Journal of Loss Prevention in the Process Industries 45 (2017) 116–132

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Measuring the benefit of investing in pipeline safety using fuzzy risk assessment

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A R T I C L E I N F O

Article history:
Received 1 April 2016
Received in revised form
8 November 2016
Accepted 30 November 2016
Available online 3 December 2016

Keywords:
Pipeline safety
Risk assessment
Fuzzy logic
Sustainability
Risk management

A B S T R A C T

This study introduces a framework to evaluate the benefits of investing in safety measures for pipelines using fuzzy logic as a tool to deal with uncertainty. Using the possibility theory of fuzzy logic, this paper provides a way to determine the surplus between the amount of risk mitigated and the costs of the activities associated with such mitigation. The framework thereby allows pipeline operators to determine whether the costs associated with these risk management activities are reasonable or not despite the common degree of uncertainty of the data derived from the lack of information or subjective judgment. The proposed model considers variables such as threat and consequence scenarios, probability of adverse events, vulnerability, failure modes, percentages of risk reduction and mitigation costs. Furthermore, this framework is developed using the fuzzy inference system toolbox of MATLAB, employing specifically the Mamdani algorithm with a triangular membership function. To illustrate the relevance of the assessment of the value-added by safety management, this paper presents an application case from the oil and gas network of Colombia. The results of this case show that although the general trend of the net value for the safety activities is positive, there are some areas in which the investment in safety is significantly less cost effective. The data indicates that for a length corresponding to the 29% of the pipeline, the costs of the safety measures are bigger than the risk mitigated. Also, the results show that it is possible to estimate an investment ratio for safety measures, which for the application case is 5.41% with a net benefit of 50 million of dollars in risk reduction.

1. Introduction

Over the last three decades, as the worlds energy consumption has increased due to processes of social and technological development for manufacture, transportation, water services, and agriculture (Valipour, 2012b, 2015; Yannopoulos et al., 2015; Mahdizadeh Khasraghi et al., 2015), the number of serious accidents related to the failure of energy infrastructure has significantly risen, and most of them have had a large impact on people and the environment. Those serious accidents have increased the public awareness about the risk of failure of certain energy infrastructure and the concern about the level of risk acceptable to governments, regulatory bodies and operators. According to Vanem et al. (2008), the accidents have also had a strong influence on engineering standards and safety legislation, which are often updated in reaction to the serious accidents.

According to the database of The International Energy Agency (2008), fossil energy sources such as oil and natural gas represent 62% of the total world energy supply. Throughout the worlds Oil & Gas supply chain, pipelines represent the most important asset used from the production to the distribution stage, with more than 1.9 million kilometers of pipelines in place worldwide (CIA World Factbook, 2008).

Although the steel pipelines are considered as the safest and most cost-effective way of transporting hazardous substances (Markowski and Mannan, 2009), in case of a failure, there is a high potential of adverse consequences. These consequences are commonly related to public health deterioration, environmental damage and heavy financial liabilities. Therefore, this harmful potential is the primary concern of the Oil and Gas operators, governance agencies, consumers and other stakeholders (Shahriar et al., 2012).

According to the databases of The European Gas Pipeline Incident Data Group EGIG (2015) and The US Department of Transportation DOT (2015), incidents with pipelines have been

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http://dx.doi.org/10.1016/j.jlp.2016.11.018

decreasing and stabilizing overall. However, the consequences caused by pipeline failures remain severe in terms of affecting people, environment and property. In the United States, for example, about 5672 significant incidents in pipelines occurred from 1995 to 2015; these incidents caused 347 fatalities, 7.5 billion dollars in property damage and the release of more than 2.3 million barrels of product into the environment (The US Department of Transportation DOT, 2015). In the last decade, due to public concern about these recurring incidents in pipelines, there has been a rapid increase in the number of guidelines and regulations related to the investment in safety measures. Canada, the United States, England and Australia have adopted regulation that mandates investment in safety measures in pipelines.

The risk of failure in pipelines cannot be totally eliminated. Therefore a risk assessment strategy may help to define measures aimed to decrease the risk to mandatory levels by means of identification of the threats, combination of probabilities and consequences of failure, and evaluation of failure risk according to tolerability criteria. There is no universal way to assess risk, but existing risk assessment techniques provide an indirect way to estimate the probability of failure; such an estimate, however, is subject to the accuracy of the data input into the assessment model (Singh, 2013).

Decreasing the risk of failure in pipelines involves a substantial operational expenditure. That is why it is necessary to evaluate the effectiveness of the safety measures applied. However, most of the decision frameworks related to the implementation of safety measures are based on screening processes under a considerable amount of uncertainty, which is commonly derived from subjective judgment or lack of information. Since the purpose of the risk screening is to prioritize activities according to mandatory or acceptable risk levels, the risk indexes cannot be used for cost benefit analysis. In addition, as Stewart (2010) argues, the main argument, which is still unresolved, concerns the quantification of the probability of failure, the risk reduction and the cost of mitigating measures to predict expected losses or benefits.

Considering the risk and safety concerns described above, studies and procedures related to the implementation of pipeline integrity have been issued in order to prevent accidental releases (API 1160, 2013; ASME B31.8.S, 2002; DNV F116, 2009) and explore the effectiveness of safety management frameworks (Pasman et al., 2009; DeWolf, 2003; Roughton and Buchalter, 1997). The results highlight the risk assessment as the core management process in making decisions and suggest that effective implementation of risk assessment frameworks requires quantifiable safety performance indicators to incorporate the influence of mitigation costs. Hence, the main limitation of the safety frameworks is related to the absence of the benefit evaluation in quantifiable terms. Studies on benefit analysis for critical infrastructure (Hochrainer-Stigler et al., 2011; Stewart, 2010; Boardman et al., 2006; Gavious et al., 2009; Vanem et al., 2008) present empirical methodologies to determine the cost effectiveness of safety measures. However, these studies miss to address of the uncertainty derived from the risk estimation.

In response to the limitations and current gaps in the aforementioned studies on the implementation of integrity and benefit analysis for pipelines, this paper aims to introduce a benefit measurement framework that applies a model of fuzzy risk assessment to deal efficiently with uncertainty and then estimate the value of investing in safety measures. By introducing a novel technique combining cost-benefit analysis for pipelines and fuzzy inference, this paper aims to justify the expenditure in safety as an investment with quantifiable returns and to enhance the value of energy companies by allowing them to realize the expectation of their stakeholders regarding safety management.

2. Research methodology

The methodology employed by this research consists of a hybrid technique of empirical research which uses qualitative research methods and quantitative analysis. This hybrid technique was employed to resolve the following question: How can pipeline operators evaluate the benefit of investment in measures aimed to diminish the risk of failure in pipelines, such as the activities of replacement, maintenance, inspection or decommissioning, in quantitative terms of risk mitigation?

While the qualitative research methods were employed to induce an empirical model to determine the net value of investing in pipeline safety, the quantitative methods were employed to simulate and test the model developed. A method of systematic review was employed to explore novel techniques in the fields of safety management, pipeline integrity, risk management and cost benefit analysis. The systematic review method investigated only publications during the last two decades made in the top journals of the fields mentioned above.

Subsequently, an application case was implemented to test how the model developed might be coherently applied using real data. The methodology employed for this case was based on a roadmap for theory creation from Eisenhardt (1989) case researches, which mainly comprise four stages: case selection, data gathering, data analysis and results evaluation., which mainly comprises four stages: case selection, data gathering, data analysis, and results evaluation.

The case selection followed generalizability criteria to make this study broadly applicable among steel pipelines employed for transportation of hazardous substances. A further description of the pipeline selected is given in section 5 of this paper.

Data gathering took place during the five-month period from January to June of 2014 via a questionnaire and a field collection activity. The collection activity involved personnel from the safety division and from the planning and budgeting division of the pipeline company. In total, a team of seven professionals supported the data gathering of the case.

Lastly, the data and results evaluation employed quantitative analysis using the fuzzy inference toolbox of MATLAB. This toolbox was employed due to its efficient ability to combine deterministic values and human reasoning. Among the successful applications of this software are the modelling of risk and stochastic processes (Markowski and Mannan, 2009; Jamshidi et al., 2013; Valipour, 2016; Valipour et al., 2013), and the simulation of fluids using complementary aids (Valipour et al., 2015; Valipour, 2012b, a).

3. Theoretical framework

The theoretical framework of this paper aims to examine mainly novel techniques of cost benefit analysis for safety measures in critical infrastructure as well as novel techniques for pipeline risk assessment. As an attempt to deal with the uncertainty of the risk assessment process, the theoretical framework also examines the fuzzy sets theory proposed by Zadeh (1965) and the modelling for fuzzy inference systems.

Across the theoretical framework, this paper delineates the current gap in the studies on pipeline safety and benefit analysis using risk data. Therefore, this section aims to discuss the relation between this study and the literature in general by reviewing three main topics: safety management of pipelines, risk-cost benefit analysis, and fuzzy logic and fuzzy inference process.

3.1. Safety management of pipelines

3.1.1. Safety and risk management approaches

As previously mentioned, due to public concern about pipeline