_j \frac{R_{i,j}}{100} - C_R \quad (3)$$

Where:

E_b: $Expeted\ Net\ Benefit$

$E(C_B)$: $Expeted\ benefit\ \ form\ indirect\ measures$

P_{attack}: $Annual\ probability\ of\ terrorist\ attack$

$\Pr(\theta_i \parallel attack)$: $Relative\ threat\ probability\ given\ an\ attack$

$\Pr(L_j \parallel \theta_i)$: $Conditional\ probability\ of\ loss\ given\ the\ threat\ \theta_i$

L_j: $Loss\ or\ consequence$

$R_{i,j}$: $Percentaje\ of\ reduction\ in\ risk$

C_R: $Extra\ cost\ of\ the\ protective\ measure$

The uniqueness that the model of [5] is the application of benefit assessment for counter-terrorism measures considering multiple protective measures, risk aversion, utility theory and discounting of future costs. Although the model proposed by [5] is focused in critical infrastructure such as buildings, highway bridges and cockpit doors, the application could be extended to other type of infrastructure, such as pipelines transporting hazardous materials–thanks to the generalized concept of risk assessment.

In summation, the concept of CBA may improve decision making in the safety management field facilitating the efficient allocation of company resources by the evaluation of the monetary difference between the benefit and costs of the implementation of safety measures. Furthermore, since in CBA the risk assessment is not commonly taken into account, the novel techniques of CBA for safety management improve the model’s capabilities employing probability and risk based estimation for decision making of risk treatment measures.

The limitations of the novel techniques of CBA are the vagueness and uncertainty derived from the risk estimation due to the lack of information and subjective judgment. Therefore fuzzy logic, introduced by Zadeh in 1965, is a suitable method to deal with such vagueness and uncertainty. For that reason, the next section of this paper will introduce a CBA framework using fuzzy logic for the risk assessment of pipelines.

V. PROPOSED FRAMEWORK FOR ASSESS THE BENEFIT OF PIPELINES SAFETY MEASURES

According to the need of establishing a new stage in the pipelines integrity management program with the objective of estimating the benefit of the investment of pipelines safety measures, this paper proposes a cost benefit framework which is schematically depicted in the figure 5.

In addition to serving for the measurement of benefits of the implementation of safety measures, the proposed framework presents a technique to assess the pipeline risk of failure using fuzzy logic in order to handle the uncertainty derived from the estimation of probabilities and consequences of failure.

The threats against the integrity of pipelines employed by this study are according to standard [11], which includes external corrosion (EC), internal corrosion (IC), stress corrosion cracking, manufacturing related defects (MD), welding and fabrication related (FW), equipment failure (EF), third party and mechanical damage (TP), incorrect operational procedure (IO), and weather related and outside force (WO). In addition, the failure modes of pipelines employed are according to publication of the Health and Safety Executive of the United Kingdom [16], which includes leak (L), hole (H), and Rupture (R). Also, the consequences of failure are according to [3], which includes social (S), environmental (E), and a variation of infrastructure and disruption (ID). As shown in figure 5, the proposed Risk CBA framework includes two main steps, the fuzzy risk assessment, and the net benefit calculation.

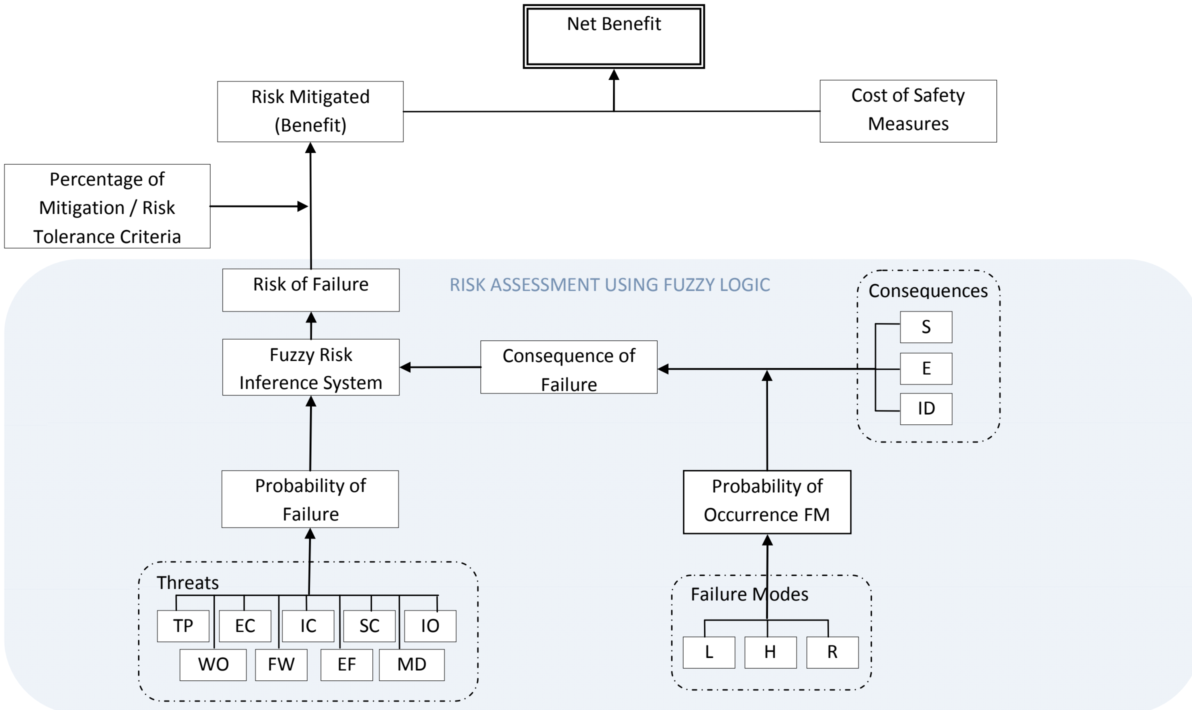

Figure 5. Framework of benefit measurement via fuzzy risk assessment.

A. Fuzzy Risk Assessment of Pipelines

Since risk assessment requires considerable amounts of detailed information about particular segments of pipelines which are uncertain and imprecise, one of the current efficient methods to deal with the uncertainty is the fuzzy logic [17]. The fuzzy logic is a powerful tool used in some knowledge-based systems and other artificial intelligence applications in which variables can have degrees of truthfulness or falsehood represented by a range of values between 1 (true) and 0 (false) [18]. This paper introduces a fuzzy risk inference system to be implemented as part of the benefit framework depicted in the figure 6.

The proposed fuzzy risk inference system is schematically presented in the figure 8. This figure shows the typical steps of a fuzzy inference system, which are the fuzzification of the crisp input variables, the construction of rules based on knowledge, the reasoning mechanism of the inference process, and the defuzzification of the risk into a crisp value.

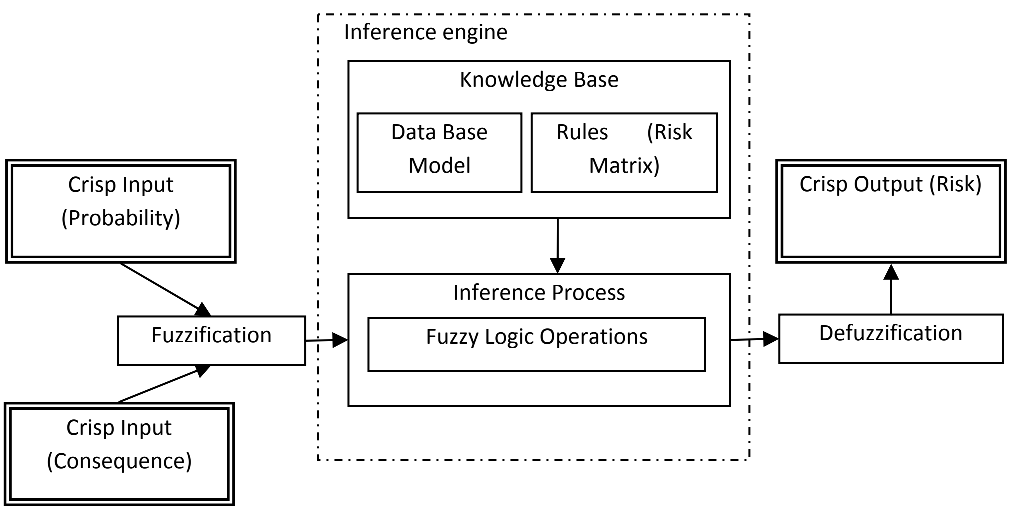

Figure 6. Structure of the fuzzy risk inference system.

1) Fuzzification of Probability and Consequence values

The process of fuzzification of the input variables establishes the conversion of the crisp values of probability and consequence into grades of memberships for linguistic terms of fuzzy sets such as very low, low, medium, high and very high. Based on the previous work done by [19], the model proposed in this paper presents the crisp and fuzzy ratings for the linguistic terms of the probability of failure as shown in the table 5.

Moreover, due to the fact that the base of the calculation proposed by this study is per threat, the consequences must be totalized before the fuzzification process. Since the monetary values of the consequence follow a logarithmic scale, table 6 shows the risk as the logarithm of monetary units with base 100. The crisp values are based on the monetary values stated by The Standard Practice for System Safety of the Department of Defense of The United States of America [20]. Also, the fuzzy values are adjusted following the proportion proposed by [19].

The Probability and Consequence values are fuzzyfied with triangular membership functions, as shown in the figures 7 and 8, due to the type of information available for each case.

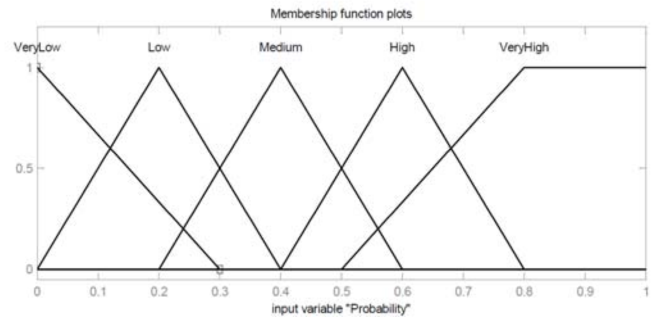

Figure 7. Membership function for probabilities

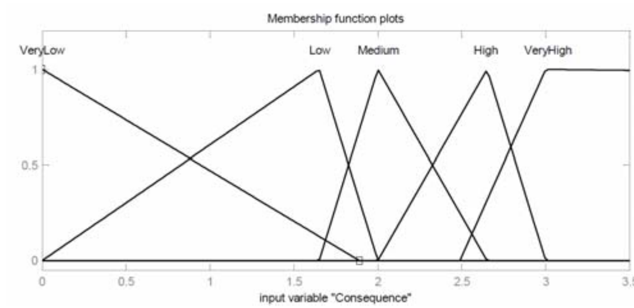

Figure 8. Membership function for the total consequence

TABLE 5 PROBABILITY RATINGS FOR CRISP AND FUZZY VALUES

Threat (θ_i)	Linguistic term	Probability crisp rating	Probability fuzzy rating
Third Party / Mechanical - Damage	Very High	0.80	$0.5 < \theta_{TPD} \leq 0.8$
	High	0.60	$0.4 \leq \theta_{TPD} < 0.8$
	Medium	0.40	$0.2 \leq \theta_{TPD} \leq 0.6$
	Low	0.20	$0 \leq \theta_{TPD} \leq 0.4$
	Very Low	0.00	$0 \leq \theta_{TPD} < 0.3$
External Corrosion	Very High	0.80	$0.5 < \theta_{EC} \leq 0.8$
	High	0.60	$0.4 \leq \theta_{EC} < 0.8$
	Medium	0.40	$0.2 \leq \theta_{EC} \leq 0.6$
	Low	0.20	$0 \leq \theta_{EC} \leq 0.4$
	Very Low	0.00	$0 \leq \theta_{EC} < 0.3$
Internal Corrosion	Very High	0.80	$0.5 < \theta_{IC} \leq 0.8$
	High	0.60	$0.4 \leq \theta_{IC} < 0.8$
	Medium	0.40	$0.2 \leq \theta_{IC} \leq 0.6$
	Low	0.20	$0 \leq \theta_{IC} \leq 0.4$
	Very Low	0.00	$0 \leq \theta_{IC} < 0.3$
Stress Corrosion Cracking	Very High	0.80	$0.5 < \theta_{SC} \leq 0.8$
	High	0.60	$0.4 \leq \theta_{SC} < 0.8$
	Medium	0.40	$0.2 \leq \theta_{SC} \leq 0.6$
	Low	0.20	$0 \leq \theta_{SC} \leq 0.4$
	Very Low	0.00	$0 \leq \theta_{SC} < 0.3$

TABLE 6 TOTAL CONSEQUENCE RATINGS FOR CRISP AND FUZZY VALUES

	Linguistic term	Consequence crisp rating $[Log_{100}(USD)]$	Consequence fuzzy rating $[Log_{100}(USD)]$
Total Consequence	Very High	3.00	$2.49 < C \leq 3.00$
	High	2.65	$2.00 \leq C < 3.00$
	Medium	2.00	$1.65 \leq C \leq 2.65$
	Low	1.65	$0.00 \leq C \leq 2.00$
	Very Low	0.00	$0.00 \leq C < 1.89$

2) Fuzzy rules based on knowledge

As stated by [19], the relationship between the input variables of the fuzzy risk inference system and the output variable is defined by fuzzy conditional functions that are known as "if-then" rules. The rules used by this study follow the risk matrix for natural gas release introduced by [3] shown in figure 9. Table 7 shows the list of the 25 rules extracted from the risk matrix used in the inference system.

3) Fuzzy inference process

The inference process maps the input variables, such as probability and consequence, into the fuzzy output set, such as risk, based on the composition of the conditional rules. The method selected in this study is the Mamdani since it is widely accepted for capturing expert knowledge and allows for describing the expertise in a more intuitive or human-like manner in contrast to the Sugeno method [14]. The fuzzy algorithm based on Mamdani method is implemented using the fuzzy tool box of the Matlab ® software.

Since the monetary values of risk also follow a logarithmic scale, table 8 shows the risk as the logarithm of monetary units with base 100. The risks values are based on the results of replacing the monetary consequences defined in table 6 in the risk matrix of figure 9, assigning probability values from 0 to 1.

Consequence	Very High	Medium	Medium	High	Very High	Very High
	High	Medium	Medium	High	High	Very High
	Medium	Low	Medium	Medium	High	High
	Low	Very Low	Low	Medium	Medium	High
	Very Low	Very Low	Very Low	Low	Medium	Medium
		Very Low	Low	Medium	High	Very High
		Probability				

Figure 9. Risk Matrix for natural gas release [3]

TABLE 7 FUZZY CONDITIONAL RULES

Number	**If** the consequence is:	**And** the probability is:	**Then** the Risk Index is:
1	Very Low	Very Low	Very Low
2	Very Low	Low	Very Low
3	Very Low	Medium	Low
4	Very Low	High	Medium
5	Very Low	Very High	Medium
6	Low	Very Low	Very Low
7	Low	Low	Low
8	Low	Medium	Medium
9	Low	High	Medium
10	Low	Very High	High
11	Medium	Very Low	Low
12	Medium	Low	Medium
13	Medium	Medium	Medium
14	Medium	High	High
15	Medium	Very High	High
16	High	Very Low	Medium
17	High	Low	Medium
18	High	Medium	High
19	High	High	High
20	High	Very High	Very High
21	Very High	Very Low	Medium
22	Very High	Low	Medium
23	Very High	Medium	High
24	Very High	High	Very High
25	Very High	Very High	Very High

TABLE 8 RISK RATINGS FOR CRISP AND FUZZY VALUES

	Linguistic term	Risk crisp rating $[Log_{100}(USD)]$	Risk fuzzy rating $[Log_{100}(USD)]$
Risk Value	Very High	2.95	$2.60 < R \leq 3.00$
	High	2.20	$1.60 \leq R < 2.80$
	Medium	1.33	$0.00 \leq R \leq 2.65$
	Low	0.65	$0.00 \leq R \leq 1.30$
	Very Low	0.58	$0.00 \leq R < 1.15$

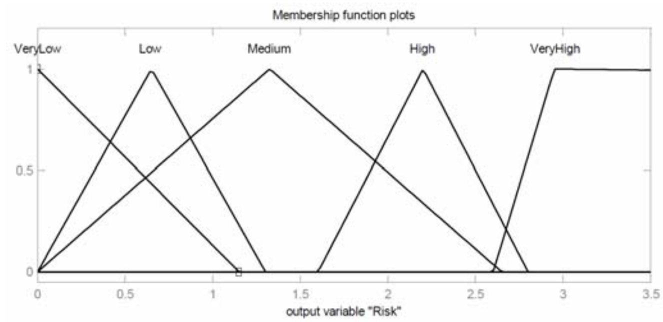

Figure 10. Membership function for the risk values

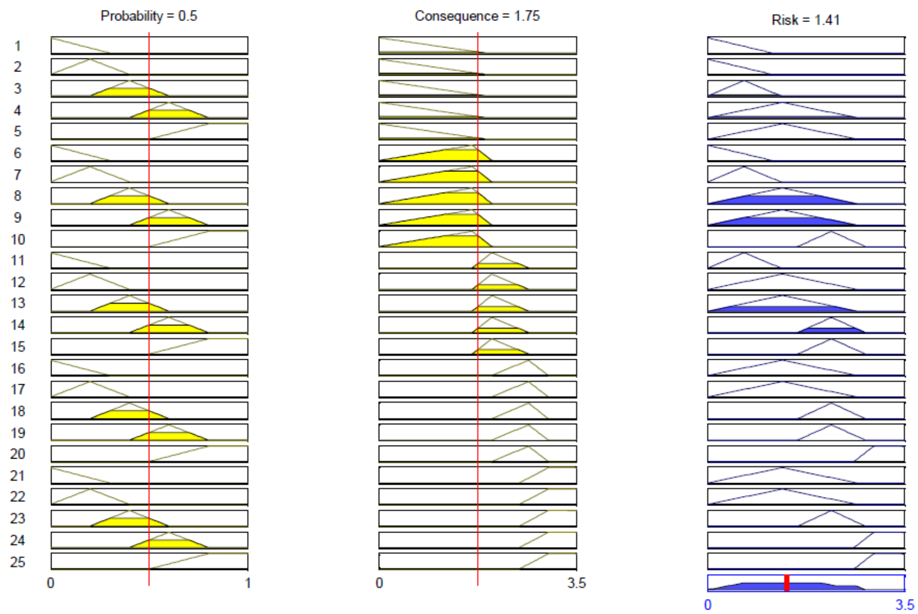

Figure 11. Sample of the fuzzy rule interaction in the inference process

According to the values of table 8, the risk output also is fuzified with the triangular membership function, as shown in figure 10.

A sample of the fuzzy rules of the model implemented in Matlab ®, and its interaction in the inference process is graphically shown in figure 11. Also, the three-dimensional plot that represents the interdependency between the input parameters (probability and consequence) and output parameter (risk value) can be shown as depicted in figure 12. This figure is interpreted as the fuzzy risk matrix developed based on expert knowledge used to establish fuzzy rating intervals and the fuzzy rules.

4) Defuzzification of the risk value

Concluding the process of fuzzy inference, defuzzification is used to convert the fuzzy risk set into a crisp value. The centroid of area (COA) is one of the most popular methods for the defuzzification process due to all active rules are taking part in the defuzzification process [19].

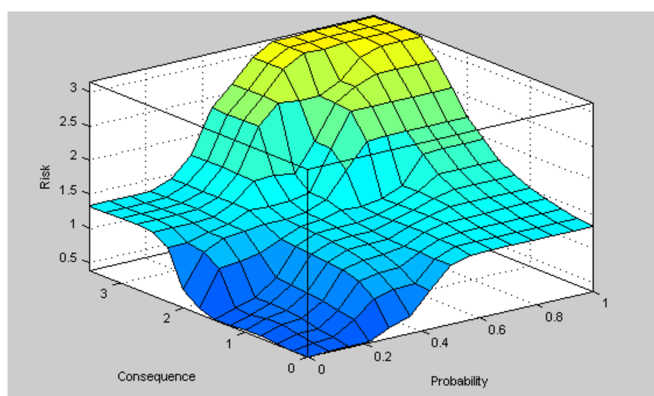

Figure 12. Fuzzy risk matrix.

B. Net Benefit calculation

After obtaining the risk value using the fuzzy inference engine, the proposed benefit framework continues with the estimation of the net benefit by estimating mitigated risk as the gross benefit minus the cost of the safety measure.

The model for the benefit framework is developed as an adaptation for pipelines of the model presented in the equation (3), and comprehensively expressed as:

$$B_m = \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{k=1}^{Q} P(\theta_i \parallel failure) \cdot L_{jk} \cdot P(\beta_k \parallel \theta_i) \cdot \Delta R_{ijk} - C_m \qquad (4)$$

Where:

$B_m = Net\ Benefit\ of\ the\ safety\ measure$
$\theta_i = Threat\ of\ failure$
$\beta_k = Mode\ of\ failure$
$P(\theta_i \parallel failure) = Relative\ Probability\ of\ Failure\ for\ the\ Threat\ i$
$L_{jk} = Consequence\ of\ failure\ j\ given\ the\ failure\ mode\ k$
$P(\beta_k \parallel \theta_i) = Probability\ of\ the\ ocurrence\ of\ the\ failure\ mode\ k\ for\ the\ Threat\ i$
$\Delta R_{ijk} = Perecentaje\ of\ Risk\ Reduction\ for\ a\ given\ measure$
$C_m = Cost\ of\ the\ given\ measure$
$M = Number\ of\ Threats$
$N = Number\ of\ Consequences$
$Q = Number\ of\ Failure\ Modes$

Equation (4) presents a classical expression of costs-benefit analysis. What is novel is the inclusion of the concept of risk mitigation as a benefit and the estimation of the risk value using a fuzzy inference system. It is important to note, as is described in figure 6, that the parameters of equation (4) included in the fuzzification process are the relative probability of failure and the total consequence of failure, which is the combination of the consequences and the probability of occurrence of the failure modes.

VI. CASE STUDY RESULTS

In order to demonstrate the potential relevance of the model depicted in equation (4), this section presents a case study based on information taken from the oil transportation network of Colombia. The sector of Oil & Gas transportation services in Colombia has increased rapidly during the last decade along with the rise of the public awareness about the safety of pipelines. Therefore, the technological development has contributed to the availability of several types of information about the infrastructure and its environment.

Taking advantage of that availability of information and the openness for new technological development, the pipeline selected was a relevant section of the network with a length of 471 Kilometers and diameters of 18, 20 and 24 inches along the way. Since the risk sources may change with the location, the pipeline is divided in 165 segments following a constant segmentation criteria established by the operator.

Tables 9, 10 and 11 show the application of the model depicted in the equation (4) for the first three segments of the pipeline, and accounting the most relevant threats for this case.

As can be observed from tables 9, 10 and 11, the total Net Benefit of invest in safety measures for the three segments is positive and the values are relatively high. However, for each case there are some particular measures in which the cost is larger than the risk mitigated, therefore there is not a positive benefit for those particular actions (e.g. such the case of the measures for Third Party Damage and Internal Corrosion in the first segment).

After running the model for the entire pipeline, the operator may be able to identify the segments where the safety measures haven't been effective enough to mitigate certain amounts of risk in comparison with the investing, or also could be interpreted as the segments where is not worth the extra spending in safety measures. Figure 13 shows the Net Benefit calculated for each segment along the pipeline, highlighting the places where the Net benefit is negative.

TABLE 9 CASE STUDY RESULTS FOR THE SEGMENT 1

Threat	Probability	Total Consequence [USD]	Fuzzy Risk Value [USD]	Percentage of mitigation	Cost of the Measure [USD]	Net Benefit [USD]
TP	0.00	$23,238,258	$457	0.30	$2,349	-$2,212
EC	0.50	$647,736	$181,970	0.20	$21,368	$15,026
IC	0.20	$647,736	$912	0.40	$420	-$55
					Total	**$12,760**

TABLE 10 CASE STUDY RESULTS FOR THE SEGMENT 2

Threat	Probability	Total Consequence [USD]	Fuzzy Risk Value [USD]	Percentage of mitigation	Cost of the Measure [USD]	Net Benefit [USD]
TP	0.00	$1,203,649	$447	0.30	$2,349	-$2,215
EC	0.70	$72,416	$245,584	0.86	$21,368	$189,133
IC	0.20	$72,416	$382	0.40	$420	-$267
					Total	**$186,651**

TABLE 11 CASE STUDY RESULTS FOR THE SEGMENT 3

Threat	Probability	Total Consequence [USD]	Fuzzy Risk Value [USD]	Percentage of mitigation	Cost of the Measure [USD]	Net Benefit [USD]
TP	0.00	$553,391	$448	0.30	$2,349	-$2,215
EC	0.10	$94,319	$407	0.20	$21,368	-$21,286
IC	0.70	$94,319	$247,856	0.40	$420	$98,723
					Total	**$75,222**

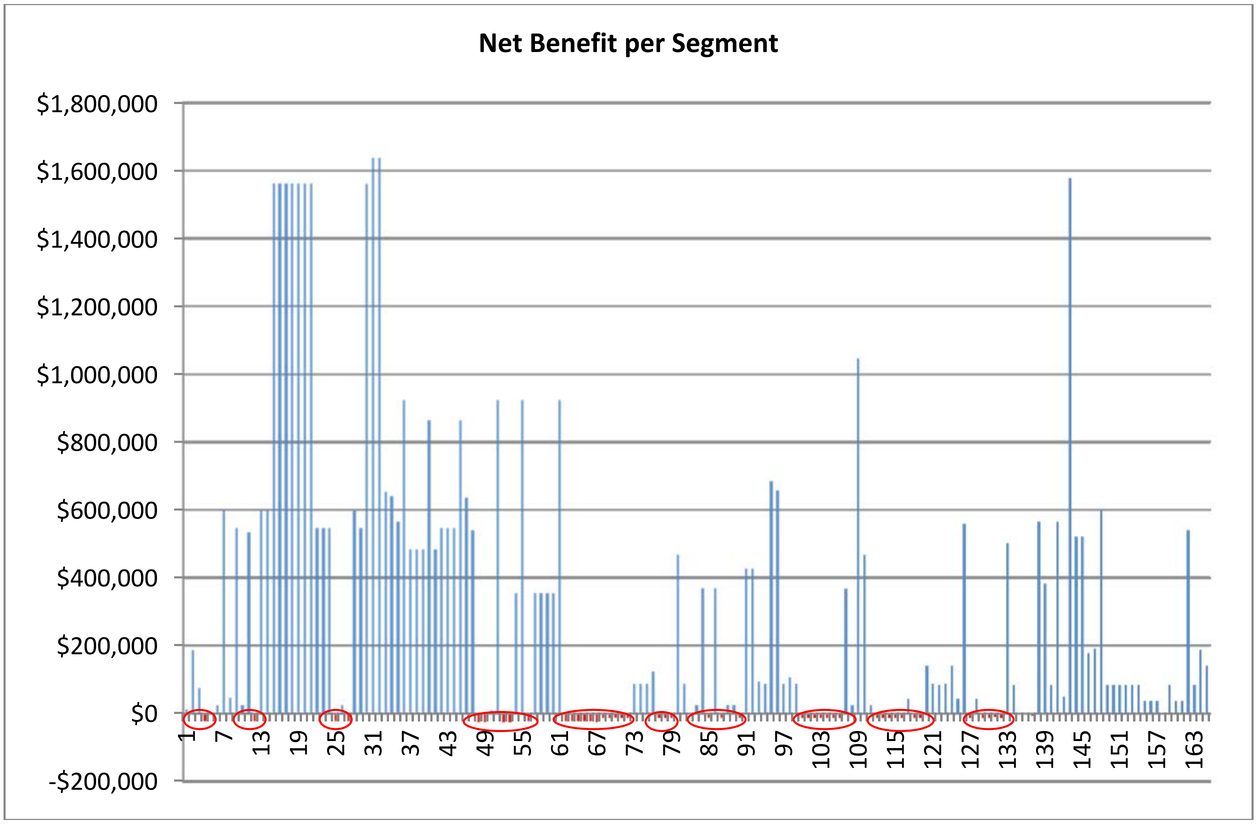

Figure 13. Net Benefit per Segment.

Concluding, the main purpose of the evaluation is to determine the magnitude in which the maintenance program is effective or ineffective in that specific area of the pipeline.

Although for some maintenance measures the relative benefit is low, such as the case for third party damage and fabrication and welding, the net benefit calculated for the entire maintenance program is quite efficient due to the high percentage of risk mitigation in areas where the probability and consequence of failure are relatively significant.

These results may help to show intangible returns of the investment in safety activities specifically in areas where the risk of failure of the pipeline is high from a social, environmental or economical perspective.

VII. CONCLUSIONS

- Although the selection of the risk assessment approach depends on the objective of the study; the availability of resources; the complexity of the environment; and the quality of the information available, the most efficient and accurate assessment could be achieved by a combination of qualitative and quantitative methods.
- The quantification of the benefit, related to the investment in new pipelines, should be evaluated with an accurate estimation of failure consequences. But to evaluate such consequences that represent energy releases, the models usually require a huge amount of data that generally is not available. Therefore, the most suitable methodology is prioritizing where the largest consequences are expected, such as populated areas and national parks, for example, and performing detailed modeling of failure consequence.

REFERENCES

[1] Vanem, Endersend and Skjong, 2007. Cost-effectiveness criteria for marine oil spill preventive measures. Reliability Engineering and System Safety 93 (2008) 1354-1368.

[2] Norse and Amos, 2010 Impacts, Perception, and Policy Implications of the Deepwater Horizon Oil and Gas Disaster. Enviromental Law Institute, Washington, DC. http://www.eli.org.

[3] Shahriar, Sadiq & Tesfamariam, 2011. Risk analysis for oil & gas pipelines: A sustainability assessment approach using fuzzy based bow-tie analysis. Journal of Loss Prevention in the Process Industries 25 (2012) 505-523.

[4] Lutchman R, 2006. Sustainable Asset Management: Linking Assets, People and Processes for Results, Destech Publications.

[5] Stewart, 2009. Risk informed decision support for assessing the costs and benefits of counter-terrorism protective measures for infrastructure. International Journal of critical infrastructure protection 3 (2010) 29-40.

[6] Sii and Wang 2001. Novel risk assessment techniques for maritime safety management. The international Journal of Quality and Reliability Management 18 (2001) 892-999.

[7] Roughton and Buchalter, 1997. OSHA's process safety management standard vs. EPA's. risk management plan: A comparison of requirements. Professional Safety 42 (1997) 36-47.

[8] DeWolf, 2003. Process safety management in the pipeline industry: parallels and differences between the pipeline integrity management (IMP) rule of the Office of Pipeline Safety and the PSM/RMP approach for process facilities. Journal of Hazardous Materials 104 (2003) 169-192.

[9] International Organization for Standardization ISO, Guide 73, 2009. Risk management- Vocabulary.
[10] American Petroleum Institute API, Standard 1160, 2001. Managing System Integrity for Hazardous Liquid Pipelines..
[11] The American Society of Mechanical Engineers ASME, Code B31.8.S, 2002. Managing System Integrity of Gas Pipelines.
[12] Pasman et al, 2009. Is risk analysis a useful tool for improving process safety?. Journal of Loss Prevention in the Process Industries 22 (2009) 769-777.
[13] International Organization for Standardization ISO31000, 2009. Risk management— Principles and guidelines.
[14] Haggag and Barakat, 2013. Application of fuzzy logic for risk assessment using risk matrix. International Journal of Emerging Technology and Advanced Engineering 3 (2013) 49-54.
[15] Boardman, Greenberg, Vining and Weimer, 2006. Cost Benefit Analysis Concepts and practice. Third Edition, Pearson International.[16] Health and Safety Executive of the United Kingdom, 1994. Risk from hazardous pipelines in the United Kingdom. http://workboostwales.net/research/crr_pdf/1994/crr94082.pdf
[17] Markowski & Mannan, 2009. Fuzzy logic for piping risk assessment (pfLOPA). Journal of Loss Prevention in the Process Industries 22 (2009) 921-927.
[18] Laszlo Pokoradi, 2002. Fuzzy logic-based risk assessment. Journal of Academic and Applied Research in Military Science, 1 (2002) 63-73.
[19] Jamshidi, Abdolreza, Siamak, Sohrab ,2012. Developing a new fuzzy inference system for pipeline risk assessment, Journal of loss prevention in the process industries, 26 (2013) 197-208.
[20] Standard Practice for System Safety,Department of Defense of The United States of America, 10 Febraury of 2000, Code: MIL-STD-882D.