Multidimensional risk evaluation: assigning priorities for actions on a natural gas pipeline

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Abstract: This paper presents a multicriteria decision model application to define actions with a view to mitigating the risks involved in this mode of transportation. Natural gas is a fossil fuel that is important for society and is transported through pipelines. It is used for different purposes in industrial and civil applications. Although pipelines are one of the safest transport systems, some accidents involving natural gas have occurred. The Multicriteria decision model described in this paper is put forward as a means to minimize such possibilities. It incorporates MAUT (Multi-attribute Utility Theory), which considers a decision maker's preferences and some aspects of the Decision Theory approach. Three dimensions of risk, namely the human, financial and environmental ones - are targeted in the context of probabilistic consequences. As an important result, the information obtained from the model is shown to be important in order to define how resources should best be allocated and to establish maintenance policies for managing and mitigating risk.

Keywords: Multicriteria, risk, natural gas pipeline.

1. INTRODUCTION

Due to the increasing in the global demand for energy (which may well triple in the first half of the 21st century) and extensive and prolonged blackouts having occurred around the world, research on the use of other energy sources has been undertaken to seek solutions to these problems [1]. Moreover, due to the need to preserve and conserve the environment, greater attention is being given to cleaner sources of energy, of which Natural Gas is one [2]. Thus, natural gas can be used in the chemical industry, in the process of producing electricity, as fuel in automobiles, homes, and in other applications.

The most common means of transporting Natural Gas is by pipeline. Pipeline extensions may range from running for a few meters to hundreds of kilometers. Long pipelines pass through different locations, each with specific characteristics e.g. agricultural, industrial or residential areas, preserved environmental sites, commercial districts, etc.). Many authors consider the transport of flammable substances in pipelines as the safest and most economic among existing modes of transportation, especially when compared to road and rail [3].

Pipelines are subject to different actions that may damage their structure. Corrosion, third party actions and human errors during operation and maintenance are examples of events that can cause holes or disruptions in pipeline, thus producing a gas leak. The release of gas can lead to accidents with catastrophic consequences that adversely affect human beings and property, causing financial loss and harming a natural gas company's image.

Most studies on risk in the natural gas pipeline environment have been conducted using different methods of evaluation which have included qualitative and quantitative approaches [4]. This paper, specifically, uses a multi-criteria decision model for risk assessment which has a risk value hierarchy and considers three dimensions of risk: human, environmental and financial. Multi-attribute Utility Theory (MAUT) is used in this model. The results are used as input in the risk management process to support the decision under conditions of resource constraint. Thus, resources can be used by the decision maker (DM) so that risk is mitigated and managed more befittingly with reality.

The paper has the following sections: Section 2 presents a review of the literature on Multicriteria risk analysis; Section 3 discusses some concepts of multicriteria decision making, including MAUT; Section 4 sets out the multicriteria decision model; Section 5 describes an application of the model; and Section 6 draws some conclusions.

2. MULTICRITERIA RISK ANALYSIS

Many risk definitions have been made over the years and especially take into account the relationship between the probability of an accident occurring and the consequences arising [5]. Therefore, [4] considers that risk can be quantified, measured and expressed as a mathematical relationship with the help of available data, with the results being applicable in widely different areas [6]. This analysis can be used to define the probability of potential accidents and their causes, and examining the measures necessary to mitigate risk.

However, there is a perceptible a tendency on assessing risk for only the number of people affected or the financial impact on the resulting scenario to be considered. However, if only one of these factors is considered, this is insufficient due to the complexity and seriousness of the issues involved in this type of analysis [7].

Since a pipeline normally extends over different areas, as mentioned, an accident in one area probably would not have the same consequences as a similar type of accident in another area. For example, an accident in an uninhabited area does not affect humans in the same way when compared to an accident in a residential or commercial area. So it is very important to use multiple criteria in the model presented in order to have a result that incorporates multiple dimensions and provides a risk analysis in accordance with the actual characteristics of the pipeline, since for each section analyzed, there will be different impacts on each of the dimensions considered. Moreover, it is of paramount importance to assess the structure of the DM´s preferences and judgments [8]. In the next section a brief introduction will be given to multicriteria decision making.

3. MULTICRITERIA DECISION MAKING

A multicriteria decision problem consists of a decision problem in which more than one alternative is analyzed in a context of conflicting objectives [9]. This decision may be taken by one DM or a group of DMs, who accept responsibility for the decision and its possible consequences. According to [10], multiple criteria decision making can work with different aspects related to the DM's characteristics, and it takes into account conflicting criteria used in the analysis.

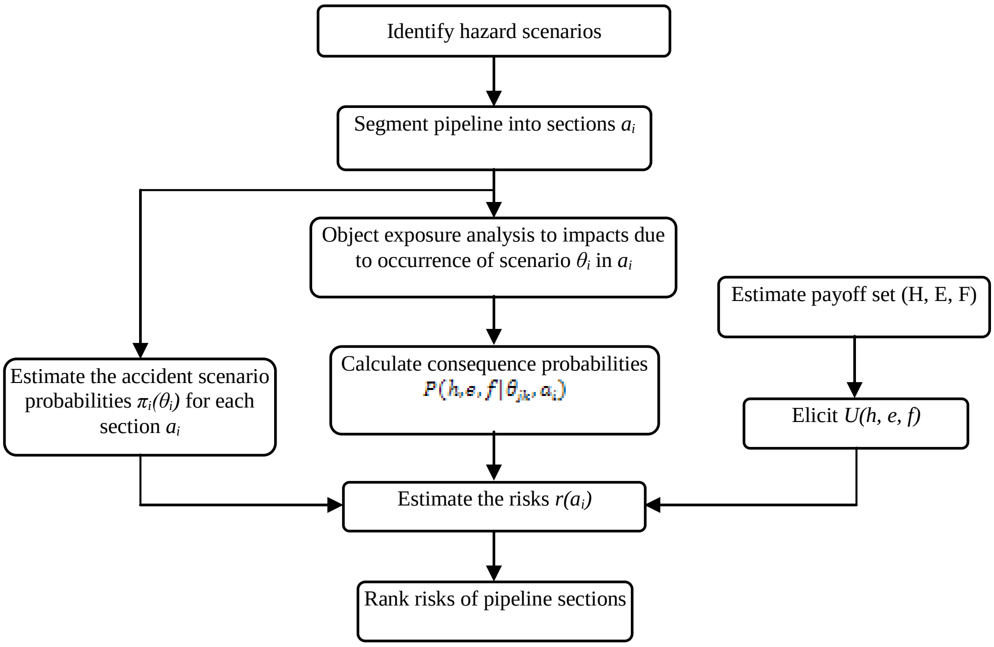
Therefore, the set of methods, techniques and concepts of multicriteria decision support (MCDA - MultiCriteria Decision Aid) seek to assist people and organizations in solving problems where multiple views can be evaluated [11], such that information provided by the DM can be synthesized and organized, so that decisions are taken more effectively. [12].

MAUT (Multi-attribute Utility Theory) is used to develop the model discussed in this paper, taking into account the probabilistic context in which pipeline risk analysis is inserted. MAUT presents a very well defined axiomatic structure, based on the axioms of utility theory. [13]. Furthermore, MAUT enables the utility function to be elicited by structured elicitation protocols.

4. MULTIPLE CRITERIA DECISION MODEL

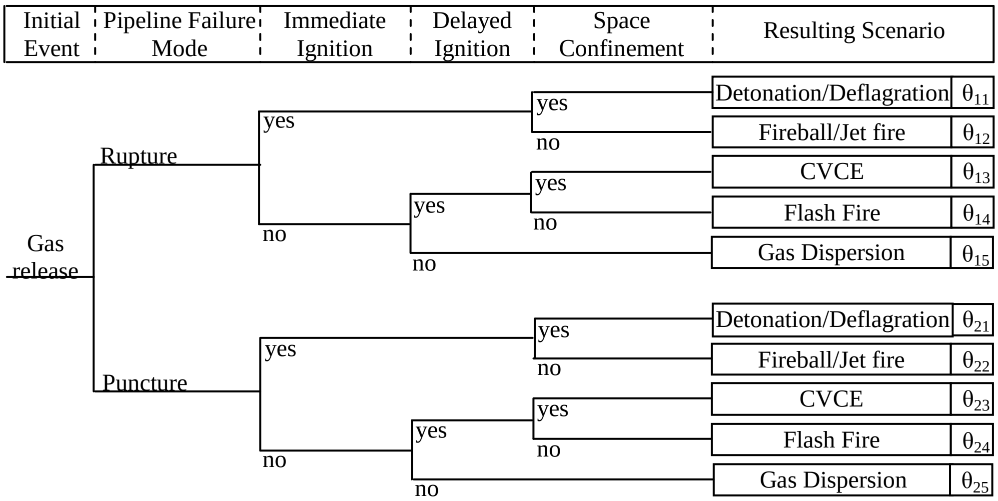
The decision model considered in this paper uses a multiple risk dimension based evaluation for each section of a pipeline network, thereby providing an idea of the hierarchy of risk between each pipeline section by comparing these sections, while taking environmental, human and financial risks into consideration as is the DM´s character as to his/her aversion to or propensity for risk for each of the dimensions. Figure 1 shows the process for applying the model and illustrates its steps which are discussed below. This model uses only one decision maker. It is important to note that the decision maker's value judgments are influenced by his/her own values and by incorporating, on his/her own, the values of the stakeholders involved. Figure 1 presents the final structures of the multicriteria decision model.

Figure 1: Model structure (adapted from [14])



Additionally, hazard scenarios that can occur in natural gas pipelines are listed as shown in Figure 2.

Figure 1: Event tree for a natural gas pipeline (Adapted from [14])



Pipelines can be divided into sections that have homogeneous characteristics such as soil type, age of piping, pipeline diameter, pressure and cathodic protection.

The probability of the occurrence of an accident for each hazard scenario ($\pi_i(\theta_{jk})$) is accounted for and evaluated in one of the steps of the model as is the probability of a normal scenario ($\pi_i(\theta_N)$), where no damage occurs. When no historical data are available for evaluation purposes, the model uses the DM´s knowledge as per *a priori* probability distributions.

The consequences due to an accident occurring are evaluated in a given set of payoffs for the deemed dimensions of risk e.g. possible losses due to the energy and heat released by overheated gas, flames or explosions. As to the human dimension, the maximum number of people present in the danger zone is considered. As for the environmental dimension, what is considered is the area of vegetation scorched by flames from the burning gas released through a hole or rupture of the pipeline, while for the financial dimension monetary losses associated with the accident should be considered.

When calculating the impact on the human and environmental dimensions, the average radiation flux due to deflagration is obtained. According to [15] η is the ratio of the irradiated heat over the total heat released; τ_a is the atmospheric transmissivity; H_c is the combustion heat of the natural gas; r is the radius of the critical danger radius; and Q_{eff} is the effective rate of the gas leak. Thus, the average flux of radiation flux is as per the following Equation (1):

$$I = \frac{\eta \times \tau_a \times Q_{eff} \times H_c}{4 \times \pi \times (r)^2} \quad (1)$$

To evaluate the consequences on the financial dimension the sum of losses due to three aspects is considered: suspension of invoicing ($F(t_Q)$, caused by revenue losses incurred due to the gas supply being interrupted; salvage and restoration works; ($W(t_Q)$); damage to property, fines and compensation payments for injuries ($W(t_Q)$) resulting from the accident in the pipeline, as per Equation (2):

$$P_f = F(t_Q) + W(t_Q) + M(t_Q) \quad (2)$$

The model also has a well-structured process for evaluating the scale constants and utility function, in which the DM's preferences as regards risk are taken into account, namely he/she be averse to, neutral about taking risks or may have a propensity towards them. An additive utility function is considered, where the additive Independence property of $U(h,e,f)$ implies the existence of preferential independence between the set of payoffs. A utility function is defined by the equation (3) [16].

$$U(h,e,f) = k_h U(h) + k_e U(e) + k_f U(f) \quad (3)$$

To calculate the risk, a consequence function is evaluated for each dimension of risk. It is considered there is no statistical correlation between human, environmental and financial damage, thereby enabling the consequences to be evaluated separately in each of the risk dimensions [14].

The estimation of risks is carried out considering the losses occasioned by a hazard scenario occurring in the section evaluated in the pipeline, where the utility function and probability density function are combined, as shown by Equation (4) [7].

$$L(\theta_{jk}, a_i) = -\int_h \int_e \int_f [P(h,e,f \mid \theta_{jk}, a_i) \times U(h,e,f)]\, dh\, de\, df \quad (4)$$

The risk is then calculated by Equation (5):

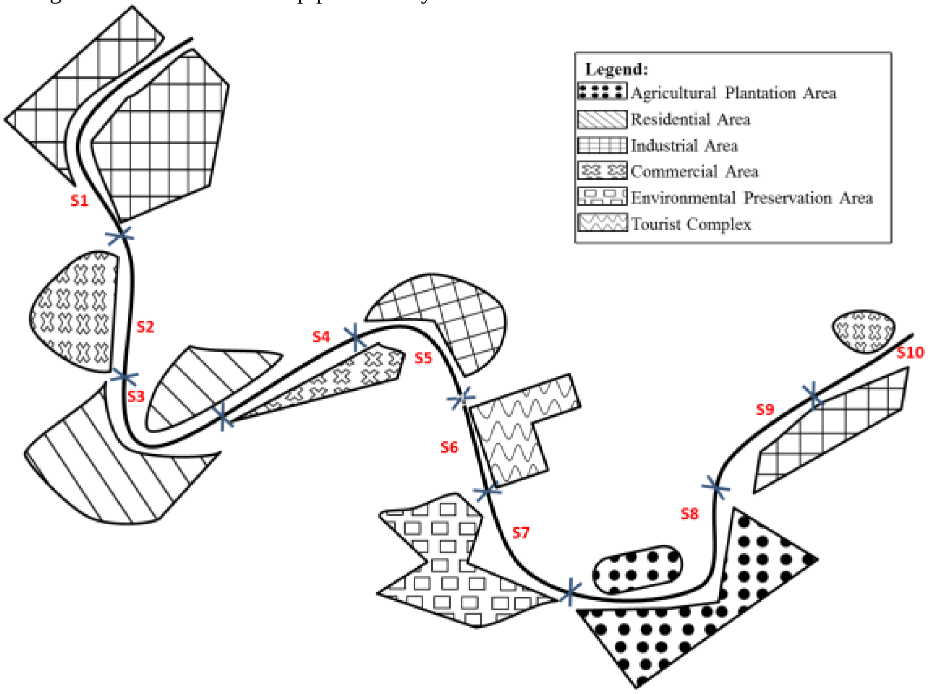
$$r(a_i) = \left\{ \sum_j \sum_k \left\{ -\begin{bmatrix} +\int_h f(h|\theta_{jk}, a) k_h u(h) dh \\ +\int_e f(e|\theta_{jk}, a) k_e u(e) de \\ +\int_f f(f|\theta_{jk}, a) k_f u(f) df \end{bmatrix} \right\} . \pi_i(\theta_{jk}) \right\} + (-1) . \pi_i(\theta_N) \quad (5)$$

5. NUMERICAL APPLICATION

In this section, a numerical application is presented in order to illustrate the multiple criteria decision model developed for assessing risk in a natural gas pipeline.

The pipeline investigated in this application has ten sections, the total length of which is 25,300 km, divided according to the characteristic of land use in the surrounding area. Figure 3 shows one stretch of this pipeline.

Figure 3: Diagram of the stretch of the pipeline analyzed and the characteristics of land use of the surrounding areas



The DM´s attitude towards risks was evaluated and scale constants were elicited. Thus the utility function U(h, e, f) could be evaluated, where the last step in risk analysis is to check the value of risk by Equation (5). From this result some interpretations can be made.

One of these interpretations is that an absolute difference index (AD) for each section should be adopted and calculated from the ratio "$r(x_i)-r(x_{i+1})$" where "x_i" and "x_{i+1}" represent the positions in the ranking of given sections of the pipeline. Another interesting index for the risk analysis is the difference ratio (DR), expressed by Equation (6).

$$DR=\frac{r_x(a_j)-r_{x+1}(a_j)}{r_{x+1}(a_j)-r_{x+2}(a_j)} \qquad (6)$$

These values are presented in Table 1.

Tabela 1: Absolute difference and difference ratio for the sections of the pipeline

Ranking position (x)	Section	AD	DR
1	S_7	11.14	9.32
2	S_9	1.19	2.33
3	S_8	0.51	0.13
4	S_6	3.69	1.37
5	S_5	2.69	2.41
6	S_4	1.11	0.09
7	S_{10}	11.71	3.89
8	S_1	3.014	2.5
9	S_2	1.2	-
10	S_3	-	-

From Table 1, it is possible to verify that Section seven (S_7) has a higher risk when all three risk dimensions are considered: human, financial and environmental. Higher losses in this section are expected because an accident when transporting gas occurred in this pipeline. On using the interval scale from the utility function, it can be inferred that the increment in risk for the risk from S_7 to S_9 is 9.32 times greater than that from section S_9 to S_8, in the same way that the increment on risk from S_{10} to S_1 is 3.89 times in relation of S_1 to S_2.

This analysis of the increment in risk enables the DM to evaluate how best to allocate resources, should these be scare. Moreover, it enables the DM to evaluate how to mitigate risk more efficiently, since a ranking for risk was generated and from this it is possible to identify which sections are most prone to the largest consequences, should an accident occur, especially in sections with homogenous characteristics.

6. CONCLUSION

This paper has demonstrated that it is possible to evaluate the risk from transporting Natural Gas by pipeline by means of a multicriteria model using Multi-attribute Utility Theory, which takes the DM's behavior into account in relation to risk in three risk dimensions: human, environmental and financial, besides considering his/her preferences when eliciting the scale constant. Thus, the interval scale of the utility theory for evaluating the increment on risk from one section to another was considered.

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