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*Original Paper*

# Risk Evaluation and Software Development of Urban Natural Gas Pipelines Based on Bayesian Networks

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***Abstract***

*Based on the urban natural gas pipeline accident statistics and semi-quantitative risk evaluation index system, this paper applies Bayesian network to establish a network model between various types of risk factors and the risk of natural gas pipeline failure. The EM algorithm was used to learn from the statistical accident data to obtain the parameters of the model. Based on the principle of evidential reasoning in reverse, the probability of occurrence of all risk indicators can be obtained when the probability of occurrence of urban natural gas pipeline accidents is 100%, the index weight is obtained by normalizing the occurrence probability. On this basis, this paper develops an efficient urban natural gas pipeline integrity risk identification and management software. The software can realize the basic data management of urban natural gas pipeline system, pipeline relative risk value calculation, pipeline risk level calculation and other functions, and the results are visualized. Finally, the practicability and effectiveness of the model and software are verified by a case of natural gas pipeline evaluation in a block.*

***Keywords***

*Bayesian network, Risk indicators, software developments*

## 1. Introduction

The urban gas pipeline is an important part of the current urban infrastructure. In the process of use, it may cause leakage and even explosion due to risk factors such as corrosion, construction quality problems, and third-party damage [1]. Its safety is directly related to the safety of urban residents and the stability of urban operation. Effective risk assessment of natural gas pipelines helps to identify and mitigate potential risks in a timely manner, thereby minimizing the significant losses caused by pipeline leakage or explosion to people and society.

In recent years, the risk assessment methods for natural gas pipelines have been continuously optimized, which not only combines the knowledge of mathematics and project management, but also introduces more calculation models and intelligent algorithms [2-3]. Badida P et al. [4] used fuzzy fault tree analysis method combined with expert consultation method to analyze the probability of natural gas pipeline failure. Lu D et al.[5] proposed a new quantitative risk assessment model to guide the excavation inspection and maintenance decision of long-distance pipelines. LI Xinhong et al. [6] proposed a failure risk assessment method based on fuzzy DEMATEL method to effectively identify the complex relationship between the causes of aging faults of urban oil and gas pipelines.

As a tool for reasoning under uncertainty, Bayesian network method is widely used to evaluate uncertainty, causality and interaction between variables in complex systems [7-12]. However, the traditional Bayesian network model construction and parameter calculation usually have strong subjectivity [13]. Lawrence J M et al. [14] constructed a causal Bayesian model to reveal the relationship between risk factors. Yang Y et al. [15] proposed a data-driven model based on graph embedding and clustering algorithm, which greatly repaired the defects of strong subjectivity in Bayesian decision-making process, and verified the accuracy of the model for pipeline accident assessment through actual cases. Cui Y et al. [16] established a third-party damage Bayesian network model and a malicious intrusion game theory model to study the failure mechanism of oil and gas pipelines.

In view of this, based on the statistical data of urban natural gas pipeline accidents and the semi-quantitative risk evaluation index system, the risk index model of urban natural gas pipeline is established by Bayesian network method. The EM algorithm in Genie software is used to learn the parameters of statistical accident data. According to the principle of evidence reasoning, the probability of occurrence of risk factors is inversely deduced when the probability of urban natural gas pipeline accidents is 100 %, so as to obtain the index weight. At the same time, this paper uses the Windows system platform and .NET technology to develop an efficient identification and management software for the integrity risk of urban natural gas pipelines. Based on the calculated weights of the indicators, applying the semi-quantitative risk evaluation method, it can realize the functions of pipeline basic data management of urban natural gas pipeline network, calculation of pipeline relative risk value, etc., and display the results visually, which can provide important guidance and support for assessing the integrity risk of urban natural gas pipelines.

## 2. Risk Assessment of Urban Natural Gas Pipeline Based on Bayesian Network

### *2.1 Bayesian Network Model Construction*

Based on the statistical data of urban natural gas pipeline accidents, and by utilizing a semi-quantitative risk assessment index system, this paper categorizes risk factors into two types: the failure possibility index and the failure consequence index. The former refers to direct risk factors that lead to pipeline accidents, while the latter identifies risk factors that could potentially cause more severe accidents, thus corresponding to the gain of failure possibility. This paper takes the construction of a Bayesian network model for urban natural gas pipeline failure possibility as a case study. The Bayesian network model for the likelihood of urban natural gas pipeline failure is shown in Figure 1. The root node represents the secondary risk indicators, the middle node represents the primary risk indicators, and the leaf nodes represent the probability of natural gas pipeline failure.

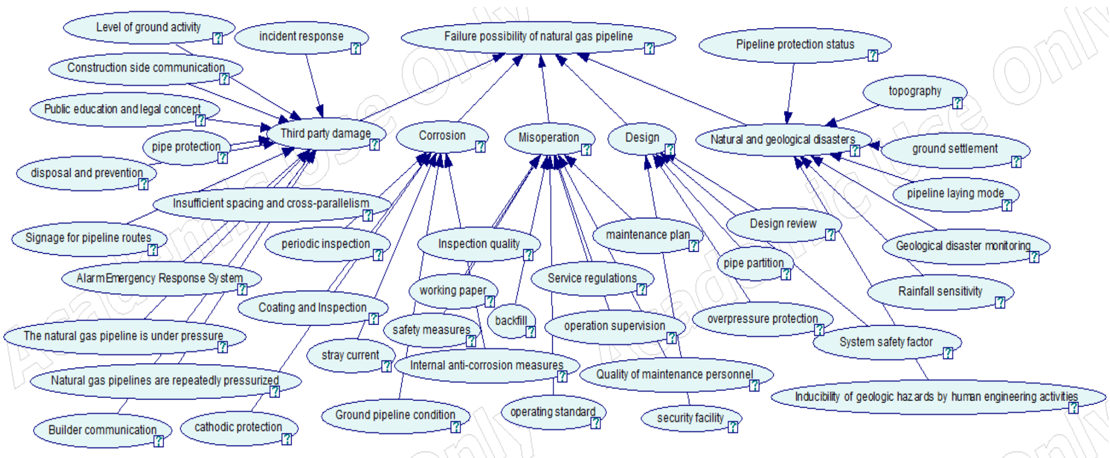



**Figure 1. Bayesian Network Model of Urban Natural Gas Pipeline Failure Possibility**

### *2.2 Parametric Computation*

In the Bayesian network method, the parameters are usually determined by expert experience. Different experts have different views on the same risk factor, resulting in inaccurate parameter values, which makes it difficult to effectively reflect the impact of risk factors on pipeline failure accidents. EM algorithm is an iterative algorithm, which is used to estimate the parameters in the probability model when there is missing data or hidden variables. In Bayesian networks, the EM algorithm can be used to estimate the probability distribution of variables that are not directly observed. Therefore, based on the statistical natural gas pipeline accident data, this paper uses the EM algorithm in Genie software to learn the statistical accident data to obtain the parameters.

Due to the excessive number of nodes in this article, only some statistical data are shown here, see Table 1. Node1 represents the possibility of failure of natural gas pipelines in leaf node cities, Node2 represents a third-party damage risk indicator, and Node3 represents corrosion, and so on. State0 means not occurring, and State1 means occurring. Each row represents whether or not each risk indicator occurred in different natural gas pipeline incidents.

**Table 1. Data Statistics Table**

| Node1 | Node2 | Node3 | Node4 | Node5 | Node6 | Node7 | … |
|---|---|---|---|---|---|---|---|
| state1 | state0 | state0 | state0 | state0 | state1 | state0 | … |
| state1 | state0 | state0 | state0 | state0 | state1 | state0 | … |
| state1 | state0 | state0 | state0 | state0 | state1 | state0 | … |
| state1 | state0 | state1 | state0 | state0 | state1 | state0 | … |
| state1 | state1 | state0 | state0 | state0 | state0 | state1 | … |
| state1 | state0 | state0 | state0 | state0 | state1 | state0 | … |
| state1 | state0 | state1 | state0 | state0 | state0 | state0 | |
| state1 | state1 | state0 | state0 | state0 | state0 | state0 | |
| … | … | … | … | … | … | … | |

*2.3 Bayesian Network Diagnosis*

Based on Genie software, the inference results of Bayesian network model in this paper are calculated. Reverse inference can obtain the probability of occurrence of each risk index when the probability of failure of urban natural gas pipeline is 100 %, so as to improve the prevention efficiency and reversely identify the key risk factors when natural gas pipeline accidents occur. The probability of occurrence of each root node obtained by reverse inference is normalized as the weight of the indicator. The normalization formula is shown in equation (1).

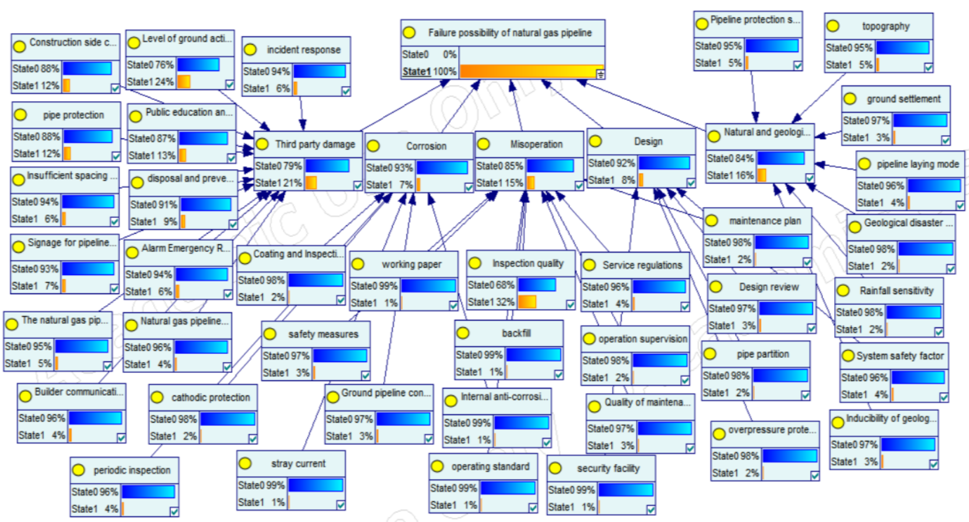



**Figure 2. Bayesian Reverse Reasoning**

$$q_i = \frac{V_i}{\sum_{i=6}^{45} V_i} \tag{1}$$

where: $q_i$ denotes the weight of node i; $v_i$ denotes the probability of node i occurring when the probability of urban gas pipeline failure is 100%. Note: i starts from 6 and indicates all secondary risk indicators.

The weights of the indicators of the likelihood of failure of urban gas pipeline risks are obtained, as shown in Table 2.

**Table 2. Risk Index Weight Table**

| Indicators | weight | Indicators | weight |
|---|---|---|---|
| Level of ground activity | 0.123 | maintenance plan | 0.011 |
| Construction side communication | 0.063 | operating standard | 0.007 |
| incident response | 0.032 | Service regulations | 0.021 |
| Public education and legal concept | 0.065 | operation supervision | 0.010 |
| pipe protection | 0.023 | Quality of maintenance personnel | 0.013 |
| disposal and prevention | 0.044 | working paper | 0.004 |
| Insufficient spacing and cross-parallelism | 0.033 | safety measures | 0.014 |
| Signage for pipeline routes | 0.034 | Design review | 0.016 |
| Alarm Emergency Response System | 0.032 | System safety factor | 0.019 |
| The natural gas pipeline is under pressure | 0.026 | security facility | 0.005 |
| Natural gas pipelines are repeatedly pressurized | 0.019 | overpressure protection | 0.009 |
| Builder communication | 0.022 | pipe partition | 0.009 |
| periodic inspection | 0.019 | Pipeline protection status | 0.023 |
| Coating and Inspection | 0.009 | topography | 0.023 |
| cathodic protection | 0.009 | ground settlement | 0.014 |
| stray current | 0.005 | pipeline laying mode | 0.021 |
| Internal anti-corrosion measures | 0.005 | Inducibility of geologic hazards by human engineering activities | 0.014 |
| Ground pipeline condition | 0.017 | Geological disaster monitoring | 0.009 |
| Inspection quality | 0.165 | Rainfall sensitivity | 0.009 |
| backfill | 0.006 | | |

## 3. The Efficient Identification and Management Software of Urban Natural Gas Pipeline Integrity Risk

### *3.1 Software Implementation Method*

Based on the above calculated weights of the indicators, combined with the semi-quantitative risk assessment methodology, the pipeline risk value and risk level can be calculated. In this paper, the efficient identification and management software of urban natural gas pipeline integrity risk is developed by using Windows system platform and .NET technology. The software has built-in related calculation functions and index weights, and can carry out risk assessment by inputting pipeline related data. The software covers the basic data management subsystem of urban natural gas pipeline network, the identification subsystem of easy failure unit, the calculation subsystem of relative risk value of pipeline network and the subsystem of risk assessment grade division. It includes 10 functional modules in 4 categories, which can realize the result switching display of 'steel pipeline' and 'polyethylene pipeline'. The design block diagram of the software is shown in Figure 3.

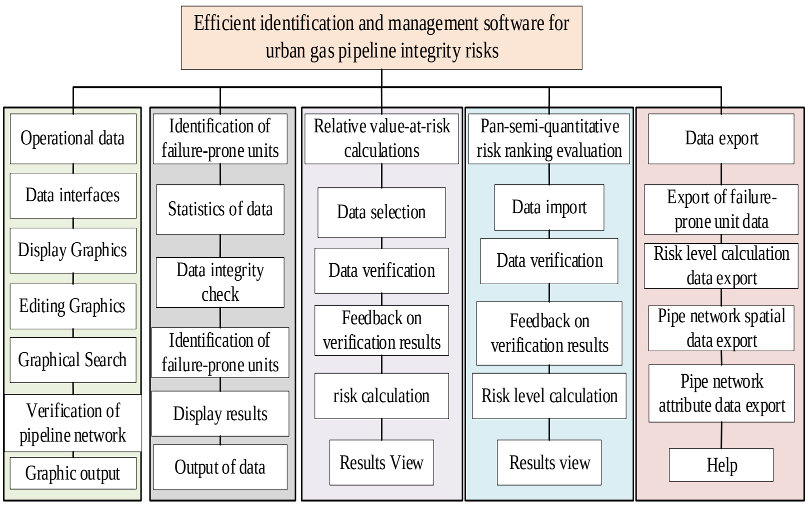



**Figure 3. Software Design Block Diagram**

Entering the main interface of the software, by importing the geographic information data of Pipeline Network, the software constructs a pipeline network topology that can fully describe the actual status of the natural gas pipeline network according to the spatial coordinates of the valve wells, flanges, valves, gate stations, regulating stations and pipeline intersection and connections, which can realize the visual display of the whole pipeline network system. Then, the pipeline failure factor status information is imported, and the corresponding calculation module is clicked. The software will perform risk assessment on the pipeline based on the risk index weight obtained by the Bayesian network and the semi-quantitative risk assessment method, including pipeline risk value calculation and risk level assessment. The software program flow is shown in Figure 4.

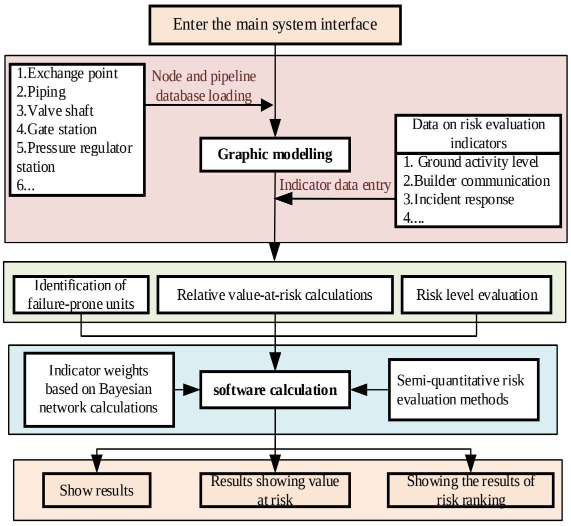



**Figure 4. Software Program Flow Chart**

*3.2 System Interfacing*

The software can realize the data interaction with EXCEL and other data statistical systems, developing corresponding data interfaces to realize the batch import of urban natural gas pipeline network topology data and pipeline property data.

*3.3 Introduction of Software Interface*

The main interface consists of three parts: the menu area, the layer example area, and the map display area. The main interface of the system is shown in Figure 5, with the menu area on the top, the layer example area on the left, and the map display area on the right.

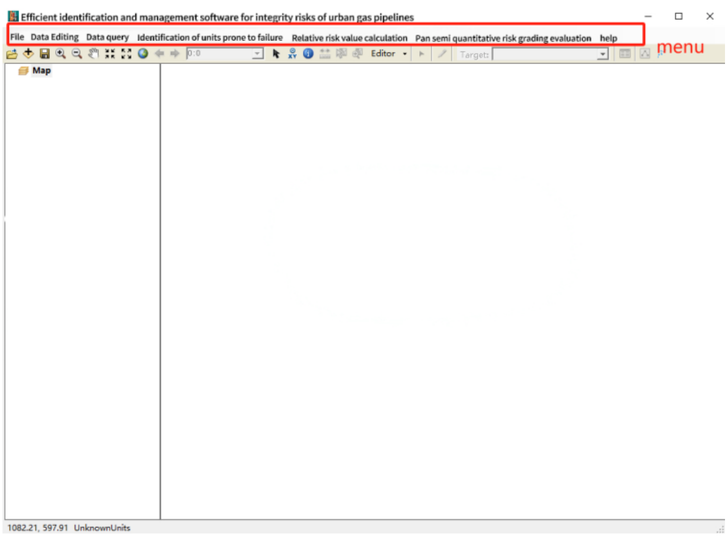



**Figure 5. System Main Interface**

## 4. Application of Examples

The risk assessment of natural gas pipeline in a certain block is carried out by using the developed urban natural gas pipeline integrity risk efficient identification and management software. These pipelines pass through a number of densely populated areas including residential areas and factories. In addition, the block also has other common problems of engineering construction and unclear pipeline ground identification. Based on the data interface with the GIS system, the natural gas pipeline network data of the block is batch imported into the software, including the corresponding geographic information data of each pipeline and the failure factor status information, which builds the pipe network topology of the current status of the actual natural gas pipeline network in the block, and realizes the visualization of the whole pipeline network system as shown in Figure 6.

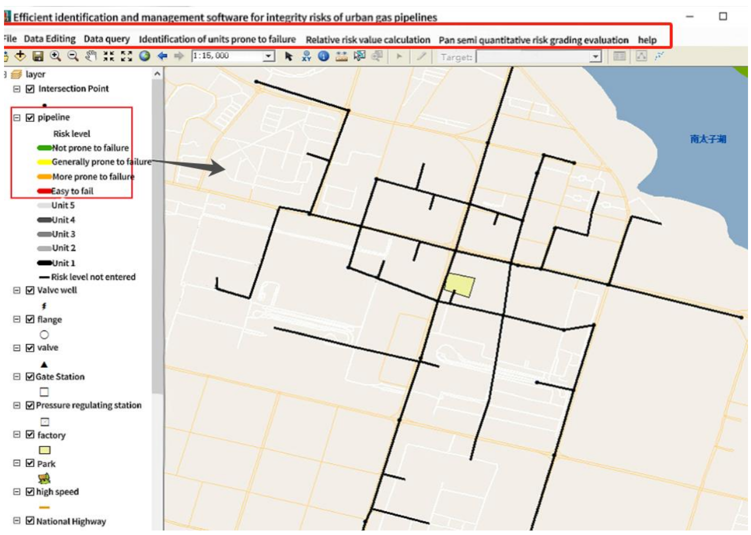
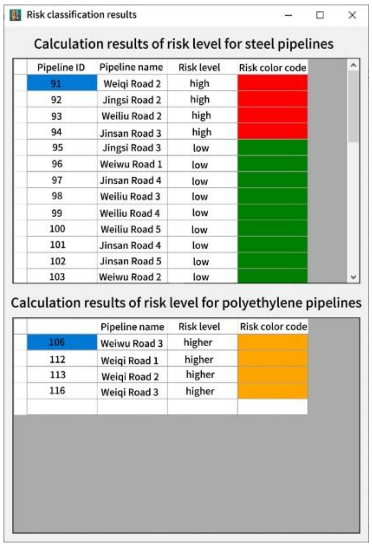



**Figure 6. Visualization of the Pipe Network System**

The risk level of each pipeline is calculated by the software, and the detailed calculation results are shown in Figure 7. Meanwhile, the risk level of the pipeline will be updated and displayed on the map according to the risk color scale, which is detailed in Figure 8.



Risk classification results

Calculation results of risk level for steel pipelines

| Pipeline ID | Pipeline name | Risk level | Risk color code |
|---|---|---|---|
| 91 | Weiqi Road 2 | high | |
| 92 | Jingsi Road 2 | high | |
| 93 | Weiliu Road 2 | high | |
| 94 | Jinsan Road 3 | high | |
| 95 | Jingsi Road 3 | low | |
| 96 | Weiwu Road 1 | low | |
| 97 | Jinsan Road 4 | low | |
| 98 | Weiliu Road 3 | low | |
| 99 | Weiliu Road 4 | low | |
| 100 | Weiliu Road 5 | low | |
| 101 | Jinsan Road 4 | low | |
| 102 | Jinsan Road 5 | low | |
| 103 | Weiwu Road 2 | low | |

Calculation results of risk level for polyethylene pipelines

| | Pipeline name | Risk level | Risk color code |
|---|---|---|---|
| 106 | Weiwu Road 3 | higher | |
| 112 | Weiqi Road 1 | higher | |
| 113 | Weiqi Road 2 | higher | |
| 116 | Weiqi Road 3 | higher | |

**Figure 7. Risk Level Evaluation Results**


**Figure 8. Risk Classification Results Shown on the Map**

Combined with the analysis of the calculation results, it can be seen that four steel pipelines in the block are in a high-risk state, and the polyethylene pipelines are all in a higher risk, so it is necessary to take corresponding measures in time. This result is consistent with the actual situation, thus verifying the rationality of the calculation of indicator weights and the practicality of the software application.

## 5. Conclusion

In this paper, a risk assessment model of urban natural gas pipeline is established based on Bayesian network method. The EM algorithm in Genie software is used to learn the parameters of statistical accident data. According to the principle of evidential reasoning, the probability of risk factors is deduced when the probability of urban natural gas pipeline accident is 100%, so as to obtain the index weight. Based on this, this paper develops an efficient identification and management software for urban natural gas pipeline integrity risk with the help of Windows system platform and .NET technology. By inputting the relevant attribute data of each pipeline section, the software constructs the topological structure graph of the urban natural gas pipeline network in the jurisdiction area, and can calculate the risk value and risk level of each pipeline section in the pipeline network, and visualize the results. It provides guidance and support for the integrity risk identification of urban natural gas pipelines, and then guides the operation and management of natural gas pipelines. Finally, this paper uses the software to evaluate the risk of a natural gas pipeline in a certain block, and verifies the feasibility and practicability of the method and software.

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