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Multidimensional Risk Assessment in Natural Gas Pipelines: Managing Risk Categories Based on Sensitivity Analysis Information

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Identifying risks ensures that organizations systematically find out where potential losses may occur. A particular aspect is that risk events should reflect multiple perspectives of losses and be evaluated in different categories of risk at different levels. In this case, sorting risk events improves perception and helps decide how best to choose strategies to mitigate levels of risk events. However, uncertainties arising from the system's external and internal parameters prevent managers from precisely managing such a strategy. For example, in the natural gas pipeline context, parameters of the infrastructure, limits placed on resources, and demand may change over time, thereby limiting the ability of the organization to meet its objectives, which for risk-based purposes is to minimize losses. In other words, the level of risk events may vary due to uncertainties in the assessment model. Therefore, investigating uncertainty in risk-based models is crucial, and an experimental evaluation should be carried out before making decisions. For this reason, it is crucial to establish appropriate risk prioritization procedures that detect uncertainty factors and estimate the variability in risk behavior concerning categories of risk and the impacts caused. A suitable way to study variability is by conducting a thorough Sensitivity Analysis (SA). SA in risk-based models is useful for investigating the influence of parameters on measurements of risk, thus generating information on the uncertainty levels of different parameters, and how measurements of risk change decisions. This study presents a risk categorization model that supports managers in developing suitable mitigation plans according to the levels of risk based on sensitivity information. The multidimensional risk assessment and categorization model (MRAC) integrates Utility Theory and the ELECTRE TRI multicriteria method to sort sections of a gas pipeline by their level of risk. Based on a Monte Carlo Simulation experiment, the input parameters of MRAC are explored, thus generating information on sensitivity levels of the sections with the potentiality of increasing and decreasing their risk category. Finally, the sensitivity information is deployed in an efficient visualization that helps practitioners understand the uncertainties that should be controlled, thereby improving the process of mitigating risks. The contributions of this paper are set out based on how to establish critical information to control the variability of risk categories and prevent losses with regard to people, the environment, and the organization.
Keywords: Risk analysis, Risk categorization, Sensitivity Analysis, Gas pipeline, Multicriteria Decision:

1. Introduction

Assessing risks in Natural Gas Pipelines (NGPs) has been a fundamental tool to manage operational and maintenance processes. Hence, several techniques have been used to assess risks in pipeline systems. Generally, measuring is based on identifying hazards, the probability of hazardous events, and the consequences of these events (Aven et al., 2018). For NGPs, the main hazards are related to the integrity of the pipeline and these are assessed in terms of physical and operational parameters. Information on failure

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scenarios, ignition sources and meteorological conditions are also used to estimate the impacts of accidents on NGPs (Jo and Ahn, 2002).

Accidents in NGPs cause multiple types of consequences such as human, environmental and financial losses. In this context, it is more appropriate to assess risk taking by taking a multidimensional risk approach (Brito et al., 2010). The multidimensional risk approach has been used for assessing multiple risks based on Utility Theory concepts (Brito and de Almeida, 2009). The behavior of consequences is evaluated regarding a Decision-Maker's (DM) preferences and inserted into the formulation of risk. Thus, managers are able to draw up suitable interventions to reduce or eliminate risks according to the level of risk. The multicriteria method ELECTRE TRI can be used to sort multidimensional risks to categorize pipeline sections in order to establish appropriate strategies to mitigate the risks (Brito et al., 2010). However, a peculiar characteristic of assessing risks in NGPs is that there are uncertainties involved regarding the external and internal parameters used in the assessment of risks. For example, the uncertainties related parameters of the integrity of a pipeline such as temperature and pressure. In this case, further investigation into the variability of the decision made is needed, e.g. categorization. Borgonovo and Plische (2016) state that it is appropriate to develop a practical validation of the risk results in order to cover all possible uncertainty scenarios. Some different analyses are possible to test uncertainties of quantitative risk models. Sensitivity Analysis (SA) is an opportune tool to assess the effect of uncertainty on risk outcomes. Zio (2018) emphasizes the importance of Sensitivity Analysis (SA) in risk assessment based on the assumption that critical and dangerous conditions may raise from the impact of a different number of combinatorial set of events, scenarios and conditions related to the expositions, sources of hazards and the inherent uncertainty. SA has been explored as a support for risk-based decision-making in NGPs. Medeiros et al. (2017) present a global SA approach for ranking risk problems. López-Benito and Bolado-Lavín (2017) explore dependent parameters of a NGP model by applying a moment independent measure for global SA. Viana et al. (2021) provide a SA framework for a risk categorization model. Monte Carlo Simulation (MCS) can be used in SA aapproaches as a procedure that gives a probabilistic approach to the model. MCS is a method for calculating parameter uncertainty based on probability distributions (Shields et al. 2015) and generating multiple replications of a single parameter (De Almeida et al. 2015). Borgonovo (2017) explains that the use of this type of analysis can be conducted when there are uncertainties observed in the parameters of the risk model. In this type of study, the inconsistency of the model's outcomes given a set of inputs is measured by uncertainty analysis, and sensitivity analysis identifies important parameters that make the output model susceptible to changes (de Brito et al. 2019). For the sake of this article, we assume that uncertainty is a component of the SA framework created for the SA of the parameters. Based on the risk assessment of an NGP, this paper develops a Global Sensitivity Analysis (GSA) to assess the uncertainties involved in a group of parameters related to the radiation heat flow (RHF) used in the assessment of a multidimensional risk categorization model. This study explored the sensitivity of the risk categorization of the sections of a pipeline. This provided the DM with information that enabled her/him to draw up effective interventions with a view to eliminating or reducing potential losses.

2. Modeling multidimensional risk categorization assessment with global sensitivity analysis for natural gas pipelines

This section provides the multidimensional risk assessment model for categorizing natural gas pipelines sections and the global sensitivity analysis procedure developed.

2.1 Multidimensional risk categorization assessment

The assessment of multidimensional risk is based on a multicriteria perspective by which NGPs are evaluated on the multiple consequences that result from accidents. Multicriteria Decision Making Models (MCDM) are suitable to represent problems involving multiple risks (De Almeida et. al, 2017). Relying on a single-perspective consequence may not embrace real scenarios in NGPs. Based on the evaluation of human, environmental and financial risk dimensions, the Multidimensional Risk Assessment and Categorization Model (MRACM) uses probabilistic consequence functions of each dimension with Utility Theory that incorporates the DM's attitude towards the risk, taken by an adjusted utility function (Brito et al., 2010). Considering a pipeline segmented into *n* sections s_i, risk is estimated as the expected value of the loss (Berger, 1985) for accidental scenarios θ of the pipeline, given as usual failure events related to operational or any other interference that precludes the operation of the NGP. Thus, risk is calculated as demonstrated in Eq (1).

$$r_{h,e,f}(s_i) = \sum_{\theta} \pi_i(\theta). \left[-\int_{h,e,f} P(h,e,f|\theta,s_i). U(p). dp \right] \tag{1}$$

where $\pi_i(\theta)$ is the probability of accidental scenarios, U(p) is the utility function obtained based on the DM's preference. The consequence functions of the dimensions $P(h,e,f| \theta, s_i)$ reflect the probability of the number of people injured, the area of vegetation burned and direct expenditures related to the interruption of systems, physical damage and indemnities. Any of the impacts inherent to these consequences is presumed with regard to accidental events. Jo and Crowl (2008) infer the impacts of accidents according to the critical level of thermal radiation estimated which is based on the Heat Radiation Flux (HRF) and the effective rate of release of the natural gas. The formulation described in Jo and Crowl (2008) models the consequences by evaluating the exposure of the aspects of impacts (fatalities and injuries to people, damage to vegetation and properties) to fires and heat resulting from the ocurrence of an accident in section s_i. Thus, risk values are calculated for each of the pipeline sections. Therefore, ELECTRE TRI (Figueira et al., 2016) is drawn up to place each section into one of the three main risk categories: High Risk Category (HRC), Moderate Risk Category (MRC) and Low Risk Category (LRC).

2.2 Conducting Sensitivity Analysis for risk categorization problems

The role of SA in decision making models comprises the need of the decison-makers (DM's) explore the variability of decisions according to changes in the *status-quo* scenario (Viana et al, 2021). For instance, an increase in pressure may reach high levels of risk in natural gas networks. In this sense, the way uncertainty is perceived in risk-safety decision making depends on some aspects, such as:

- The combination of risk scenarios and the consequences inherent;
- The experiment designed for exploring the uncertainty in risk-based models;
- The information obtained from the experiment (decision variability outcomes);
- Communication of uncertainty in risk and the perception of DM's.

In view of the uncertianties of the parameters used in the assessment, a GSA is carried out to explore the variability of the risk categories of the sections. Thus, SA conducts an exploration of numerical models with the aim of identifying critical parameters that influence the performance of the model (Borgonovo and Plischke, 2016). Local SA assumes one-at-a-time variation of parameters, assuming uncertainty of a single parameter, while GSA takes into consideration a group of parameters and varying them to test the numeric model (Borgonovo and Plischke, 2016).

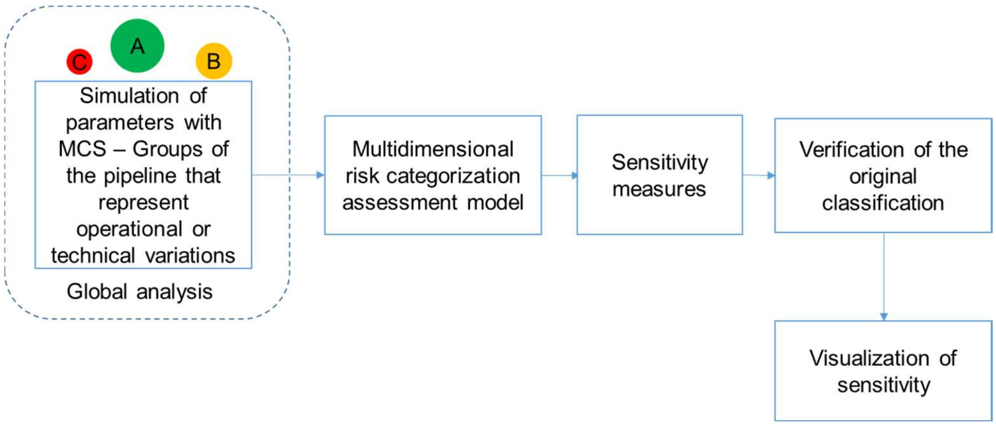

Figure 1: Global Sensitivity Analysis with Monte Carlo Simulation for risk categorization assessment in Natural Gas Pipelines

As illustrated in Figure 1, the uncertainties of parameters are generated with a Monte Carlo Simulation which provides simulated parameters of the NGP used to replicate the MRACM. The group of parameters (A, B, C…) outlined for this procedure represent operational or technical information necessary to control and monitor the performance of the pipeline in regard to safety standards. Other parameters that reflect strategical conditions such as economical shortages, demand projections, supply capacity and preference statements can be used (Viana et al. 2021).

For the simulation, in each replication of the MRACM a probability distribution is used to generate the parameters, recalculating the dimensions of risks (human, environmental and financial values) and the risk categories of the NGP sections with ELECTRE TRI. The sensitivity of the sections is tested according to their stability in the original category by generating a sensitivity measure indicating the level of robustness for each section of the pipeline s_i. Different sensitivity measures are available for SA (Borgonovo and Plischke 2016).

The defined level of sensitivity enables for the investigation of the original category's behavior and highlights the original category's stability, which is represented by a line chart. The goal of this visualization is to influence the DM's perception towards the original risk category's variability.
In the same perspective, another visualization (bar graph) is provided for the DM conduct an in-depth exploration of the increase and decrease in the categories for each section, thereby providing enough data to estimate the expected risk category for NGP sections. This information is useful for planning resources needed to mitigate the risks in the NGP network.

3. Numerical application

A numerical application of the MRACM and the GSA is presented and is illustrated with realistic information from an NGP operation based on the case of Viana et al. (2021). For this application, a 24.300 m long NGP is segmented into 8 sections named as S1, S2, S3, S4, S5, S6, S7 and S8 which passes through industrial, residential and environmental areas. Thus, the multidimensional risks of the sections are assessed and evaluated according to the categorization procedure of ELECTRE TRI shown in Table 1, where HRC stands for High-Risk Category, MRC for Moderate-Risk Category and LRC for Low-Risk Category.

Table 1: Multidimensional risk values of the pipeline sections

	Risk			**Risk**
Sections	**Human**	**Environmental**	**Financial**	**Category**
S1	0.1259	0.0137	0.1259	HRC
S2	0.0671	0.0121	0.1321	MRC
S3	0.0691	0.0111	0.1281	MRC
S4	0.0869	0.0114	0.1315	HRC
S5	0.0522	0.0114	0.1280	LRC
S6	0.0927	0.0117	0.1173	HRC
S7	0.0869	0.0120	0.1312	HRC
S8	0.0801	0.0112	0.1341	MRC

As visualized in Table 1, S1, S4, S6 and S7 are categorized in the HRC (highlighted in red). S2, S3 and S8 are categorized in the MRC (yellow cells). S5 is the only section allocated to the LRC (the green cell).
The GSA is undertaken with a group of some parameters that represent the Heat Radiation Flux (HRF). This group interacts with other parameters intefering in the value of the human, environmental and financial risk dimensions. In this case, the Monte Carlo Simulation was conducted to replicate the MRACM model 10,000 times by varying the parameters by 5%, 10% and 15% with a triangular distribution.

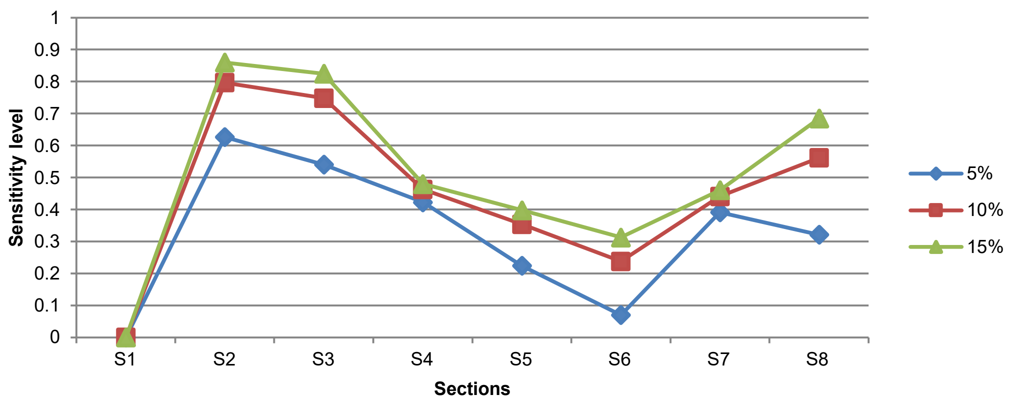

Figure 1: Sensitivity levels of the sections for 5%, 10% and 15% variation of the HRF in the MRACM

For a 5%, 10% and 15% variation, S1 is robust in relation to its original category (HRC). For S4, S5 and S7, there is a slight difference among the sensitivity levels for the percentages tested, thus providing information on modifications of the original risk category of these sections. S2, S3, S6 and S8 show significant modifications in the original category for the percentages tested, suggesting that different modifications in the values of the HRF parameters should be controlled and drive the DM's perception towards mitigation strategies. For example, S2 and S3, originally categorized in the MRC, reach 0.87 and 0.81 in level of sensitivity. The extreme value 1 reflects a total modification of the original category. In general, at least 4 sections reach high levels of sensitivity.

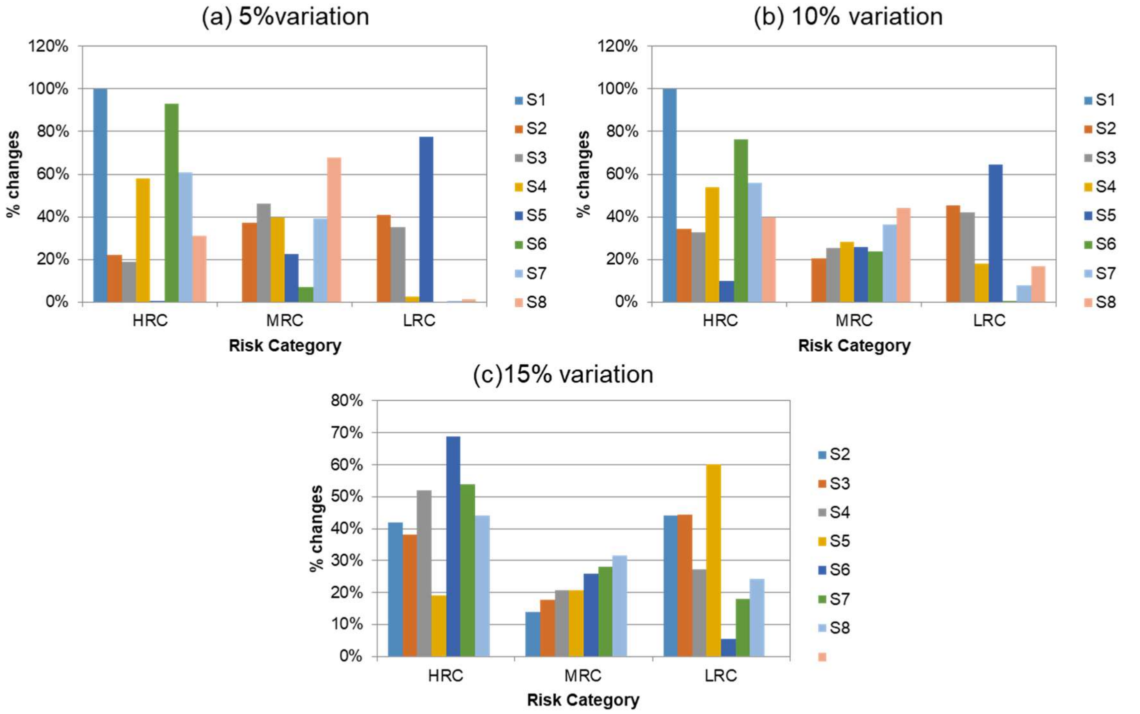

Figure 2: Increase and decrease of the risk categories of the sections for a 5%, 10% and 15% variation of the HRF

A second aspect of sensitivity explores the increase and decrease in terms of risk category. For a 5% variation (Figure 2a), S2, originally categorized in the MRC varies 22% of the time to the HRC, 27% to the MRC, and 41% to the LRC. S1, S4, S6 and S7 are allocated to the HRC with significant values of variation. As to the percentage increases for 10% (Figure 2b) and 15% (Figure 2c), more sections are allocated to the HRC. This visualization helps the DM understand the variability of the sections through categories, thereby identifying increases and decreases in the level of risk. This type of information provides enough evidence to plan mitigation for imminent threats.

4. Conclusions

This work presents an analysis of assessing risk and managing risk categories from the point of view of sensitivity. The sensitivity of the categorization of the NGP sections is evaluated by varying the Heat Radiation Flow (HRF) parameters, thus showing that these change the categorization of the sections. Three conditions were evaluated for this case, namely a 5%, 10% and 15% variation in the HRF using a triangular distribution for the Monte Carlo simulation.

As a first analysis of the study, the group of HRF parameters in the three variations values (5%, 10%, 15%) is evaluated in view of the variability of the categories, generating information on the sensitivity measures of the categories. Sections are evaluated according to how stable they remain in their original category. In this case, 3 sections demonstrate significant modifications in their original category due to variations in the level of the HRF. This information is demonstrated in a line chart. A second perspective of the sensitivity shows the increase and decrease of the risk category. This visualization complements the information of the first visualization, informing how the risk category of the sections behaves according to the uncertainty of the group of HRF parameters. For a 5% variation, 4 sections are found to remain in the High Risk Category, which calls for critical attention for planning mitigations. This visualization shows the DM a quick identification of which sections are expected according to each risk category. In this case, the expected sections in the higher risk classes should be prioritized in mitigation planning. The results show that risk categorizations for NGP sections can be better analyzed based on the sensitivity visualization approach. Thus, it has been shown that with the support of procedures that access the uncertainty of multidimensional risk assessment models, mitigation policies can be set out and indorse a rational use of resources, safety for everyone involved in the natural gas pipeline system, and thus avoid losses in terms of people, the environment and the company.

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