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Comprehensive risk evaluation of long-distance oil and gas transportation pipelines using a fuzzy Petri net model

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ABSTRACT

Pipeline transportation is a safe and reliable way for transporting dangerous and flammable substances, such as oil and gas. In the process of transportation, third-party damage, corrosion destruction, design flaws, misuse of factors and other risk factors can also cause leakage or rupture of pipelines, which has a serious influence on social security and environment. In this paper, a comprehensive risk evaluation method based on a fuzzy Petri net (FPN) model for long-distance oil and gas transportation pipelines is proposed. In the process of the fuzzy reasoning, to tackle the impact of subjective factors and objective factors, the related parameters are optimized. In terms of risk factors weights, the combination weighting method is proposed, which combines AHP model and EM model. To reflect the fuzziness and randomness of risk factors, apply the cloud model to calculate the initial degrees of membership of the risk factors under the different risk grades. Furthermore, the risk evaluation values can be modified via the credibility. It is verified that the risk evaluation method based on the FPN model applies for the long-distance oil and gas transportation pipelines and provides some decision support for the risk management of the oil and gas pipelines.

1. Introduction

As a key link in the process of oil and gas transportation, long-distance pipelines have formed a national backbone network of connecting the east and west, the north and south, and overseas (Brito and Almeida, 2009). However, in the process of oil and gas pipelines operation, due to suffering corrosion damage, natural hazard, third-party damage, material defects and so on, moreover, the substances in the pipeline are flammable and dangerous, once pipelines accidents occur, they will cause heavy national security and economic even public health, safety and environmental pollution (Jamshidi et al., 2013; Han and Weng, 2011). Although pipelines failures can never be completely avoided, an appropriate and accurate risk evaluation method can contribute to offering reasonable and effective risk management measures to reduce the overall risk of failure.

Fault tree analysis (FTA) is a commonly logical and graphical description of various combinations of failure events to evaluate the probability of an undesired accident in all aspects (Rao et al., 2009). In conventional FTA, the probability of failure of the basic event must be known and considered as an accurate value. However, accurately, the probabilities of failure of most of basic events are imprecise, deficient or vague (Khakzad et al., 2011). To solve these difficulties and limitations in conventional FTA, a large number of researches have been conducted. For example, Kim et al. (Kim et al., 1996) have employed *L-R* type fuzzy numbers as the possibilities of the basic events and the value *m* as a triangular fuzzy number to overcome the weak point of conventional FTA. Dong Yuhua et al. (Dong and Yu, 2005) have combined expert elicitation and theory of fuzzy set to evaluate failure probability of basic events of oil and gas transmission pipelines due to insufficient data or vague characteristic of the events. Shahriar et al. (Shahriar et al., 2012) have employed fuzzy logic to derive fuzzy probabilities of basic events in FTA to estimate fuzzy probabilities of output event consequences. Lavasani et al. (Lavasani et al., 2015) have proposed fuzzy theory to solve the problem of lack of data for calculating the probabilities of failure of components in the drilling

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industry. Further, considering the combustibility and the difficulties in detecting leakage, Lu Linlin et al. (Lu et al., 2015) have combined a risk matrix with a bow-tie model to evaluate a natural gas pipeline, and so on.

Analyzing the above-mentioned methods, because the conventional FTA method has some shortcomings, several researches have been proposed to optimize the FTA method. However, due to lack of effective means of mathematical expression, FTA can't conduct further quantitative analysis automatically and find the weak links of the system precisely, describe the propagation of fault and represent the characteristics of the system before and after improvement (Nguyen et al., 2015). In recent years, a new fault analysis model named Petri net is presented, which is a kind of mathematical and graphical modeling tool. With the researches of some scholars, the Petri net model has gotten some extension and can combine with the fuzzy logic to further risk evaluation (Wu et al., 2010; Bharathi et al., 2013; Németh et al., 2009). To systematically study the relationship between scattered risk factors and overall risk of power coal supply chain system, Guo et al. (Guo et al., 2010) have proposed a risk element transmission Petri net (RPN) model to analyze and control the risk elements' transmission and influence on the entire power coal supply chain. Bharathi et al. (Bharathi et al., 2012) have used the FPN model to evaluate the risk of failure in small and medium enterprises. Chen et al. (Chen et al., 2014a,b) have proposed a rule-based decision-making method, fuzzy Petri nets, to evaluate the degree of stenosis in routine examination. Li et al. (Li and Lara-Rosano, 2000) have presented adaptive fuzzy Petri net, which could not only implement knowledge inference, but also have a learning ability like a neural network. To solve large-scale and complex railway traffic control problems in case of disturbance, Cheng et al. (Cheng and Yang, 2009) have applied the FPN model to analyze the railway traffic control. Wu et al. (Wu et al., 2011) have combined fault tree analysis with fuzzy reasoning Petri net to address the impact of solar array anomalies for solar array reliability. Milinković et al. (Milinković et al., 2013) have proposed a FPN model to estimate train delays for more accurate timetable.

Due to the uncertain, vague and random characteristics of risk factors of oil and gas pipelines, the FPN model can more conform to human thinking and cognitive style and has a good parallel processing capability, thus, in this study, the FPN model combined with fuzzy reasoning algorithm for the risk evaluation of long-distance oil and gas transportation pipelines is proposed. Meanwhile, the analytic hierarchy process (AHP), entropy method (EM), and cloud model are adopted to improve the evaluation accuracy. And the organization of this paper is as follows. The risk evaluation index system of a long-distance oil and gas transportation pipeline is established in Section 2. In Section 3, the FPN model to simulate the risk factors of the long-distance oil and gas transportation pipeline is represented and the evaluation process is introduced in detail. Then, a practical case is studied by using the proposed method in Section 4. Conclusions are provided in the final Section.

2. Risk evaluation index system of oil and gas pipelines

Since long-distance oil and gas transportation pipelines suffer all kinds of destructions during runtime, it is unavoidable to have accidents. An accurate and effective risk evaluation method can not only help us know the safety status of the pipeline real-timely, but also help us take effective measures in time to reduce accident loss to the greatest extent when the accident happens. According to the collected information and the handbook of 'Pipeline Risk Management Manual', the main risk factors of a long-distance oil and gas pipeline include the following four factors: the third party damage, misuse of factors, corrosion damage and design flaws. And each risk factor also contains several sub-factors. The risk evaluation index system is established in Fig. 1, which can be seen that the risk evaluation index system of a long-distance oil and gas transportation pipeline is divided into three layers. The left-most level is the first-level index, which the purpose is to obtain the risk evaluation value and risk grade of the system. The middle level is the second-level indexes and the right-most level is the third-level indexes.

Moreover, according to the risk evaluation index system, the risk evaluation grade can be presented as follows:

$$\mathbf{Q} = (2, 4, 6, 8, 10) \tag{1}$$

where (0–2) indicates the risk grade is "low"; (2–4) indicates the risk grade is "relatively low"; (4–6) indicates the risk grade is "medium"; (6–8) indicates the risk grade is "relatively high"; (8–10) indicates the risk grade is "high".

3. The fuzzy Petri net evaluation model and evaluation process

3.1. Definition of the fuzzy Petri net

A fuzzy Petri net, which consists of a Petri net and the fuzzy logic, is formally defined as a 9-tuple set (Bharathi et al., 2012, 2013; Chen et al., 2014a,b; Li and Lara-Rosano, 2000; Cheng and Yang, 2009):

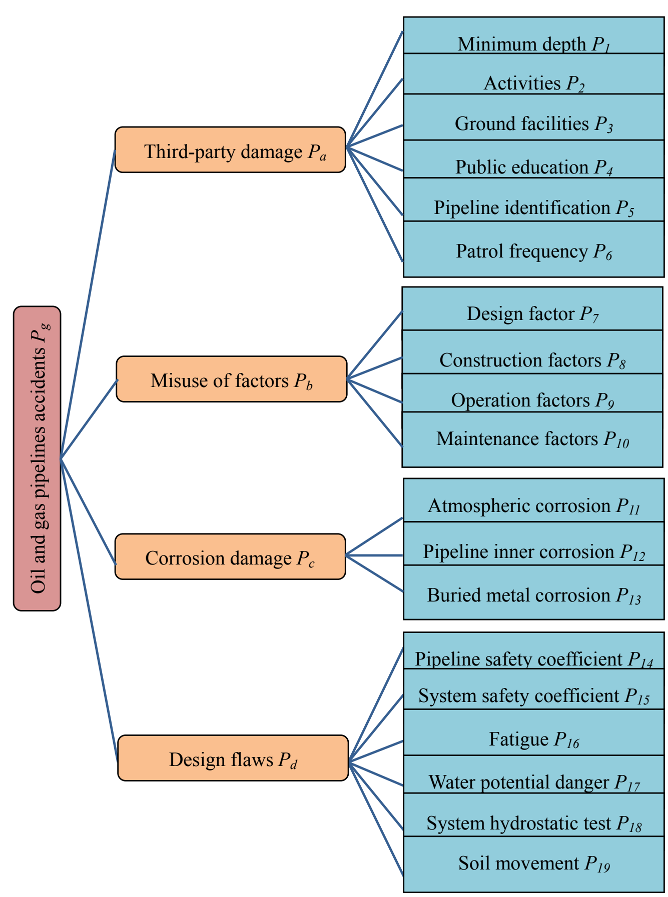

Fig. 1. Risk evaluation index system of a oil and gas pipeline.