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Reliability Analysis of Hydraulic System of Tunnel Erecting Machine Based on Dynamic Fault Tree and Bayesian Network †

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Abstract: Prefabricated utility tunnel plays an important role in the modern urban infrastructure construction. However, the weight of prefabricated utility tunnel segment is heavy and the hoisting conditions are complicated, which puts forward higher requirements on the reliability of the main equipments for the erection and paving of the utility tunnel, especially the hydraulic system of the tunnel erecting machine. Therefore, the reliability analysis of the hydraulic system of the tunnel erecting machine is carried out in this paper. Firstly, the working principle of the tunnel erecting machine and hydraulic system is analyzed, and the Takagi-Sugeno (T-S) dynamic fault tree model is constructed by using the T-S dynamic fault tree analysis method, and it is transformed into a Bayesian Network (BN) model. Secondly, according to the failure probability of the root node, combined with the BN Conditional Probability Table (CPT), the failure probability of the leaf nodes of the hydraulic system of the tunnel erecting machine in each time period and task time is forwardly inferred. Then, through the quantitative analysis of the sensitivity parameters in the BN analysis method, the importance of the components in the system can be reflected. Finally, the posterior probability of the root node of hydraulic system fails is calculated through the reverse reasoning of the BN analysis method, and the sensitive components of the system are found. The results show that the proposed method can find out the main reasons that affect the hydraulic system of the tunnel erecting machine, and provide reference for the safe operation of the equipment and system maintenance.

Keywords: tunnel erecting machine; dynamic fault tree; Bayesian network; hydraulic system; reliability analysis

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1. Introduction

The utility tunnel is a modern, intensive and scientific urban infrastructure that integrates various underground pipelines such as heating, water supply and drainage, communication, etc. It is also equipped with intelligent detection, alarm and monitoring systems [1–3]. The prefabricated utility tunnel is a new construction method. Compared with the traditional cast-in-place type, it has the advantages of shortening the construction period, saving labor, and less environmental pollution. However, special equipment tunnel erecting machine are required for hoisting and laying during the installation process. The hydraulic system realizes the movement of the crane and the lifting of each outrigger during the working process of the tunnel erecting machine. In the actual working process, the failure of the hydraulic system seriously affects the working efficiency of the tunnel erecting machine. Therefore, it is of great significance to analyze the reliability of the hydraulic system of the tunnel erecting machine.

Dynamic Fault Tree Analysis (DFTA) and Bayesian Network (BN) are both basic methods for reliability analysis and fault diagnosis, and have been widely studied and applied [4,5]. In recent years, scholars have used DFTA and BN to analyze the reliability of construction machinery. Wu and Tao [6] made a dynamic analysis of the hydraulic system of the loader based on the Takagi-Sugeno (T-S) model, and used the probability importance to judge the impact of the bottom event on the system. Li et al. [7] used the BN transformed from fault tree to analyze the risk of well collapse accidents. Li et al. [8] used the T-S fuzzy fault tree to analyze the reliability of the hydraulic circuit of the outrigger of the truck crane. Wang et al. [9] analyzed the hydraulic system of shearer height adjustment based on the dynamic fault tree model, and obtained the subtree with the highest probability importance. Chen et al. [10] carried out reliability analysis on fully hydraulically driven construction machinery based on evidence theory and BN, and calculated the failure probability interval, root node importance and sensitivity interval of leaf nodes. In view of the problems of insufficient dynamic logic gates, inability to effectively express dynamic failure behaviors, and limitations of polymorphic systems in traditional fault tree, DUGAN dynamic fault tree, T-S fault tree and other analysis methods, Yao et al. [11] introduced the T-S fault tree analysis method in the paper. Based on the extension, a T-S dynamic fault tree analysis method is proposed. BN can not only describe the polymorphism between systems and the logical relationship of uncertainty between events, but also can carry out bidirectional reasoning [6]. Fault tree analysis has a good effect in analyzing the causes of accident failures, while BN has outstanding advantages in studying complex systems and expressing multimodal variables, and can accurately analyze and diagnose the causes of event failures.

In view of the complementarity of T-S dynamic fault tree and BN, this study uses a certain type of prefabricated gantry crane to analyze the reliability of the hydraulic system of the tunnel erecting machine based on the Dynamic Fault Tree Analysis and Bayesian Network (DFTA-BN) analysis method.

2. Working Principle of Hydraulic System of Tunnel Erecting Machine

The tunnel erecting machine is mainly composed of the main beam, front outriggers, middle outriggers, rear outriggers, electrical system, hydraulic system and crane, etc. The tunnel erecting machine is shown in Figure 1.

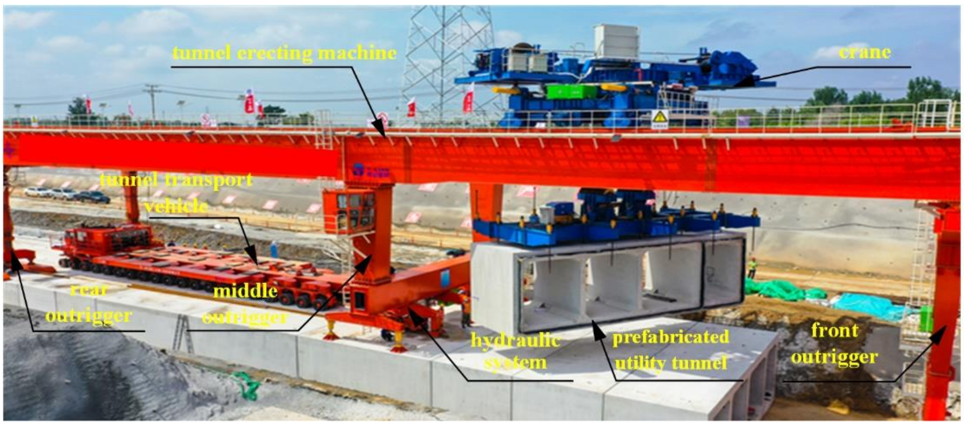
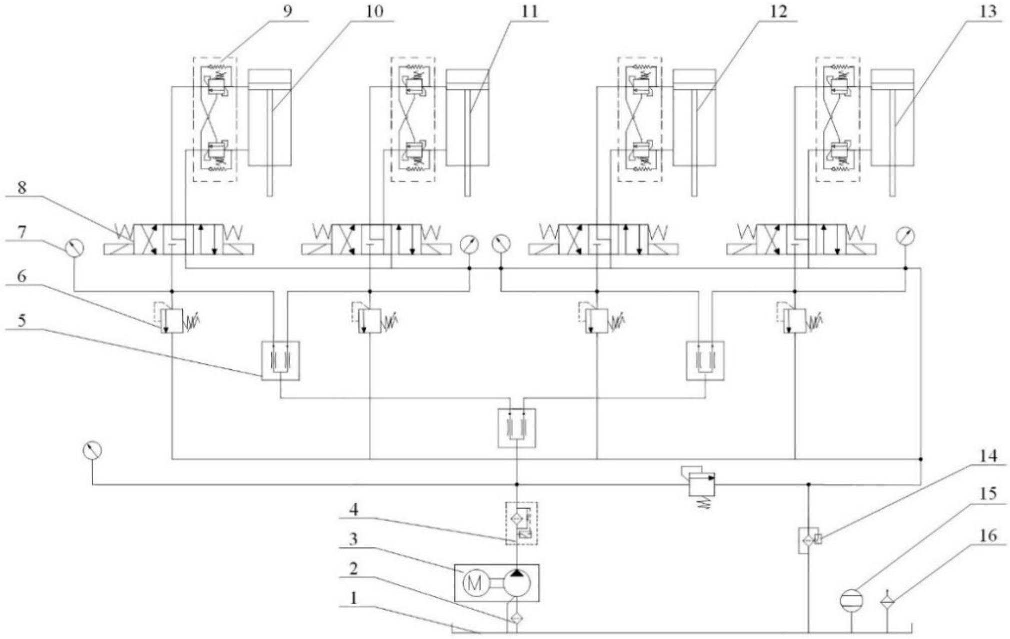


Figure 1. Tunnel erecting machine of prefabricated utility tunnel.

The working principle of the hydraulic system is shown in Figure 2. Under the action of the oil pump motor unit, the pressure oil is shunted by the two-stage shunt valve, and then flows to the crane traverse cylinder group, the front outrigger lifting cylinder group, the middle outrigger lifting cylinder group, and the rear outrigger lifting cylinder group through the electromagnetic reversing valve. The diverting and collecting valve is used in each cylinder group to ensure the same flow to each hydraulic cylinder, thus ensuring the synchronization of the expansion and contraction of each group of hydraulic cylinders and ensuring the smooth operation of the system. The relief valve unloading in the system can not only realize the constant pressure state of the system, but also ensure the safe operation of the system. The system has a single-action function to ensure that the system can achieve independent action when synchronization errors occur. The two-way balance valve can prevent the hydraulic cylinder from falling over speed and make it run smoothly, and it has good pressure-holding locking characteristics.



1 oil tank; 2 filter; 3 oil pump motor unit; 4 pressure oil filter; 5 diverter valve; 6 relief valve; 7 pressure gauge; 8 electromagnetic reversing valve; 9 balance valve; 10 crane hydraulic cylinder group; 11 Front outrigger hydraulic cylinder group; 12 Middle outrigger hydraulic cylinder group; 13 Rear outrigger hydraulic cylinder group; 14 Oil return filter; 15 Liquid level gauge; 16 Air filter

Figure 2. Principle diagram of hydraulic system.

3. Construction of DFTA-BN Model of Hydraulic System

3.1. DFTA Modeling of Hydraulic System

Taking the hydraulic system of the tunnel erecting machine as the research object, the established T-S dynamic fault tree model is shown in Figure 3. The intermediate events y1~y9 are the gallery crane hydraulic system failure, hydraulic pump source failure, hydraulic component failure, oil pump motor unit failure, filter failure, hydraulic actuator failure, hydraulic control valve failure, jacking cylinder failure, traverse cylinder failure. The dynamic gates of G1~G9 are all OR gates. The name and failure rate of the root node event are obtained by searching the data, as shown in Table 1.

Table 1. Basic event name and failure rate.

x_i	Basic Event Name	$\lambda_i(10^{-6}/\mathrm{h})$
x_1	Motor failure	6.8
x_2	Hydraulic pump failure	7.9
x_3	Auxiliary oil pump failure	7.9
x_4	Oil suction filter failure	0.8
x_5	Oil return filter failure	1.3
x_6	Fine filter failure	0.6
x_7	Insufficient fuel supply in the tank	1.3

x_8	The frictional resistance of the jacking cylinder is large	1.44
x_9	The back pressure of the return oil of the jacking cylinder is large	1.35
x_{10}	Large friction resistance of the traverse cylinder	1.44
x_{11}	The back pressure of the traverse cylinder is large	1.35
x_{12}	Diverter valve failure	10.5
x_{13}	Balance valve failure	10.5
x_{14}	Relief valve failure	11.7
x_{15}	Solenoid valve failure	12.0
x_{16}	Poor guide rail lubrication	10.4

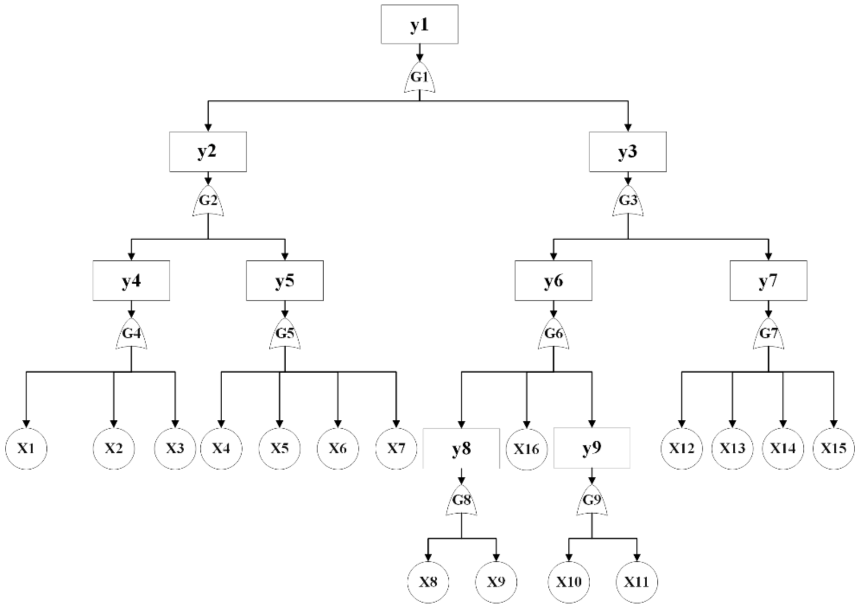


Figure 3. T-S dynamic fault tree.

3.2. BN Modeling of Hydraulic System

According to the transformation method given by the basic event in the T-S dynamic fault tree corresponding to the root node of BN, the intermediate event corresponding to the intermediate node, and the top event corresponding to the leaf node, the T-S dynamic fault tree is transformed into a BN directed acyclic graph, as shown in Figure 4, and the Conditional Probability Table (CPT) of the corresponding node of BN is obtained according to the T-S dynamic gate, and the root nodes y2, y3 represent the failure of the hydraulic pump source and the failure of hydraulic components are the main reasons for the failure of the hydraulic system of the gallery crane, so the CPT of node y1 is shown in Table 2.

Table 2. Conditional probability tables of y_1

.Serial Number	$\boldsymbol{y_2}$	$\boldsymbol{y_3}$	$\boldsymbol{P(y_1^{[j_{y1}]} = 1 \mid y_2, y_3)}$				
			1	**2**	**3**	**4**	**5**
1	1	1	1	0	0	0	0
2	1	2	1	0	0	0	0
3	1	3	1	0	0	0	0
…	…	…	…	…	…	…	…
25	5	5	0	0	0	0	1

According to the BN directed acyclic graph, it can be determined that the sub-node y1 and other sub-nodes have the same transformation process in CPT, and are not listed here.

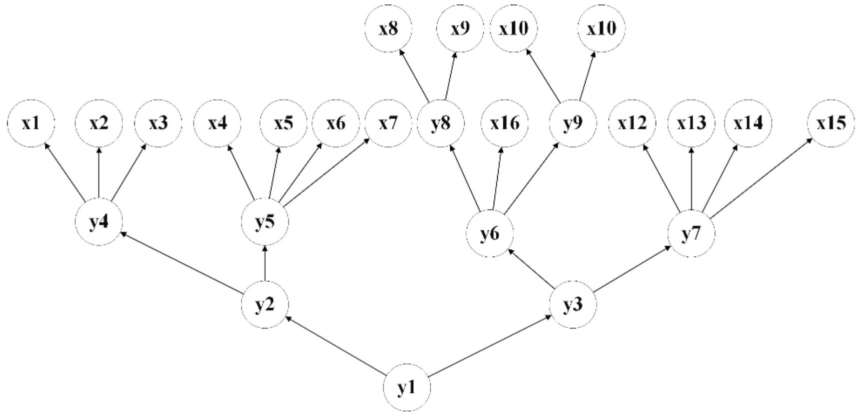


Figure 4. Directed acyclic graph.

4. Reliability Analysis of Hydraulic System Based on DFTA-BN

4.1. Node Failure Probability Reasoning

According to the forward inference algorithm of BN, the failure probability of the leaf node is calculated. The task time T_M = 10,000 h is discretized, and it is divided into m = 4 segments on average, and the interval between each segment is Δ = 2500. The time outside the task time is regarded as the fifth segment, and the fault state of the root node x_i in the time segment j_i is $x_i^{[j_i]}$, the failure probability $P(x_i^{[j_i]})$ is shown in formula (1):

$$F_i(t) = 1 - e^{-\lambda_i t}$$

$$P\left(x_i^{[j_i]}\right) = \int_{(j_i-1)\Delta}^{j_i\Delta} f_i(t)dt = \int_{(j_i-1)\Delta}^{j_i\Delta} \frac{F_i(t)}{dt}dt \quad (1)$$

BN satisfies conditional independence. In the system $X = \{x_1^{[j_1]},\ x_2^{[j_2]},\ \dots, x_n^{[j_n]}\}$ of n variables, it can be obtained according to the conditional independence of n variables, for any x_i exists $\pi\left(x_i^{[j_i]}\right) \subseteq \{x_1^{[j_i]}, \dots, x_n^{[j_n]}\}\}$, such that $x_i^{[j_i]}$ is the same as $\{x_1^{[j_i]}, \dots, x_n^{[j_n]}\}$ are conditionally independent, then the probability joint distribution of n variables is shown in formula (2):

$$P(X) = P\left(x_1^{[j_1]}, x_2^{[j_2]}, \dots, x_n^{[j_n]}\right) = P\left(x_1^{[j_1]}\right) P\left(x_n^{[j_n]} | x_1^{[j_1]}, \dots, x_{i-1}^{[j_{i-1}]}\right) == \prod_{i=1}^{n} P(x_1^{[j_1]} | \pi(x_i^{[j_i]}) \quad (2)$$

Due to conditional independence the failure probability of child nodes can be passed. From Equation (2), the joint probability when the child node $y^{[j_y]}$ is 1 can be obtained as shown in Equation (3):

$$P\left(x_1^{[j_1]}, x_2^{[j_2]}, \dots, x_n^{[j_n]}, y^{[j_y]} = 1\right) = P\left(X, y^{[j_y]} = 1\right) = P\left(y^{[j_y]} = 1 | X\right) P(X) = P\left(y^{[j_y]} = 1 | X\right) \prod_{i=1}^{n} P(x_1^{[j_1]} | \pi(x_i^{[j_i]}) \quad (3)$$

The probabilities of leaf nodes in each time period are obtained by calculation, as shown in Table 3.

Table 3. Failure rate of leaf node y_1.

.Period	Failure Rate
1	0.196163
2	0.157369
3	0.126729
4	0.102016

It can be seen from Table 3 that the probability of failure of the oil pump motor unit and the diverter valve, balance valve, relief valve and electromagnetic reversing valve is high, and the probability of failure of the hydraulic system within the task time reaches 0.582277.

4.2. Posterior Probabilistic Inference

Posterior probability and reverse reasoning can find out the factors that are prone to failure of the system through reverse reasoning, so as to maintain and replace them to ensure the normal operation of the system. In a two-state system, the reverse reasoning of the root node is shown in Equation (4):

$$P\left(x_i^{[j_y]}=1|y^{[j_y]}=1\right)=\frac{P(x_i^{[j_i]}=1,y^{[j_y]}=1)}{P(y^{[j_y]}=1)} \quad (4)$$

According to formula (4), the posterior probability of each root node in each time period and task time is obtained as shown in Table 4.

Table 4. Posterior probability of each root node.

x_i	Period				
	1	**2**	**3**	**4**	T_M
x_1	0.020338	0.024347	0.029442	0.035404	0.109530
x_2	0.024220	0.028967	0.034930	0.042130	0.130247
x_3	0.024220	0.028967	0.034930	0.042130	0.130247
x_4	0.002049	0.002499	0.003046	0.003714	0.011309
x_5	0.003328	0.004185	0.004950	0.006038	0.018500
x_6	0.001528	0.001863	0.002271	0.002769	0.008430
x_7	0.003328	0.004185	0.004950	0.006038	0.018500
x_8	0.003758	0.004586	0.005441	0.006798	0.020584
x_9	0.003540	0.004193	0.005264	0.006240	0.019237
x_{10}	0.003758	0.004586	0.005441	0.006798	0.020584
x_{11}	0.003540	0.004193	0.005264	0.006240	0.019237
x_{12}	0.033941	0.040602	0.048668	0.058313	0.181524
x_{13}	0.033941	0.040602	0.048668	0.058313	0.181524
x_{14}	0.038716	0.046314	0.055298	0.065984	0.206311
x_{15}	0.040037	0.047631	0.057100	0.067961	0.212729
x_{16}	0.033601	0.040185	0.047975	0.057688	0.179450

From Table 4, it can be reflected that the posterior probability values of root nodes x_2, x_3, x_{12}, $x_{13}, x_{14}, x_{15}, x_{16}$ are large, that is, the basic event that is prone to failure of the system through reverse reasoning is the oil pump motor unit, diverter valve, balance valve, relief valve and electromagnetic reversing valve. When the hydraulic system fails, it can be checked, maintained and replaced as a priority to ensure the normal operation of the system.

4.3. Sensitivity Analysis

Sensitivity analysis is widely used in system feature analysis and abnormal feature discovery. Through sensitivity evaluation, it can find high-risk events in the system, improve the reliability of the system, and provide a basis for formulating security measures. When the system is a two-state system, when y fails in the j_y time period, $S(x_i = 1, y^{[j_y]} = 1)$ is shown in formula (5):

$$S(x_i = 1, y^{[j_y]} = 1) = \frac{I^{Pr}(x_i = 1, y^{[j_y]} = 1)}{\sum_{j_y=1}^{m} P(y^{[j_y]} = 1 | x_i = 1)} \tag{5}$$

The sensitivity $S(x_i = 1)$of the root node in the task time is shown in formula (6):

$$S(x_i = 1) = \sum_{j_y}^{m} S(x_i = 1, y^{[j_y]} = 1) \tag{6}$$

It can be seen from Table 5 that the sensitivity values of the root nodes $x_2, x_3, x_{12}, x_{13}, x_{14}, x_{15}, x_{16}$ are relatively large, and the main oil pump, auxiliary oil pump, diverter valve, balance valve, relief valve, electromagnetic reversing valve, etc. are high risk factors, thus it should be checked and replaced in time to improve the reliability of the system.

Table 5. Sensitivity of each root node.

x_i	Period				
	1	**2**	**3**	**4**	T_M
x_1	0.092257	0.092724	0.093124	0.093505	0.371610
x_2	0.107016	0.107543	0.107998	0.108440	0.430998
x_3	0.107016	0.107543	0.107998	0.108440	0.430998
x_4	0.011067	0.011125	0.011177	0.011227	0.044596
x_5	0.017866	0.017964	0.018043	0.018124	0.071997
x_6	0.008297	0.008340	0.008377	0.008415	0.033429
x_7	0.017866	0.017964	0.018043	0.018124	0.071997
x_8	0.019812	0.019920	0.020006	0.018831	0.078569
x_9	0.018562	0.018663	0.018749	0.018826	0.074799
x_{10}	0.019812	0.019920	0.020006	0.018831	0.078569
x_{11}	0.018562	0.018663	0.018749	0.018826	0.074799
x_{12}	0.141295	0.141963	0.142503	0.143044	0.568805
x_{13}	0.141295	0.141963	0.142503	0.143044	0.568805
x_{14}	0.156927	0.157652	0.158219	0.158787	0.631584
x_{15}	0.160898	0.161609	0.162205	0.162770	0.647480
x_{16}	0.139992	0.140653	0.141175	0.141725	0.563544

5. Conclusions

The DFTA-BN analysis method not only makes up for the insufficiency of T-S dynamic fault tree operation and the inability of traditional BN to describe the fuzzy logic relationship between nodes, but also solves the problems that the BN model and node CPT are difficult to construct and the T-S dynamic fault tree cannot be reasoned in both directions.

Through forward inference, the failure probability of the leaf nodes of the hydraulic system of the tunnel erecting machine is derived, and the BN posterior probability is used to infer the factors that the system has failed, so as to maintain and replace it. At the same time, the sensitivity of each root node is calculated, which provides a reliable basis for equipment routine maintenance and fault diagnosis.

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