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Article

A decision support system for assessing cross country pipeline systems: An approach based on Evidential Reasoning (ER) and Cost-Benefit-Analysis (CBA)

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Abstract
This paper outlines a decision support model based on Evidential Reasoning (ER) and Cost-Benefit-Analysis (CBA) to support the assessment of risk control measures for pipeline loss of containment following third party damage. The model identifies the main Risk Control Options (RCOs) as basic attributes, which are grouped into three categories: technical or technological, governmental and managerial solutions. The CBA examines the costs associated with the loss of containment in regard to human safety, the economic and environmental aspects that are required to reduce or eliminate the threat of using RCOs. ER is chosen because of its capability in dealing with Multiple Criteria Decision Making (MCDM) problems with uncertainties, aggregation of conflicting information and the hybrid nature of the information. This corresponds with the challenges of analysing different and often conflicting information identified in this study. The results show the attributes of each decision, their effectiveness in reducing the failure likelihood and the estimated cost of each attribute. The study reduces the complexity of the decision-making into a simple hierarchical output and provide guidance to the infrastructure operator. This makes it possible for the operator to select one or more risk reduction attributes and immediately see a potential reduction in the failure likelihood. Furthermore, the study provides knowledge to the operator on budgetary expenditure required to implement the RCO.

Keywords: Cross Country Oil Pipeline, Risk Based Decision Making, Evidential Reasoning, Cost Benefit Analysis

1. Background

1.1 Introduction

Even though pipelines are the safest and most cost-effective mode of transporting oil and gas for long distances (Furchtgoth-Roth, 2013), when a failure occurs, the resulting consequence in terms of safety, economic loss and environmental pollution could be devastating. Available data from literature (Onuoha, 2009; Rowland, 2010; Ekwo, 2011; Fadeyibi *et al.*, 2011; Omodanisi *et al.*, 2014) indicates that since the late 1980s thousands of fatalities, economic losses and environmental damage have occurred, linked to pipeline incidents in Nigeria. Incidents like Jesse in 1998, with more than 1,000 fatalities and Abule Egba in 2006, with circa 500 fatalities are among the worst globally. The direct product loss for the cross-country pipeline system in the country run into hundreds of million dollars per annum. One pipeline system alone – system 2B - is estimated to be losing about fifty million dollars per annum due to direct product loss (Ekwo, 2011). When costs due to compensation, fines, and environmental clean-up are included, the annual monetary losses are significantly higher.

The failure of oil and gas pipelines in developed economies have been extensively studied and addressed. The data required for analysing and assessing the risks is available and reliable; see for example EGIG (2018) and Concawe (2019) for Europe. This data-driven assessment results in a consistent downward trend in terms of pipeline failure since the 1970s in Europe (EGIG, 2015; Haswell & McConnell, 2015; Cech *et al.*, 2018) and a flat-lining of the number of failures in the US in the 20 years up to 2016 (PHMSA, 2017). In Nigeria and other developing countries, the absence of reliable failure data and effective maintenance and management procedures, amongst other factors, make it difficult to conduct an effective assessment of pipeline risks. Such absence also makes it difficult to put in place measures to control the risks. This lack of data makes the application of appropriate risk assessment tools ineffective and results in increased pipeline loss incidents which might have devastating consequences.

This work aims to provide a risk-based decision-making framework that helps reduce the pipeline's exposure to the identified hazards and provide a cost-benefit model for optimum decision-making.

1.2 Risk Based Decision Support

Decisions in risk management and engineering involve the selection of different risk control measures or alternatives, with each alternative having both qualitative and quantitative attributes. Generally, the qualitative attributes are assessed using human judgement, which has the weakness of being subjective and often associated with uncertainties as a result of ignorance, incomplete information and fuzziness. Therefore, decisions may not be properly made without fully considering all the related attributes whilst quantifying their uncertainties (Mokhtari, 2011; Grenyer *et al.*, 2021; Simohammed & Smail, 2021).

An example of a decision-making model is provided by de Almeida *et al*. (2015). The model is a quantitative one that incorporates the decision maker's preferences and behaviour with respect to risk. This enables alternatives to be prioritised by using a hierarchical ranking of the risks and allows for a multidimensional risk approach to be taken with respect to different consequences.

Different decision-making approaches that aim to capture and treat uncertainties have been proposed; these include probabilistic and subjective approaches. Within the subjective methods, Multiple Criteria Decision Methods (MCDM) have been widely used to solve practical challenges in engineering and particularly in the areas of risk, reliability and maintenance.

Several studies present MCDM models to aid decision-making for pipeline systems (Loganathan *et al.*, 2021; Hasan, 2016; El-Abbasy *et al.*, 2015; Dawotola *et al.*, 2012; Mosleh *et al.*, 2016) with others for safety synthesis and evaluation (Grenyer *et al.*, 2021; Simohammed & Smail, 2021; Wang *et al.*, 1996; Boral *et al.*, 2021; Hu *et al.*, 2020; Zarei *et al.*, 2021).

Loganathan *et al*. (2021) used Analytical Hierarchy Process (AHP) to support inspection and monitoring decisions for large diameter pipes. They developed a Condition Assessment Index (CAI) by describing various inspection techniques, analysed their various failure modes and causes and then used the AHP methodology to develop a model to select the optimum inspection technique based on the influencing failure factors.

El-Abbasy *et al*. (2015) developed a model that assesses the condition of oil and gas pipelines based on several factors, including corrosion, using both Analytic Network Process (ANP) and Monte Carlo simulation. The study identified the pipeline conditions and conducted a questionnaire-based survey, which gave input into the ANP model. The proposed ANP process consisted of a number of steps, from employing pairwise comparison to calculation of the final global matrix. Monte Carlo simulation was, subsequently, used to determine the attribute's effect value and its probability distribution.

Mosleh *et al.* (2016) utilised a combination of ANP, Fuzzy Set Theory (FST) and hierarchical Evidential Reasoning (ER) to develop a condition assessment model for offshore gas pipelines by using the inspection report from the pipeline operator as an input variable. First, the assessment used the ANP module to determine the factors' mean final global weights. Then, the FST module was used to assign the fuzzy thresholds and membership functions for the main model's inputs and outputs. Finally, the ER module was used to determine the degrees of belief for the main model's outputs, which were then defuzzified using the FST module.

Most MCDM methods handle problems quite well. However, when there is information uncertainty for a particular problem, it is often difficult for most MCDMs to incorporate it as they will only provide a single number output, which will not adequately capture the uncertainty. Different solutions have been proposed to address these concerns including using Probability Theory (PT), Dempster-Shafer Theory (DST) and Fuzzy Set Theory (FST). However, all these solutions have limitations and weaknesses. For instance, PT is incapable of adequately capturing ignorance, and has the constraint that the sum probability of all possible states should be equal to one (Shan, 2015). This has been shown to be not necessarily the case in real life problems though (Zadeh, 1965). The DST's limitation is that when it is applied to problems requiring aggregating conflicting evidence, the ensuing results may be irrational. The assessment for certain problems can also result in an exponential increase in computational complexity (Buchanan & Shortliffe, 1984).

While FST works well when applied to MCDM problems, however, when applied to measurement-oriented problems, it is difficult to arrive at any accurate prescription (Kangari & Riggs, 1989).

As a result of the above-mentioned weaknesses of the existing MCDM approaches, the use of ER is proposed, which is a modification of the DST. ER is considered a good alternative that addresses the weaknesses of both Probability Theory and Dempster-Shafer Theory. It aims at providing a rigorous reasoning process for aggregating conflicting information. This is achieved by using an extended decision matrix in which each attribute of an alternative is described by a distributed assessment using a belief structure (Xu & Yang, 2001; Shan, 2015). For example, a distributed assessment for a quality of intervention measures to prevent 'pipeline loss of containment' could be {(Excellent, 25%), (Good, 30%), (Average, 35%), (Poor, 10%), (Worst, 0%)}, which means that the intervention is assumed as 'Excellent' with a 25% belief degree, 'Good' with a 30% belief degree, 'Average' with a 35% belief degree, 'Poor' with a 10% belief degree and 'Worst' with a 0% belief degree. Using a belief structure approach, ER can deal with MCDM problems under uncertainties and the hybrid nature of information. The uncertainties are related to the absence of data, incomplete description of an attribute, and their random nature (Xu & Yang, 2001). The hybrid nature of the information concerns the mixture of data from incommensurable criteria, the mixture of data from qualitative and quantitative criteria, and the mixture of data from deterministic and probabilistic criteria.

The ER method has been widely adopted, since its development, in MCDM problems such as engineering safety analysis (Zhang *et al.*, 2021; Loughney *et al.*, 2021), pipeline leak detection (Xu *et al.*, 2007; Mosleh *et al.*, 2016) and maritime safety and security (Yang *et al.*, 2019; Yu *et al.*, 2021) amongst others.

2. Evidential Reasoning Application/Methodology

This section describes the methodology for the development of the proposed ER model that is applied to the risk of 'loss of containment due to third-party intervention' in a pipeline. The methodology takes into account and builds upon the previous work of the authors (Hassan, 2018; Hassan *et al.*, 2019; Hassan *et al.*, 2022b; Hassan *et al.*, 2022a). Figure 1 provides the methodology schematic for the proposed model.

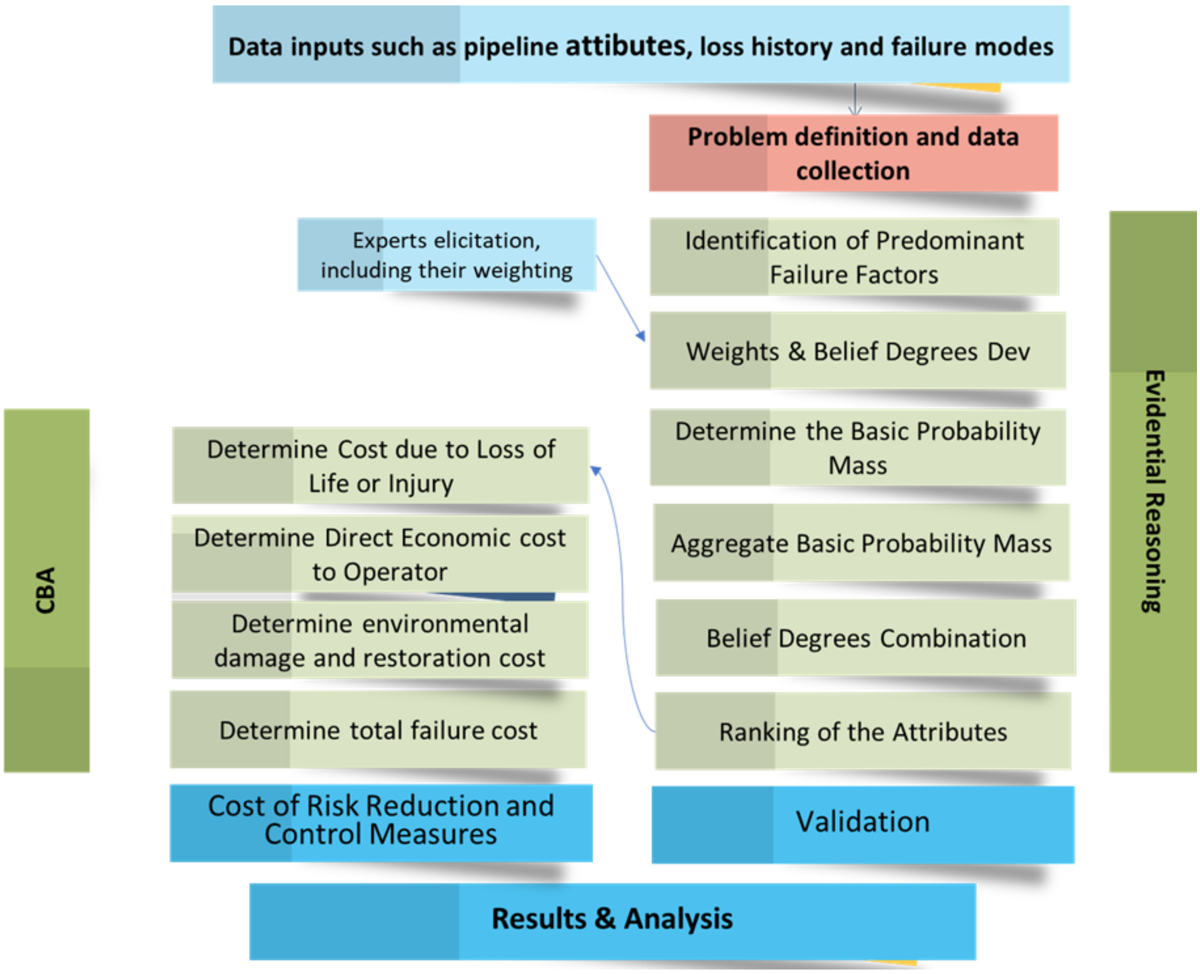

Figure 1: Proposed Methodology

2.1

2.2 Identification of Predominant Failure Factors

This is the first step in the modelling process. In this step, the predominant failure factors are identified. These are the factors that rely on the ER algorithm for insight. Generally, the failure factors should be identified from a separate study, which forms the foundations of the analysis.

The identification of the major failure factors and their potential consequences are based on Hassan *et al* (2022a; 2022b). The assessment also identified the failure factor with the highest probability of occurrence as being the 'third-party related pipeline failure'.

2.3 Developing the Evaluation Matrix

The second step in the analysis is the identification and development of the evaluation matrix. The matrix that will be used depends on the problem at hand but will include general attributes, basic attributes, alternatives and their interconnectivity. In identifying and developing these attributes, reference will be made to the literature including industrial and international standards and other guidance documents, which identify the risk control measures necessary for reducing the threat of third-party related pipeline damage.

2.4 Weights and Belief Degrees Development Using Experts' Elicitation

The third step in the process is the calculation of the weight of each of the identified general and basic attributes. The belief degrees of the attributes must also be determined. Such information informs the evaluation grades and ensures that attributes and alternatives have a relationship in terms of their effectiveness with respect to the overall analysis.

AHP and the pairwise comparison method were used to determine both the weight and belief degrees by utilising experts opinion through questionnaires. A questionnaire is developed to address the subjective questions which form part of the input of the ER part. The questionnaire has two parts: one assesses the weighting of the basic attributes for each of the main attributes, and the other assesses the belief degrees associated with each attribute.

A minimum of five experts were invited to give their professional opinion based on their expertise and experience. All experts have experience in the pipeline industry supply chain – varying from operators to consultants and academics. Their input forms the foundation of the assessment and ensures that a wide view is taken on board for the assessment. It should be noted here that future research could investigate the impact of a higher number of experts on the results. It is expected, mainly for practical reasons e.g., limited availability, the busy schedule of relevant experts and the complexity of the process, that pipeline operators would use a small group of researchers. The accuracy and reliability of the results depend on the quality and the reliability of the experts input and the weighting mechanism. The expertise and the competenc of the experts used in this work ensure that the results are reliable and consistent."

2.5 Determine the Basic Probability Mass

The ER approach utilises a belief structure to represent an assessment as a distribution. Assuming there is a threat of a loss of containment in a pipeline and intervention measures are to be evaluated and assuming the problem has D alternatives $O_j\,(j=1,....,D)$, an upper-level criterion called 'general attribute' and lower-level criteria $C_i(i=1,.....L)$ called 'basic attributes'. The ER decision matrix is developed by:

i. Assigning weightings $W=\{w_i,\ i=1,.....L\}$ to the basic attributes, which show their relative importance. The weights of the basic attributes need to be normalised, such that $\sum_{i=1}^{L} w_i = 1 \text{ and } 0 \le w_i \le 1$. L is the number of basic attributes sharing the same general attribute.
ii. Defining a set of evaluation grades (H) to enable alternatives of the basic attributes to be assessed and is represented as $H=\{H_n,\ n=1,.....N\}$ where H_n is the evaluation grade *n*.

Using the evaluation grades, the assessment S of an attribute C_i on an alternative O_j, denoted by $S(C_i(O_j))$, can be represented as:

$$S(C_i(O_j)) = \{(\beta_{n,i}(O_j), H_n), \quad n = 1, \ldots. N, \quad i = 1, \ldots.. L; \quad j = 1, \ldots.. D\} \tag{1}$$

where $1 \geq B_{n,i} \geq 0$ represents the degrees of belief that an attribute C_i is assessed to an evaluation grade H_n to a degree of $B_{n,i}$ (x100%) for an alternative O_j. The degrees of beliefs distributed assessment must be $\sum_{n=1}^{N} \beta_{n,i} \leq 1$. If $\sum_{n=1}^{N} \beta_{n,i} = 1$ then $S(C_i(O_j))$ can be considered a complete assessment and if $\sum_{n=1}^{N} \beta_{n,i} < 1$ it is considered to be an incomplete assessment.

To aggregate the two assessments, the ER approach employs a different algorithm from the traditional MCDM approaches because it aggregates average scores only. Five evaluation grades are used to assess the effectiveness of an intervention, such that:

$H = \{H_1, H_2, H_3, H_4, H_5\}$

= $\{Very\ Low,\ Low,\ Medium,\ High,\ Very\ High\}$

Furthermore, suppose two assessments are represented by Eqs. 2 and 3:

$$S\big(C_1(O_1)\big) = \{(H_1, \beta_{1,1}), (H_2, \beta_{2,1}), (H_3, \beta_{3,1}), (H_4, \beta_{4,1}), (H_5, \beta_{5,1})\} \tag{2}$$

$$S\big(C_2(O_1)\big) = \{(H_1, \beta_{1,2}), (H_2, \beta_{2,2}), (H_3, \beta_{3,2}), (H_4, \beta_{4,2}), (H_5, \beta_{5,2})\} \tag{3}$$

The steps below are followed to determine the basic probability mass as part of the aggregation of the two assessments.

Combining the evidence requires the belief degrees to be transformed into a basic probability mass. Supposing both assessments are complete and able to generate a combined assessment of the two $S\big(C_1(O_1)\big) \oplus S\big(C_2(O_1)\big)$. Let:

$$m_{n,j} = w_i \beta_{n,i} \quad (n = 1, \ldots., N; \quad i = 1, \ldots. L; \quad j = 1,2) \tag{4}$$

$$m_{H,j} = 1 - w_i \sum_{n=1}^{N} \beta_{n,i} \quad (n = 1, \ldots., N; \quad i = 1, \ldots. L; \quad j = 1,2) \tag{5}$$

$m_{n,j}$ is the basic probability mass and $m_{H,j}$ is the remaining belief for attribute j, unassigned to any of the evaluation grades $H_n (n = 1, \ldots.. N)$. w_i is the weighting of the *i*th attribute, $\beta_{n,i}$ represents the degrees of belief.

Applying Eqs. 4 and 5, the basic probability mass for $S\big(C_1(O_1)\big) \oplus S\big(C_2(O_1)\big)$ aggregation will be:

$m_{n,1} = w_1 \beta_{n,1}$ and $m_{H,1} = 1 - w_1 \sum_{n=1}^{N} \beta_{n,1}$

$m_{n,2} = w_2 \beta_{n,2}$ and $m_{H,2} = 1 - w_2 \sum_{n=1}^{N} \beta_{n,2}$

2.6 Aggregate Basic Probability Mass for Combined Probability Mass

The ER algorithm requires the aggregation of the basic probability masses to generate combined probability masses, represented as $m_{n,I(j+1)}$ $(n = 1, \ldots N)$ and $m_{H,I(j+1)}$ using the following equations:

$$m_{n,I(j+1)} = k_{I(j+1)}(m_{n,j} m_{n,j+1} + m_{n,j+1} m_{H,j} + m_{n,j} m_{H,j+1}), \ n = 1, .. N; \ j = 1, .. L - 1 \tag{6}$$

$m_{H,I(j+1)} = k_{I(j+1)}(m_{H,j}\ m_{H,j+1})$ (7)

where

$$k_{I(j+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{n=1 \\ n \neq t}}^{N} m_{t,j}\ m_{n,j+1}\right]^{-1} \quad (8)$$

Applying the above equations to $S(C_1(O_1))\ \oplus\ S(C_2(O_1))$, the aggregation will give:

$m_{n,I(2)} = k_{I(2)}(m_{n,1}m_{1,2} + m_{n,2}m_{H,1} + m_{n,1}m_{H,2});$

$m_{H,I(2)} = k_{I(2)}(m_{H,1}m_{H,2})$

$$k_{I(2)} = \left[1 - \sum_{t=1}^{5} \sum_{\substack{n=1 \\ n \neq t}}^{5} m_{t,1}m_{1,2}\right]^{-1}$$

$k_{I(2)}$ is the normalising factor so that for example $\sum_{n=1}^{5} m_{n,I(2)} + m_{H,I(2)} = 1$.

2.7 Belief Degrees Combination

The next step is the combination of the belief degrees β_n as part of the decision-making process. It is calculated using Eq. 9:

$$\beta_n = \frac{m_{n,I(j+1)}}{1 - m_{H,I(j+1)}}, \quad n = 1, \ldots. N \quad (9)$$

$$\beta_H = 1 - \sum_{n=1}^{N} \beta_n$$

Applying it to this example, β_n will thus be:

$$\beta_n = \frac{m_{1,I(2)}}{1 - m_{H,I(2)}}$$

β_H is the belief degree that is unassigned to any individual evaluation grade after all the basic attributes have been properly assessed. It indicates assessment incompleteness (Liu *et al.*, 2005).

Thus, the combined assessment for the alternative O_1 can be represented as:
$S(O_1) = \{(H_1, \beta_1), (H_2, \beta_2), (H_3, \beta_3), (H_4, \beta_4), (H_5, \beta_5)\}$

2.8 Ranking of the Attributes

The final stage is the ranking of the attributes based on their aggregated belief degrees as obtained using the ER approach. This uses a utility assessment method. If an evaluation grade, H_n, is denoted by $u(H_n)$, the utility of the evaluation grade must be predetermined. If there are five evaluation grades, $u(H_1)$ will be taken as zero whilst $u(H_5)$ is taken as one. In the absence of a specific utility function a linear approach can be used, *i.e.*, the values of $u(H_n)$ can be taken to be equally distributed as shown below:

$$u(H_n)\ =\ \{\ u(H_1) = 0, u(H_2) = 0.25, u(H_3) = 0.5, u(H4) = 0.75, u(H5) = 1\} \quad (10)$$

and the utility for the attributes, denoted as *(Oj)*, for the given sets of evaluation grades is given as:

$$u(O_j) = \sum_{n=1}^{N} u(H_n)\beta_n \quad (11)$$

where $u(H_n)$ is the utility of the *n*-th evaluation grade of H_n as established in Eq. 10 for an assumption that is equidistantly distributed. β_n is as defined in Eq. 9.

3. Case Study: Application to Pipeline Third-Party Damage

The proposed ER decision model is applied to assess risk control measures related to theft/intentional third-party pipeline damage. This is based on a case study of a cross-country pipeline segment in Nigeria, specifically pipeline Section 2B, as described below. The pipeline runs between Lagos and Ilorin in south-western Nigeria; see Hassan *et al.* (2022a) for a description of the pipeline system, which includes the transmission pipelines, pumps, the compressors and other facilities that form the transmission system. Pipeline 2B is representative of the country's pipeline system with respect to failure frequency, as it is in the middle of the overall in the failure records across the country. Note that in this case study, the entire pipeline system is assessed and the analysis is based on the hazards identified in Hassan et al. (2022a). The decision-maker might also be willing to assess parts of the system and also more specific hazards; this is a straightforward application of our framework.

In previous studies (Hassan *et al.*, 2022a), theft/intentional third-party damage has been identified as the major cause of pipeline failures in Nigeria. Therefore, measures must be put in place to ensure the threat is reduced or eliminated. The ER approach is a suitable tool for this assessment as it allows for the aggregation of multiple attributes and sub-attributes within the control measures, and therefore being able to provide a rank of the alternatives.

Based on literature review (*e.g.*, Muhlbauer (2004)) and expert opinion (obtained through interviews) several risk control measures have been identified. The most significant ones, and those that are practical for a geographical area like Nigeria, have been broadly grouped into four general categories: (a) Detection measures, (b) Prevention measures, (c) Mitigation measures and (e) Other measures. Each of these general attributes has basic attributes that outline the intervention that is being assessed for their effectiveness and ranking of alternatives.

The ER algorithm requires a structure that maps the variables and their attributes against the risk control measures to be developed. The attributes that have been developed are tailored for a cross-country pipeline and the identified threat which is particular to geographical areas similar to that of Nigeria. To that extent, the model and proposed solutions could be applied to other similar geographical areas.

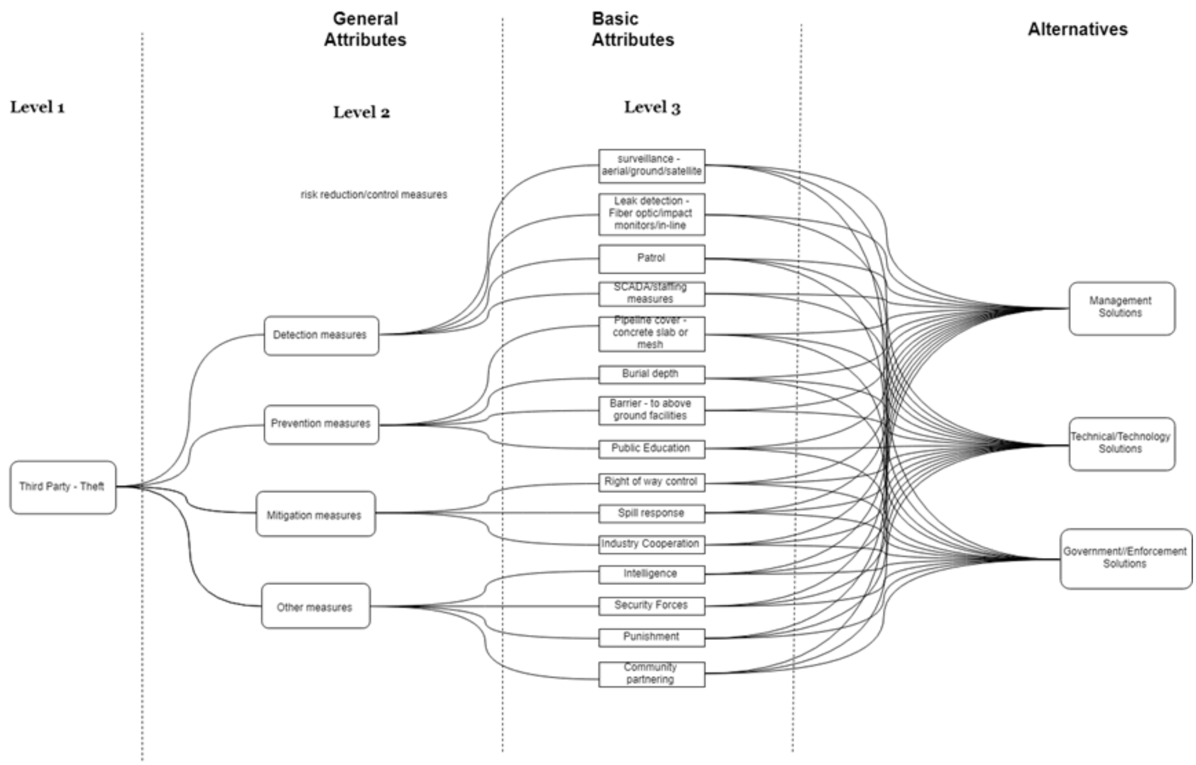

Figure 2: Attributes Matrix for the Control Measures

Figure 2 shows the graphical relationships between the main attributes, the basic attributes and the alternatives used in the analysis. All attributes contribute towards the control measures (alternatives), which are grouped into management solutions, technical (or technological) solutions and government (or enforcement) solutions.

3.1 ER Assessment

The weight of each of the identified general and basic attributes, is first assessed to determine belief degrees of the attributes to inform the evaluation grades.

Analytic Hierarchy Process (AHP) and the pairwise comparison method are used to determine both the weight and belief degrees by utilising expert elicitation through questionnaires. Five experts have been asked to rank each attribute in relation to the others.

The input provided by the experts allows for the completion of the belief degrees for the basic attributes. The belief degrees are arrived at by averaging the responses provided by all the experts for each of the attributes. The matrix and (normalised) weights of all attributes as well as the assessed belief degrees for each of the basic attributes are presented in **Error! Reference source not found.**.

The number of experts that have been chosen ensures a balance and a diversity of opinions, thus balanced belief degree inputs for the basic attributes. Other publications (Animah & Shafiee, 2019; Asuquo et al., 2019) have adopted similar approach. If more experts were to be involved, that could help refine and narrow the standard deviation of the results. Therefore, it is deemed unlikely that it would affect the overall assessment outcome.

The weights and belief degrees of all the attributes as obtained by the experts are shown in Table 1. The next step is to extract the weights and belief degree values for input into the ER model and follow the steps outlined in the Methodology Section and carry out the assessment.

An example assessment following the methodology for the mitigation general attribute under the governmental solution alternatives. The effectiveness of the mitigation approach as part of the risk control measures, using the attributes right of way control (***C****1*), spill response (***C****2*) and industry cooperation (***C****3*) is thus:

$$S(mitigation\ (gov't\ solutions)) = S(c_1 \oplus c_2 \oplus c_3)$$
= {(very low, 0), (low, 0.071), (medium, 0.347), (high, 0.402), (very high, 0.155)}

4. ER Results and Analysis

The assessment carried out in Section 3.1 through to Section 3.3 examines the general attributes of mitigation and their basic attributes under the broader set of risk reduction measures entitled 'government solutions'. This assessment has been repeated for other RCOs and under all the proposed solution groupings. **Error! Reference source not found.** shows the number of the general attributes, their corresponding basic attributes and the proposed solution grouping that each basic attribute belongs to. The calculations have been carried out following the Yang and Xu (2005) approach. The results for the aggregation are shown in Figures 3-6. *H1* occurs when an approach has a *very low likelihood* of being effective, *H2* is when an approach has a *low likelihood* of being effective, *H3* is when it is *medium*, *H4* is when it is *high* and *H5* is when it has a *very high* likelihood of being effective.

Figure 3 shows the detection attributes aggregation for management, government and technical solutions. The results show that technical solutions have a higher very high (*H5*) belief degree, meaning that it is more effective than other proposed solutions. The government solutions have the *highest H1 and virtually no H5* rating. This is consistent with the types of basic attributes under the detection main attribute, which are mostly technical.

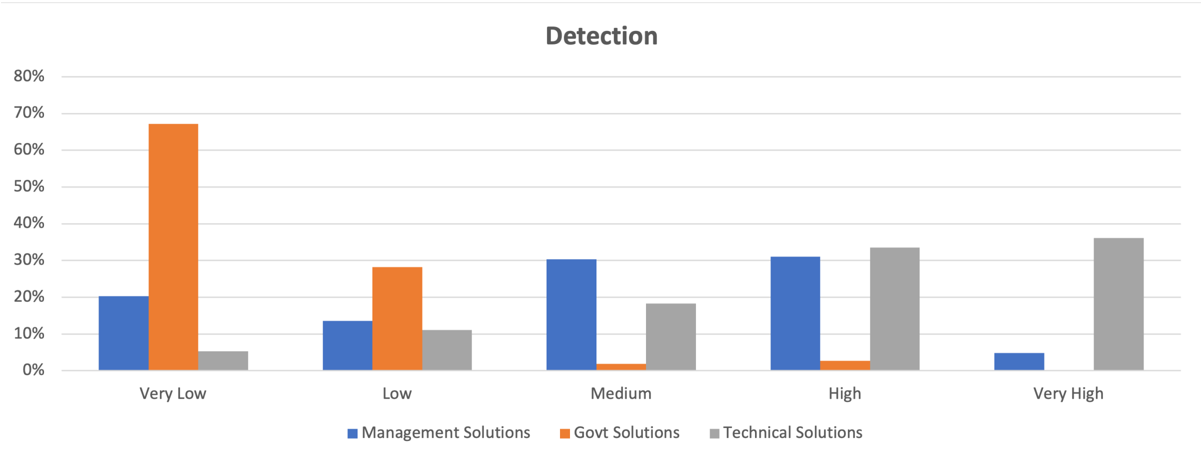

Figure 3: Detection Attributes Aggregation for the Solution Groupings

Table 1: Attribute Weightings and Belief Degrees

General Attributes	ω	Basic Attributes	Ω	Management Solutions H1	H2	H3	H4	H5	Govt Solutions H1	H2	H3	H4	H5	Technical Solutions H1	H2	H3	H4	H5
Detection (*a*)	ω_1= 0.29	Surveillance *(a1)*	ω_{11}= 0.298	0.30	0.30	0.40	0.00	0.00	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.14	0.38	0.48
		Leak Detection (a2)	ω_{12}= 0.355	0.30	0.00	0.30	0.40	0.00	0.80	0.20	0.00	0.00	0.00	0.00	0.10	0.00	0.40	0.50
		SCADA/Staffing (a3)	ω_{13}= 0.211	0.00	0.11	0.17	0.44	0.28	0.90	0.10	0.00	0.00	0.00	0.00	0.20	0.60	0.20	0.00
		Patrol (a4)	ω_{14}= 0.136	0.00	0.27	0.20	0.53	0.00	0.00	0.50	0.20	0.30	0.00	0.50	0.30	0.20	0.00	0.00
Prevention (*b*)	ω_2= 0.45	Pipeline Cover (b1)	ω_{21}= 0.161	0.90	0.10	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.13	0.60	0.27	0.00
		Burial Depth (b2)	ω_{22}= 0.214	0.00	0.90	0.10	0.00	0.00	0.50	0.30	0.20	0.00	0.00	0.00	0.00	0.14	0.38	0.48
		Public Education (b3)	ω_{23}= 0.174	0.00	0.00	0.50	0.30	0.20	0.00	0.00	0.00	0.17	0.83	0.90	0.10	0.00	0.00	0.00
		Barrier (b4)	ω_{24}= 0.452	0.10	0.90	0.00	0.00	0.00	0.90	0.10	0.00	0.00	0.00	0.00	0.13	0.38	0.50	0.00
Mitigation (*c*)	ω_3= 0.17	Right of Way Control (c1)	ω_{31}= 0.553	0.00	0.50	0.50	0.00	0.00	0.00	0.00	0.32	0.42	0.26	0.50	0.50	0.00	0.00	0.00
		Spill Response (c2)	ω_{32}= 0.225	0.00	0.11	0.15	0.21	0.53	0.00	0.30	0.30	0.40	0.00	0.90	0.10	0.00	0.00	0.00
		Industry Cooperation (c3)	ω_{33}= 0.222	0.00	0.00	0.00	0.35	0.65	0.00	0.20	0.50	0.30	0.00	0.80	0.20	0.00	0.00	0.00
Other Measures (*d*)	ω_4= 0.09	Intelligence (d1)	ω_{41}= 0.439	0.00	0.00	0.13	0.00	0.87	0.00	0.50	0.30	0.20	0.00	0.50	0.50	0.00	0.00	0.00
		Security Forces (d2)	ω_{42}= 0.138	0.00	0.00	0.00	0.25	0.75	0.07	0.14	0.43	0.00	0.36	0.60	0.40	0.00	0.00	0.00
		Punishment (d3)	ω_{43}= 0.156	0.00	0.50	0.50	0.00	0.00	0.00	0.00	0.50	0.22	0.28	0.40	0.40	0.20	0.00	0.00
		Community Partnering (d4)	ω_{44}= 0.266	0.00	0.00	0.00	0.55	0.45	0.00	0.00	0.00	0.20	0.80	0.40	0.40	0.20	0.00	0.00
				H_1 =	**Very Low**		**H_2 =**	**Low**		**H_3 =**	**Medium**		**H_4 =**	**High**		**H_5 =**	**Very High**	

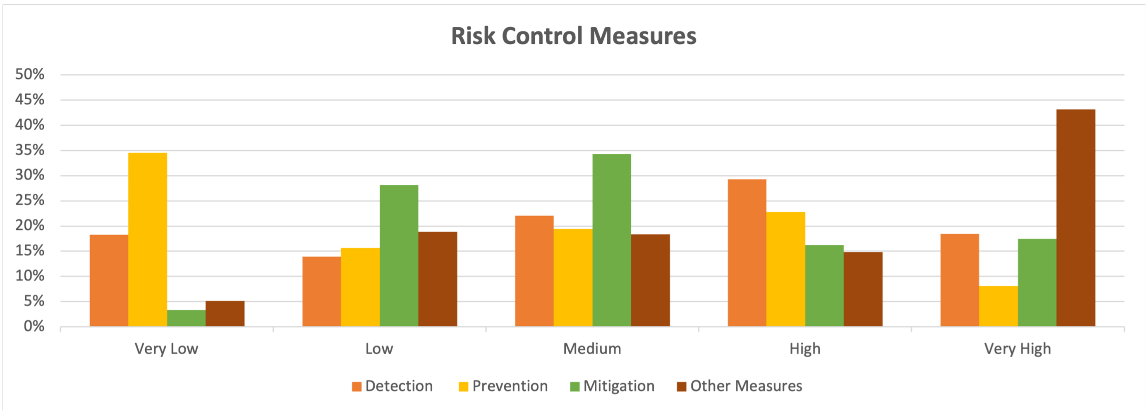

Figure 4: General Attributes Aggregation

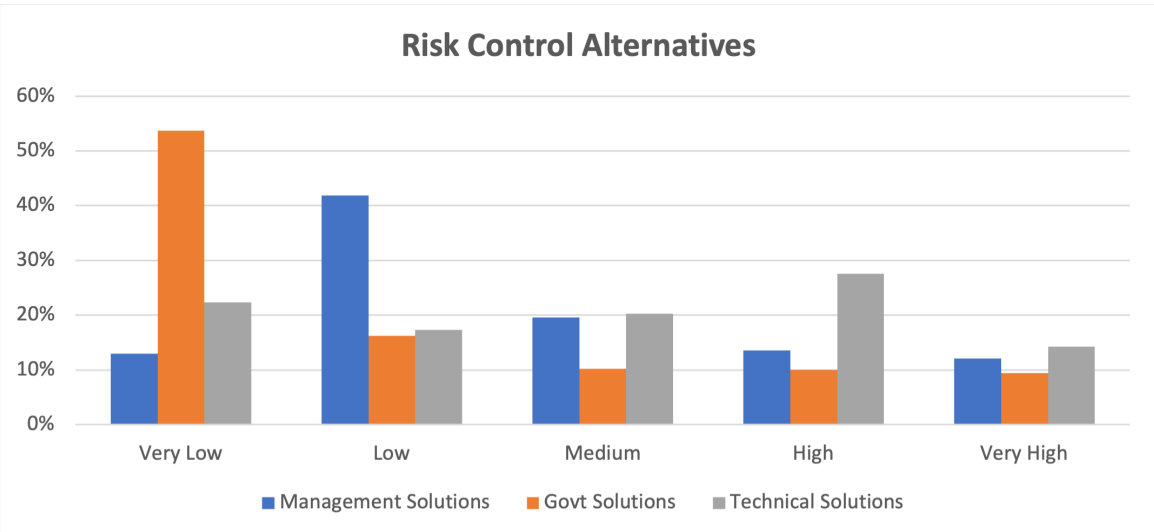

Figure 5: Aggregation of Alternatives for their Effectiveness

Figures 4 and 5 show the overall aggregation results based on the assessed risk control options and intervention solutions, respectively. The results show a clustering of attributes, making it difficult to identify which of the attributes have the most effective likelihood of success across all the main RCO groupings. To address this and calculate the ranking in a numerical format, Eqs. 10 and 11 are utilised to calculate their utility values.

In this work, a linear utility function (see Eq. 10) is used with values as follows:

$$u(H_n) = \{u(H_1) = 0, u(H_2) = 0.25, u(H_3) = 0.5, u(H4) = 0.75, u(H5) = 1\} \quad (12)$$

The utility for the attributes, denoted as O_J, for the given sets of evaluation grades as given in Eq. 11. Assuming the least effective intervention is H_1 and the most effective is H_N, then the maximum, minimum and average utilities of *Oj* are given by:

$$u_{max}(O_j) = \sum_{n-1}^{N-1} \beta_n(O_j)u(H_n) + \left(\beta_N(O_j) + \beta_H(O_j)\right) u\ (H_N)$$

$$u_{min}(O_j) = \left(\beta_1(O_j) + \beta_H(O_j)\right) u\ (H_1) + \sum_{n-2}^{N} \beta_n(O_j)u(H_n)$$

$$u_{aver}(O_j) = \frac{u_{max}(O_j) + u_{min}(O_j)}{2}$$

With the above equation, a single utility value can be calculated for each main attribute and the overall effectiveness of the intervention options to allow ranking. For example, for the mitigation general attribute (for government solutions) that was calculated in Section 3 above, the utility value (complete belief) can be calculated as:

$U\big(S(mitigation(gov't\ solutions\ )\big)$

= $u(H_1)\beta_1$ + $u(H_2)\beta_2$ + $u(H_3)\beta_3$ + $u(H_4)\beta_4$ + $u(H_5)\beta_5$

= (0 x 0) + (0.25 x 0.071) + (0.5 x 0.347) + (0.75 x 0.402) + (1 x 0.155)} = 0.65

This utility calculation has been carried out for all main attributes and the risk control solutions. The assessment also combines the overall effectiveness of all attributes and risk control solutions to enable ranking them, which could be used by the decision-maker.

Table 1: Utility Values and Ranking for the Detection Main Attribute

			Detection				
Grades	H1 (Very low)	H2 (Low)	H3 (Medium)	H4 (High)	H5 (Very high)	U (Total)	Ranking
u (Grades)	0	0.25	0.5	0.75	1		
Management Solutions	0.203	0.136	0.303	0.311	0.048	0.47	2
Gov't Solutions	0.672	0.283	0.018	0.027	0.000	0.10	3
Technical Solutions	0.053	0.111	0.183	0.335	0.362	0.73	1

Table 2 shows the utility value and ranking for the detection attribute. It can be deduced that, for detection measures – which have basic attributes that include surveillance, leak detection, SCADA/staffing measures and patrols – technical solutions have a higher belief degree of being the most effective. The assessment shows that they are the most effective measures in reducing the risk of pipeline failure due to third-party activities.

Table 2: Utility Values and Rankings for Overall Effectiveness of Different Interventions

			Overall				
Grades	H1 (Very low)	H2 (Low)	H3 (Medium)	H4 (High)	H5 (Very high)	u (Total)	*Ranking*
u(Grades)	0	0.25	0.5	0.75	1		
Management Solutions	0.130	0.419	0.194	0.136	0.121	0.42	2
Gov't Solutions	0.537	0.162	0.103	0.101	0.095	0.26	3
Technical Solutions	0.223	0.173	0.203	0.276	0.142	0.49	1

Table 3 shows the total ranking considering all the main and basic attributes. The technical solutions emerge as the set of intervention options that will provide the most effective tool to reduce the threat of third-party activities on the pipeline. The next most effective set of options is management solutions, followed by government intervention. The results are deemed consistent in that technical solutions are mostly aimed at preventing the third-party incident in the first instance. The technical solutions make any attempt to get to the pipeline difficult. If technical solutions are effective, then only a minimal amount of sabotage attempts will be successful.

Assessment has been carried out also using Non-linear utility grade $u(H_n)$ assuming a risk seeking approach such that

$$u(H_n) = \{u(H_1) = 0, u(H_2) = 0.8, u(H_3) = 0.9, u(H4) = 0.95, u(H5) = 1\}$$

The results of the rankings for all the attributes and the interventions remain unchanged even with the different utility grades. This further indicates the stability of the results.

Table 4 shows the comparison and the ranking for the two utility grades.

Table 3: Utility Values and Rankings Comparison for Linear and Non-linear Utility Grades

Grades		Linear Utility		Non-linear Utility	
u(Grades)		u (Total)	Ranking	u (Total)	Ranking
Detection	Management Solutions	0.47	2	0.72	2
	Govt Solutions	0.10	3	0.27	3
	Technical Solutions	0.73	1	0.93	1
Prevention	Management Solutions	0.27	2	0.69	2
	Govt Solutions	0.15	3	0.22	3
	Technical Solutions	0.56	1	0.82	1
Mitigation	Management Solutions	0.53	2	0.89	2
	Govt Solutions	0.65	1	0.906	1
	Technical Solutions	0.08	3	0.27	3
Other Measures	Management Solutions	0.87	1	0.97	1
	Govt Solutions	0.62	2	0.91	2
	Technical Solutions	0.15	3	0.42	3

5. Cost Benefit Analysis of Pipeline Loss of Containment

The loss of containment of a pipeline is associated with financial costs, and so are the risk control measures that would be put in place to minimise or mitigate such losses. The related damages could broadly be categorised into:

1. Cost of compensation for loss of life or injuries sustained (including hospital treatment and other compensation for the injured).
2. Cost of damage to the environment, habitat, population livelihood and physical property.
3. Damages as a result of economic loss, which includes production losses, contract penalties and repair losses.

Valuing the total damages is a difficult task. For example, the Nigerian Employee's Compensation Act (Federal Government of Nigeria, 2010) has created an agency with the responsibility to compensate the families of employees that suffer work-related injuries or fatalities. However, the law does not outline the compensation procedure if the accident affects a third party (that is, members of the public). Evidence from previous incidents shows that the majority of those affected by pipeline accidents are members of the public, not the personnel working for the pipeline operator or the pipeline contractor (Carlson *et al.*, 2015) . The affected third parties often resort to civil law for compensation by the courts in the absence of any relevant law.

The main cost associated with any loss of containment in a pipeline in Nigeria, therefore, includes all three components – cost due to loss of life or injury, direct economic loss cost and the cost of environmental restoration. Sections 5.1, 5.2 and 5.3 below outline how the relevant cost components have been approached. Section 5.4presents the approach to calculating the total cost.

5.1 Loss of Life and Injury-related Costs

In the literature, several approaches based on Cost of Saving Lives (CSX) value, willingness to pay (WTP), human capital, life-quality index (LQI) or value of statistical life (VSL) has been used to incorporate the costs associated with the loss of life or due to injury in risk management (Arends *et al.*, 2005; Sánchez-Silva & Klutke, 2016). The most widely used approaches to quantify the costs related to loss of life, and, thus, the benefit of avoiding a fatality are through the Life Quality Index (LQI) and the Value of a Statistical Life (VSL).

LQI is a compound social indicator of human welfare that considers the expected length of life in good health and enhancement of the quality of life through wealth. The VSL approach, on the other hand, consists of estimating the potential number of casualties and assigning them a value often based on the value of statistical life. VSL is assessed as the value assigned for compensation to the relatives of any individual in case of an accident.

When looking at the risks and trade-offs related to human safety, economists consider VSL. It should be noted that this is not to be considered as the value of an actual life, but the value placed on changes in the likelihood of death. VSL is deemed as the most appropriate way of ascertaining the direct cost for compensation. Without getting into much detail, VSL is more of an estimate of willingness to pay for small reductions in mortality risks and obtaining values directly applicable to the investigated case is a difficult task. A value to be used for Nigeria is obtained based on values obtained for other countries *e.g.*, the United States of America (USA)..

The VSL could be obtained following Robinson, Hammitt and O'Keefe (2019):

$$VSL_t = VSL_b \times (\frac{Y_t}{Y_b})^n \tag{12}$$

where VSL_t is the VSL for the target country, VSL_b is the VSL for the baseline country, Y_t is the target country's income and Y_b is the baseline country's income, both in GNI (Gross National Income) per capita, and n is the elasticity which measures the rate at which VSL changes with income.

The VSL for Nigeria can be then calculated using Eq.12, as below.

$$VSL_{Nig} = VSL_{US} \times (\frac{Y_{Nig}}{Y_{US}})^n$$

where:

VSL_{Nig} is Nigeria's VSL, to be calculated; VSL_{US} is the baseline country VSL, in this case the USA, with a value of \$9.6 million; Y_{Nig} is Nigeria's income in GNI per capita which is \$2,820; Y_{US} is the USA's income in GNI per capita which is \$ 55,980; and *n* is the elasticity, which is taken as 1.

Using a USA VSL figure of $9.6 million and a GNI per capita figure of $ 55,980– both based on 2015 figures (Viscusi & Masterman, 2017)- and a GNI per capita figure of $2,820 for Nigeria we arrive at a VSL value for Nigeria of $485,000. This figure is in line with the average VSL for a lower middle-income economy of $420,000 as calculated in (Viscusi & Masterman, 2017).

The expected risk, outlined in terms of annual fatalities, is estimated below. The calculations arrive at an expected risk of 652 fatalities annually, therefore the expected damage cost related to human loss or injuries and therefore the benefit from averting them is equal to $316.2 million per year (652 expected fatalities annually multiplied by a VSL of $485,000)

Table 4: 10-Year Failure Statistics for Pipeline System 2B (NNPC, 2016)

Year	Number of Pipeline Failures	Product Loss ('000 mt)
2006	486	183
2007	479	142
2008	530	13
2009	609	110
2010	191	145
2011	468	127
2012	481	163
2013	1080	269
2014	1077	333
2015	1114	471
Annual Average	652	196

First, the number of expected pipeline failures per year is estimated. Table 5 shows the annual pipeline failures for a decade up to 2015, which gives an average of 652 failures annually. This figure is higher than the annual average of circa 250 incidents for the previous decade up to 2006 (Okoli & Orinya, 2013). This should not be surprising since the spate of pipeline damage due to third-party events has increased significantly in the decade up to 2015 compared to the previous decade. Most of these failures do not result in any life safety consequence. However, the few that result in fires and explosions often record higher fatality or fatality equivalent numbers. For example, Carlson *et al.* (2015) report several pipeline accidents in Nigeria where more than 100 people were reported dead.

A Failure Mode and Effects Analysis (FMEA) assessment has been carried out using expert elicitation and reported in Hassan *et al* (2022b). The FMEA ranking uses five categories (see **Error! Reference source not found.**); this is based on approaches presented in the International Maritime Organization (IMO) guide (2018) and the Det Norske Veritas (DNV) recommended practice (2010).

Table 5: Modified Safety Consequence Qualitative Ranking

Category	Description	Equivalent Fatalities
1 (negligible)	No person(s) are injured	0.001
2 (marginal)	Single or minor injury	0.01
3 (moderate)	Multiple or severe injuries	0.1
4 (critical)	Single fatality or multiple severe injuries	1
5 (catastrophic)	Multiple fatalities	10

The FMEA results for third-party damage show that the three experts have assigned consequence severity rankings of 5, 4 and 4, respectively. This would put the consequence severity of pipeline accidents in Nigeria's System 2B to be between critical and catastrophic. However, not all third-party pipeline damage results in a fire, explosion or any safety consequences. Nevertheless, the few pipeline accidents that result in safety consequences, for example Carlson *et al.* (2015), do have significantly higher fatalities than the 10-fatality value assigned for the catastrophic ranking. It could, therefore, be reasonably argued that using a conservative approach, where it is assumed that each pipeline incident is assigned a ranking of five – catastrophic – is more appropriate. However, this research takes a less conservative approach of assigning a ranking of four – critical – for assessing life safety consequences, with sensitivity assessment carried out in Section 5.5. to assess the changes to the results if different ranking is used.

5.2 Direct Economic Cost to the Operator

This covers the cost of business interruption, including loss of production, contract penalties, the cost of repair or replacement of the affected pipeline section. As the costs increase, the more time it takes to repair the pipeline, which is often assumed to be a linear relationship. Previous research (Ekwo, 2011) has estimated the approximate number of pipeline failures and their total cost due to shut-in and repairs. Table 8 shows the number of System 2B pipeline failures for a decade up to 2015. The average annual cases of pipeline failure, the cost of repair, the product loss and the estimated economic cost are shown in Table 7.

Note that this figure is of a very high level and only includes the actual repair cost and the cost of product loss due to spillage. The figure may not include the cost of lost revenue due to shut-in or third-party liabilities which could be an order of magnitude higher.

Table 6: System 2B Average Annual Damage and Economic Costs (Ekwo, 2011)

System	Number of Pipeline Damage Incidents (per yr)	Product Loss ('000 mt/yr)	Economic Cost (Total/yr)	Cost per Damage (Average)
2B	652	196	$ 51,865,983	$ 79,943

5.3 Environmental Damages (due to oil spills)

The cost associated with oil spills can be divided into three groups: clean-up (removal, research, and other related costs), socioeconomic losses and environmental costs (Kontovas et al, 2010). Various models to estimate oil spill costs have been developed, including work carried out by Etkin (1999; 2000) and Kontovas *et al*., (2010; 2011). Note that these studies derived their data primarily based on spills on water, however the Kontovas *et al*. (2010; 2011) approach has been used in pipeline-related studies, including onshore pipeline spills (Eglington *et al.*, 2012; Gunton & Broadbent, 2015). In this work, the formula proposed by Kontovas et al. (2010) is used; this cost function has been incorporated into the International Maritime Organization's 'Formal Safety Assessment' (IMO, 2018).

The annual expected oil spill volume of 196,000 metric tonnes for the System 2B pipeline (see Table 8) has an equivalent cost of around $285 million (in 2005 USD), or $345 million (in 2015 USD). To estimate the 2015 values, US inflation figures have been used. Note that the IMO formula estimates oil spill costs in 2009 US dollars; to bring these figures to 2015 US dollars US inflation figures have been used; see Table 8.

Table 7: Total Oil Spill Cost

	Spill Volume (mt)	Formula	Total Cost (2009 USD)	Total Cost (in 2015 USD)
Total Cost	196,000	$42301\ V^{0.7233}$	$284,602,985	$345,370,750

5.4 Total Expected Failure Cost

The estimated expected failure cost of pipeline 2B includes the cost of human losses, the direct economic cost and the environmental damage (due to the oil spilled) have been presented in the previous sections. The direct economic cost is calculated as an average of the losses over 10 years to 2015 and is estimated at $51.9 million. The environmental cost is estimated as $345.4 million at 2015 prices. The cost associated with life safety, in equivalent fatalities, is estimated as $316.2 million, also at 2015 prices. The total expected annual cost is, therefore, $712.6 million. Note that this is based on conservative estimated (see the assumptions above) and therefore the actual damage, and, thus, the benefit of averting the relevant risk is probably way higher.

5.5 Cost of Risk Control Measures

An assessment has been carried out to determine the costs required to implement the identified risk reduction and control measures. Based on the ER aggregation results shown in

Section 3, some measures are more effective than others. However, for this assessment, it is assumed that all measures may be implemented. The cost of each RCO varies and so does its effectiveness. First, the failure likelihood of the baseline scenario (*i.e*., business as usual) needs to be established. This is achieved by using the failure likelihood derived for intentional third-party damage from Hassan *et al.* (2022a), which is 0.30, and the belief degrees provided by the experts, as represented as the weightings in Table 1 **Error! Reference source not found.**. The two values are then used to estimate the failure likelihood for the inadequate provision of the basic attributes. For example, to obtain the failure likelihood estimates relating to inadequate surveillance the following are used: the intentional third-party damage failure likelihood of 0.300, the detection general attribute weight of 0.290, from Table 1, and the surveillance basic attribute weight of 0.298, also from Table 1. This gives inadequate surveillance a failure likelihood of 0.0263, that is, *0.300* x *0.290* x *0.298.* The failure likelihood of the rest of the attributes is shown in Table 9. The sum of the failure likelihood of all attributes in Table 9 should be equal to 0.3, which is the likelihood of failure due to intentional third-party damage estimated in Hassan *et al* (2022a).

Table 8: Failure Likelihood for Baseline Studies - System without any RCO

S/N	Lack of or Inadequate Provision the Basic Attributes	Failure Likelihood (per yr)
1	Lack of or Inadequate Surveillance	0.0263
2	Leak Detection	0.0313
3	SCADA/Staffing Measures	0.0186
4	Patrol	0.0120
5	Pipeline Cover	0.0215
6	Burial Depth	0.0287
7	Public Education	0.0233
8	Barrier	0.0606
9	Right of Way Control	0.0277
10	Spill Response	0.0112
11	Industry Cooperation	0.0111
12	Intelligence	0.0121
13	Security Forces	0.0038
14	Punishment	0.0043
15	Community Partnering	0.0073

To obtain the estimated cost of intervention, two levels of risk reduction options for each of the attributes have been identified: the basic RCOs and advanced RCOs. The "as-installed" provisions are cost-neutral because they are already installed ('business-as-usual' scenario) and therefore do not require any additional expenditure. This is the baseline scenario and is used to calculate the benefit using the other options. The 'basic RCO' scenario assumes adoption of the risk control options that minimise expenditure on top of the existing measures ('business-as-usual'). The 'advanced RCO' scenario includes detailed provisions that aim to reduce the likelihood of the threat being realised to significantly low levels. The implementation of this scenario (adoption of the relevant risk control options on top of the existing measures) will lead to a high-risk reduction at a very high cost though. Note that the majority of RCOs are aimed at reducing the likelihood of a failure event happening. Some of them such as patrols, could reduce the failure likelihood as well as the consequences. However, as consequence analysis has not been carried out as part of this research, assessment of the consequence reduction potential of the RCOs have not been investigated.

Table 9: Costs for Implementing Risk Reduction Measures

General Attributes	Basic Attributes - Risk Reduction Options	Reduction in Failure Likelihood	Estimated Cost in $ (per yr)	Reference
Surveillance	No surveillance	-	-	(PPMC, 2014)
	Weekly	0.2999	1,846,769	
	Daily	0.0001	5,207,272,727	
Leak Detection	Basic LDS (*e.g.*, pressure/flow monitoring)	-	-	(Hill, 2011)
	Mid-range LDS (*e.g.*, real time transient model)	0.1999	1,022,693	
	Advance LDS (*e.g.*, fibre optics leak detection)	0.0001	14,548,750	
SCADA/Staffing measures	No SCADA and minimal staff monitoring	-	-	(Oriental Consultants, 2011)
	Basic SCADA and limited staff monitoring	0.0999	487,085	
	Advanced SCADA and robust staff monitoring	0.0001	1,948,339	
Patrol	Irregular and ineffective patrol	-	473,388	(PPMC, 2014)
	Weekly	0.3332	1,420,591	
	Daily	0.0001	4,733,884,298	
Pipeline Cover	No cover	-	-	(Knoope, 2016)
	Reinforced concrete slab, *etc*., above the pipeline	0.0999	62,150,000	
	Reinforced concrete slab or high tensile netting plus visible warning above the pipeline	0.0001	62,274,300	
Burial Depth	≤ 0.4	-	-	(Knoope, 2016)
	≤ 1.0	0.4999	19,662,000	
	>1.6	0.0001	36,047,000	
Public Education	No public education	-	-	(USDT, 2012)
	Good, less effective public education	0.2999	500,000	
	Very good and effective public education	0.0001	2,000,000	
Barrier	No barrier	-	-	
	Basic physical barrier to the most vulnerable segment of the pipeline	0.0999	925,000	
	Fence, alarms and CCTV on all segments of pipeline subject to attack	0.0001	2,259,000	
Right of Way Control	No effective RoW enforcement	-		(Rui *et al.*, 2011)
	Less effective RoW control with pockets of incursions in some corridors	0.4999		
	Strick RoW control	0.0001	578,314	
	No specified emergency spill response	-	-	

General Attributes	Basic Attributes - Risk Reduction Options	Reduction in Failure Likelihood	Estimated Cost in $ (per yr)	Reference
Spill Response	Facility response plan in place but no coordination with outside entities	0.3157	101,376	(O&G UK & OPOL, 2012)
	Well planned emergency spill response including facility response plan, coordination and cooperation with nearby facilities and robust coordination with public emergency planning authorities	0.0001	126,720	
Industry Cooperation	No cooperation	-	-	
	Uncoordinated and informal cooperation	0.3477	250,000	
	Detailed coordination and cooperation with the rest of the industry and especially a formal coordinated approach to tackling asset threat	0.0001	1,000,000	
Intelligence	No intelligence gathering and sharing	-	-	(Amunwa, 2012)
	Some intelligence is gathered but actions are inconsistent.	0.1303	1,216,021	
	Optimum intelligence gathering and sharing with and between all relevant parties. Actions are taken based on intelligence.	0.0001	4,864,083	
Security Forces	Inconsistent and uncoordinated security provision	-	-	(Aghedo & Osumah, 2015)
	Less effective security provisions	0.3999	4,864,083	
	Robust, coordinated and effective security provisions by both the companies and govt	0.0001	19,456,333	
Punishment	No fear of punishment to serve as a deterrent	-	-	
	Some provision in place such that a fear exists of punishment if apprehended	0.2777	1,216,021	
	Robust provision in place such that absolute fear of the consequence of any pipeline vandalization or interference exists	0.0001	4,864,083	
Community Partnering	Bad relationship with the community and relevant interest groups	-	-	
	A somewhat good relationship but the community does not play an active role in pipeline security	0.2544	500,000	
	Excellent relationship with the community and interest groups within the community help in pipeline security	0.0001	2,000,000	

Error! Reference source not found. shows the RCOs and their estimated cost in US dollars (2015 prices) for each of the intervention scenarios. There are three cost alternatives for each RCO. The first is for the operator to do nothing ('business-as-usual' or baseline scenario), the second assumes the implementation of a basic provisions and the last one is the implementation of the most advanced RCOs. Most of the estimated costs are taken from literature (see sources in Table 13), which looks at similar interventions and in some cases is adjusted to reflect the Nigerian environment. Where no public information is available, expert opinion has been used.

The assigned value for reduction in failure likelihood is subjectively assessed with the support of experts based on the perceived effectiveness of each RCO and the level of the intervention. For example, advanced RCOs have been assumed to be capable of reducing the failure likelihood by more than 99% *i.e.*, almost eliminating the relevant risk.

The estimated total cost includes the initial purchase of the equipment, its maintenance, spare parts, and repairs. The entire lifetime of the investments (*i.e.*, the implementation of specific risk control measures) is considered, using the net present value (NPV) approach to take into account future cash-flows. The present value of a future cost, say for maintenance or spares, is calculated using the net present value formula $NPV = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$ where *i* is the discount rate or the interest rate, R_t is the outlay cost and *t* is the number of years of interest.

For example, the costs for a real-time transient leak detection facility includes a purchase cost of $1,000,000, annual maintenance costs of $2,000 and repairs/spare parts cost of $500 per year for an expected service lifetime of 25 years. The cost of the capital or interest rate is assumed to be 10%.

The present value (PV) of the cost components is as follows:

1. Purchase cost = $1,000,000

(No need to be discounted as this incurs only at the start of the project)

2. PV(maintenance) = $\sum_{t=1}^{25} \left(\frac{2{,}000}{(1+10\%^{25})}\right) = 2{,}000 \times \left(\frac{(1+10\%)^{25}-1}{10\% \ x \ (1+10\%)^{25}}\right) = \$18{,}154.08$

3. PV(spares) = $\sum_{t=1}^{25} \left(\frac{500}{(1+10\%^{25})}\right) = 500 \times \left(\frac{(1+10\%)^{25}-1}{10\% \ x \ (1+10\%)^{25}}\right) = \$4{,}538.52$

The total cost is therefore $1,022,693. **Error! Reference source not found.** provides the estimated costs for implementing each of the RCOs. As outlined earlier, the assigned values for the reduction in failure likelihood is based on expert opinion.

Assuming that all RCOs are to be implemented, basic provisions will cost about $96 million whilst advanced provisions are expected to cost about $10 billion. The limited budget and cost effectiveness imply that not all RCOs will be implemented. Therefore, the operator may decide to explore different options, such as assessing the cost effectiveness of implementing all basic provisions, for example, or only a selection of basic provisions. Table 11 shows the RCO scenarios, the cost of the RCOs and the net benefit for each of the intervention combinations chosen. Other different combinations are possible, and each combination affords the user the opportunity to calculate the cost implication of their selection and the net benefit.

Table 10: Net Benefit of Different RCO Scenarios

S/N	RCO Scenarios	Failure Likelihood	Pipeline Losses	Cost of RCO	Net Benefit
1	Baseline scenario ('Business-as-usual' or 'do-nothing' scenario)	0.3000	$712,608,000	$ 0	$-712,608,000
2	Basic RCO provisions scenario - implement all	0.076962	$182,812,456	$96,469,411	$433,326,133
3	Basic RCO provisions scenario - implement the most effective	0.035200	$83,612,672	$68,329,445	$560,665,883
4	Advanced RCO provisions scenario	0.000030	$71,261	$10,093,123,948	$-9,380,587,209

Note: only seven of the thirteen RCOs including surveillance, leak detection, SCADA, patrol, pipeline cover, public education and physical barriers are assumed to be implemented under item 3.

As can be seen in Table 11 although doing nothing costs the operator zero dollars in intervention expenditure (no risk control measures are implemented) this is associated with an estimated expected losses of $712.61 million annually, as calculated in Section 5.4. On the other extreme, implementing all the advanced RCO provisions would cost about $10.09 billion, but will reduce pipelines losses from $712.61 million per annum to $71,261 per annum. The net benefit of the intervention will be actually a loss of $9.38 billion, this is due to the huge expenditure required. Clearly, this will not be effective either in terms of return on investment or in terms of effective utilisation of the available funds. The basic RCO provisions would seem to provide the best opportunity for cost-effective solutions. If all the basic provisions are implemented, this would cost about $96.47 million and will reduce the expected pipeline losses from $712.61 million per annum down to $182.81 million per annum. The net benefit of the interventions would be circa $433.33 million. On the other hand, if the available budget does not allow full implementation of the basic provisions, the operator may choose to implement those provisions that have the most impact on risk reduction. As an example, if the operator were to implement basic provisions of the seven out of the thirteen RCOs (*i.e.*, the ones with the highest positive effect on reducing the failure likelihood), this would result in a net benefit of about $560.67 million. Note that under this scenario, the RCOs to be implemented include surveillance, leak detection, SCADA, patrols, pipeline cover, public education and physical barriers.

The effective RCOs fall largely within the broader areas of technical solutions (surveillance, leak detection, pipeline cover, physical barriers) and management solutions (SCADA, patrol). This is consistent with the results of Table 3, which shows these solutions to be the most effective interventions – technical solutions first, followed by management solutions.

A sensitivity assessment investigates the impact of reduced or increased fatalities to the overall results in order to test how sensitive the results are to the assumptions made regarding the calculated number of fatalities. Implementing the basic RCO provisions or implementing the most effective basic RCOs gives a positive present value estimate, even if the costs due to loss of life are excluded from the assessment. The two options are still beneficial (*i.e.*, the associated benefits are greater than the costs) even if it is assumed that a 'catastrophic consequence' results in 10 fatalities per incident, as opposed to the previous assumption of one fatality per incident. Conversely, implementing advanced RCO provisions cannot be recommended based on a CBA analysis (*i.e.*, the costs are way higher than the benefits) even if a catastrophic consequence is assumed. Advanced RCOs only become cost-effective when 30 fatalities per pipeline failure are expected, this corresponds to an expected number of about 19,000 total fatalities per year. This is obviously not a plausible scenario. In summary, the CBA criterion (*i.e.*, benefits of implementing the RCOs greater than the costs) is met when implementing either all RCO provisions or only selected basic RCO provisions, even if the life safety aspect of the calculation is excluded from the analysis. Note that a more detailed sensitivity analysis could be used especially in estimating the cost of the measures; however due to the large net savings the main findings would not change.

6. Discussion

The analysis carried out in this work provides a set of tools that a pipeline operator may use to reduce their exposure to loss of containment as a result of intentional third-party damage. The model, employing ER, expert elicitation and CBA, identifies the most effective set of interventions that the pipeline operator could implement to reduce the identified threat.

The failure factor analysed is 'intentional third-party damage', which is usually driven by political, economic and social factors. Therefore, it would have been expected that the government intervention alternative – via the use of security personnel to prevent and provide deterrence for criminal actions – is the most effective. However, the results indicate that such solutions are the least effective. The results instead support that the technical solutions are deemed be the most effective, followed by the operator's implementation of management-related measures. A possible explanation is that the technical solutions probably make it difficult for the saboteur to access the pipeline in the first place.

The experts' belief that technical solutions are the most effective is perhaps based on the expectation that, once implemented, access to and damaging of the pipelines becomes difficult, thus eliminating the need for measures that fall under the 'government' and/or 'management' group of measures. One set of control solutions or alternatives alone will not address the challenge and a combination of control solutions is required. Identifying the most effective combination of solutions can be better appreciated by interrogating the basic attributes and their contribution to risk reduction and control measures. Interrogating the basic attributes indicates that the attribute with the most effective impact is the provision of a physical barrier to the exposed and the most vulnerable sections of the system, such as pumping stations and river crossings. The attribute which is least effective is the provision of security forces, which directly corroborates with the results that show government intervention solutions as being the least effective, as outlined earlier.

The cost-benefit analysis of possible interventions provides guidance on the net benefit of any one intervention or set of solutions. This offers the pipeline operator access to an easy and straightforward tool which could help them implement interventions that are the most effective or the ones that the operator's current budget could allow. The assessment indicates that implementing advanced RCOs will have a significant budget outlay but will almost entirely put a stop to third-party damage. However, that intervention is not cost-effective, with a net benefit of minus $9.4 billion. Conversely, the basic RCO interventions are the most cost-effective, in that they require a lower financial outlay of $96 million, significantly less than the operator's estimated losses annually. The net benefit for basic RCOs is circa $433 million. A sensitivity assessment, which has been discussed in Section 5.5 provides further managerial insights.

Although the assessment is detailed and complete, both the ER-based decision-making and CBA have a number of areas that could be improved. The most significant part is the dearth of directly applicable data for the geographical area under consideration and the subjectivity of the input from the subject matter experts. In terms of decision-making, a more refined aggregation, and a higher number of evaluation grades than the five used could provide more granular results. These could better assist to decision-makers by providing visibility of the impact of a very small intervention to the overall aggregation results. However, the more evaluation grades or attributes are introduced, the more complex the analysis becomes. Also obtaining expert inputs via questionnaire becomes burdensome. Nevertheless, using a higher number of evaluation grades has been shown by Ren, *et al*. (Ren *et al*., 2005) to provide better and more accurate basic attributes belief degrees.

7. Conclusions

This study presents a decision-support model to support the assessment of measures to reduce the risk related to pipeline loss of containment as a result of third-party activities and identifies the most effective RCOs to reduce the overall risk. A pipeline system in Nigeria is presented as a case study. The ER algorithm has been applied to this problem, aggregating the attributes and hierarchies of each of the risk control measures. The assessment results identify the most optimal alternative as being technical solutions in reducing the threat of a pipeline loss of containment due to a third party.

An economic analysis has also been carried out to estimate the current risk, expressed in monetary terms, of the current or 'business-as-usual' scenario as a result of third-party damage to the pipeline system. It has been estimated that the annual expected loss, based on data up to 2015, is around $713 million. The CBA then calculated the expected expenditure required to implement the measures for different levels of details and the loss reduction that such measures would provide.

The work will provide pipeline operators with easy-to-apply tools that will hopefully allow them to prioritise their investment in reducing the loss of containment threat. It will also give them a good idea of the relative effectiveness of the many RCOs available and their estimated costs. Due to limited directly applicable data, the CBA uses data from other countries, and where no relevant data is available, a number of assumptions were made. Therefore, the estimated cost may vary within a real-life assessment but the relative costs of one option compared to the other should be reasonably in line with the actual differences between the options. For decision-making processes, that relative difference may be the most important factor.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Disclaimer

The opinions expressed in this article are the author's own and do not necessarily reflect those of their employers.

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