J. Shanghai Jiao Tong Univ. (Sci.), 2018, 23(6): 770-775
https://doi.org/10.1007/s12204-018-1986-x

Reliability Analysis of Aero-Engine Main Fuel System Based on GO Methodology

ZHANG Sheng[1] (张　生), *REN Chenhui*[2] (任晨辉), *WAN Liyong*[1] (万里勇), *YI Xiaojian*[3] (伊枭剑), *DONG Haiping*[2*] (董海平)
(1. Shenyang Engine Research Institute, Aero Engine Corporation of China, Shenyang 110015, China;
2. School of Mechatronical Engineering, Beijing Institute of Technology, Beijing 100081, China;
3. China North Vehicle Research Institute, China North Industries Group Corporation Limited, Beijing 100072, China)

Abstract: To improve the reliability of an aero-engine main fuel system, the quantitative and qualitative reliability analysis of the system is conducted based on goal oriented (GO) methodology. The quantitative reliability analysis results and the minimum cut sets of the fuel system are obtained, respectively. These results are compared with the results of the FTA (Fault Tree Analysis) method, and the comparison result shows GO method is rational and applicable. Therefore, it is feasible to apply the GO method in the reliability analysis of an aero-engine main fuel system.
Key words: aero-engine main fuel system, reliability analysis, GO methodology, FTA
CLC number: TK 402 **Document code:** A

0 Introduction

Aero-engine main fuel system supplies quantitative fuel for the aero-engine and ensures the normal work of the engine and the safe operation of the aircraft. The reliable operation of the fuel system is significantly crucial for the engine and the aircraft, so the reliability requirement of the aero-engine main fuel system is extremely high. At present, to improve the reliability of an aero-engine main fuel system and other related subsystems in an aircraft, Wang et al.[1] conducted a semi-physical simulation experiment of a fuel control system in an aero-engine, and found the weak links of the equipment and gained the corresponding solutions. Chen et al.[2] analyzed the aero-engine fuel leakage using the fuzzy fault tree analysis (FTA) method and determined the importance level of the failure causes to make a decision of the maintenance. Liu et al.[3] enhanced the reliability of systems and components by fault diagnosis and semi-physical simulation of aero-engine fuel conditioning actuators and their sensors. However, the reliability models in the above methods are more and less influenced by the subjective factors, and the reliability models established by different people for a same system are not always consistent, so the reliability analysis results for the same system are often inconsistent.

GO methodology[4] is a goal-oriented (GO) system probability analysis method. The reliability model in the GO method, namely GO model, is established with certain rules according to the system working principle diagram, or engineering flow drawing, and so on. The GO model, therefore, can reflect the original appearance of the system and is endowed several unique characteristics such as strong objectivity, sound consistency and low human factors. At present, the GO method has been applied in the reliability and safety analysis of natural gas pipeline systems, power systems, nuclear industry systems, inertial navigation systems and other systems[5-9], and achieves good results. Many researchers are developing functions of the GO method and making it more perfect in recent years [10-17]. In this paper, the principle and the analysis process of the GO method are briefly introduced. Then, the quantitative and qualitative reliability analysis of an aero-engine main fuel system is conducted through the GO method. Finally, the analysis results with the GO method are compared with the results of the FTA method.

1 Fundamentals and Analysis Process of GO Methodology

1.1 Fundamentals and Ideas of GO Method

A GO method mainly consists of establishment of

Received date: 2018-06-07
Foundation item: the Shenyang Engine Research Institute, Aero Engine Corporation of China (No. A0920132002)
∗**E-mail:** donghaipingphd@126.com

GO model and GO operation. GO model is established with certain rules according to the system principle diagram, functional chart or engineering drawing and so on, then the state probability of the system can be obtained by GO operation based on the GO model. There are two algorithms in GO operation: the state combination algorithm and the probability formula algorithm. The state combination algorithm needs to list all the state combination of operators and input signals to calculate the joint probability. The probability formula algorithm, however, significantly simplifies the calculation via introducing the signal flow state accumulation probability and deriving the calculation formula of the GO operator directly[18]. For reliability analysis of a complex system, the probability formula algorithm is generally adopted at present.

1.2 Signal Flow and Operator of GO Method

The GO operator and the signal flow are included in the GO model and operation of GO method. The existing 17 types of standard operators defined by GO method consisting of function and logical operator are shown in Fig. 1. Here, S denotes the input signal of each component related to true system units and R expresses the component's output signal. They are used to represent the function and logical relationship between the input and output of the system units and all of these operators have three attributes of type, data and operation rule[18]. Signal flow is used to link GO operators and represents specific fluid or logical process, including two attributes of the state value and the state probability.

1.3 Analysis Procedures of GO Method

The general analysis procedures of GO method are: system analysis, establishment of GO model, data acquisition and processing, GO method quantitative analysis, GO method qualitative analysis and evaluation of system reliability. The specific process is shown in Fig. 2.

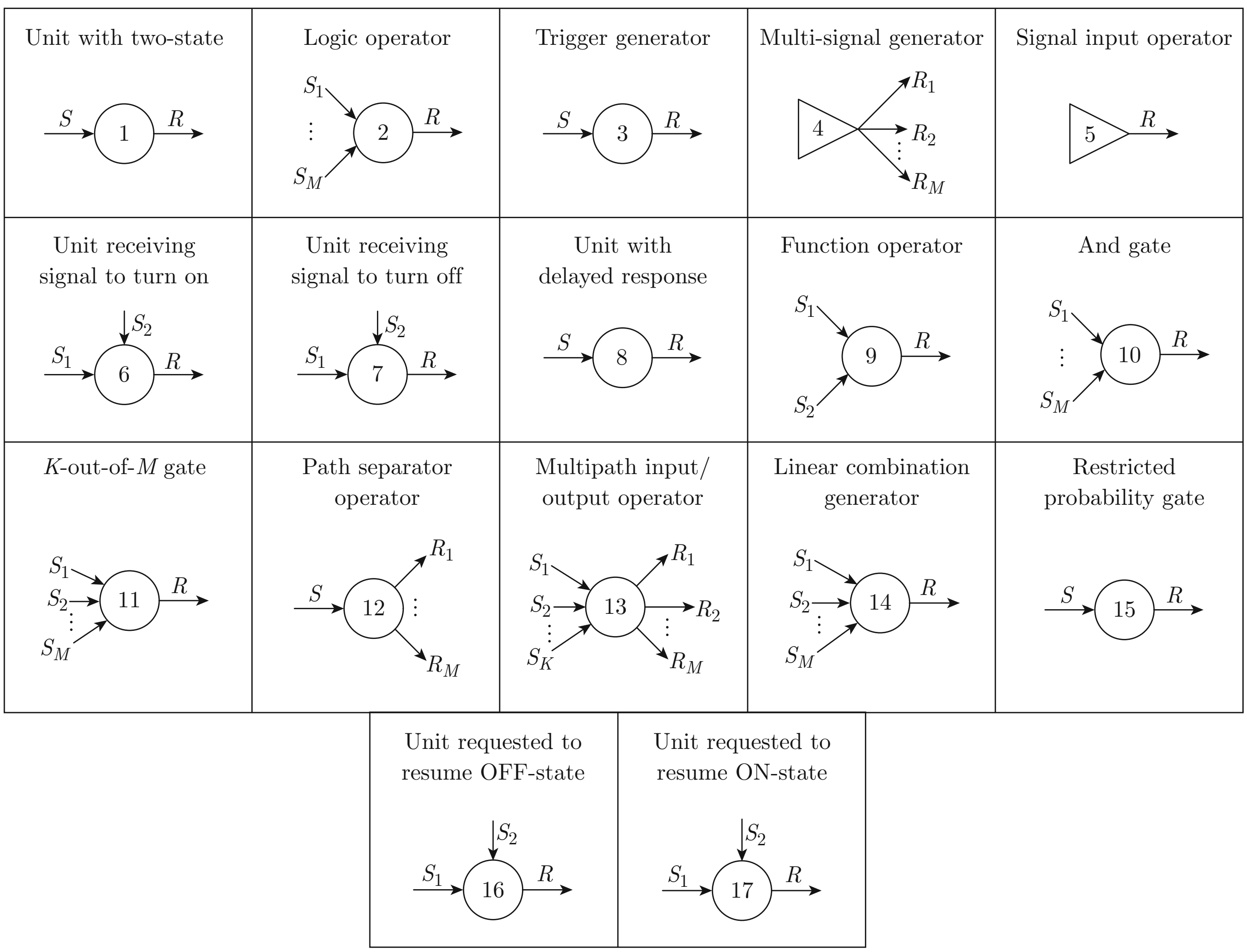

Fig. 1 17 types of standard operators in GO method

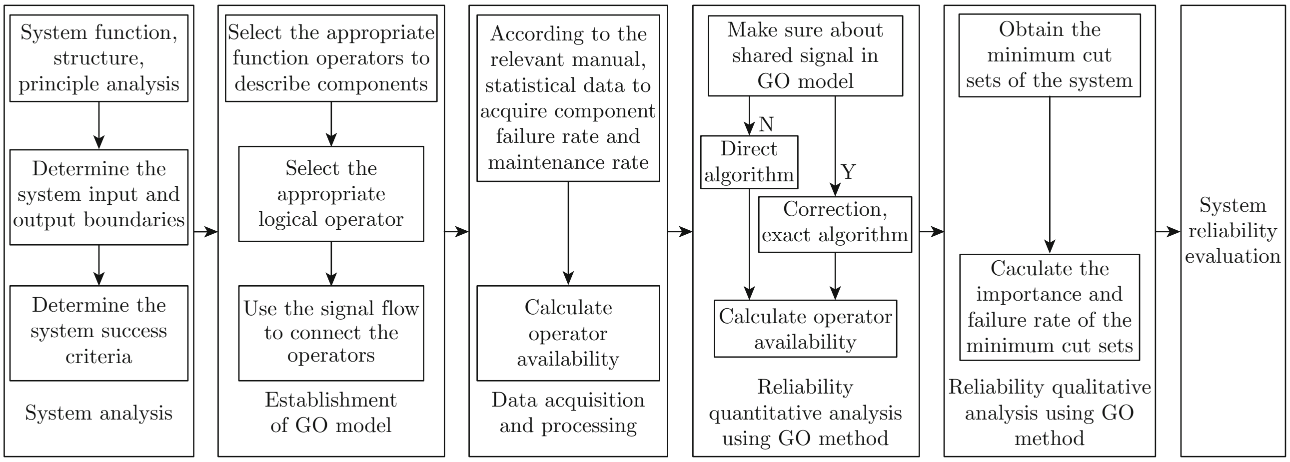

Fig. 2 Reliability analysis flow diagram of GO method

2 Reliability Analysis of the Main Aero-Engine Main Fuel System Based on GO Method

2.1 Analysis of the Aero-Engine Main Fuel System

Aero-engine fuel is provided by the aero-engine fuel system. The quantitative fuel supply of engine ensures the engine to achieve different working conditions. A function block diagram of an aero-engine main fuel system is shown in Fig. 3.

The basic principle of an aero-engine main fuel system is: firstly, the fuel from the aircraft tank flows through the transfer tube, and the fuel is inhaled to the fuel booster pump. Then, the pressurized fuel from the fuel booster pump is filtered by fuel filter. Secondly, the filtered fuel flows into the fuel pump regulator that combines all kinds of information, such as fuel pressure, fuel flow, temperature and other parameters, with electronic controller instructions to give hydraulic instructions to control the main fuel flow. Then, the main-fuel passes through the fuel oil heat exchanger, and the fuel assignment needle will make a movement with the raised fuel pressure, which will allow the fuel to flow through fuel tube 1 and 2 of main combustion chamber. Then, the fuel will flow into the main combustion chamber through the fuel nozzle.

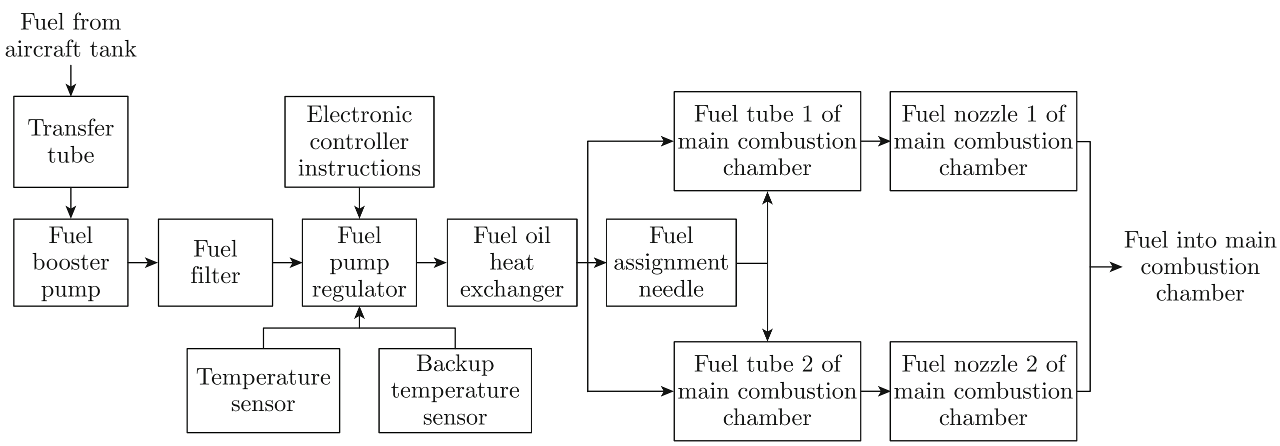

Fig. 3 Function block diagram of an aero-engine main fuel system

If the fuel system can provide the required amount of fuel into the main combustion chamber to meet the requirements in the practical conditions, then the system is viewed as normal work condition. That is the success criteria of the aero-engine main fuel system.

2.2 Establishment of GO Model

Based on the theory of GO method and according to the function block diagram of the aero-engine main fuel system in Fig. 3, we select the appropriate operators and use signal flows to build the GO model of the fuel system. The GO model of the fuel system is shown in Fig. 4. The electronic controller instructions, fuel from the aircraft tank and temperature sensors are the input signals, so the type 5 operator can be adopted to describe them. Each fuel tube is controlled by a fuel assignment needle and can be described by the type 6 operator. The fuel pump regulator works normally when multiple signal inputs are valid, so the type 10 operator can be used to deal with multiple input signals and type 1 operator can be used to describe the fuel pump regulator. Other components are single-input and single-output's two-state units, and type 1 operator can be used to describe them. In Fig. 4, the first number in each operator represents the operator type number and the latter number represents the operator serial number. The number on the signal flow represents the signal serial number, and S17 represents the output signal of the aero-engine main fuel system. The reliability parameters of the operators in Fig. 4 can be obtained according to the relevant manuals and statistical engineering test data, as shown in Table 1.

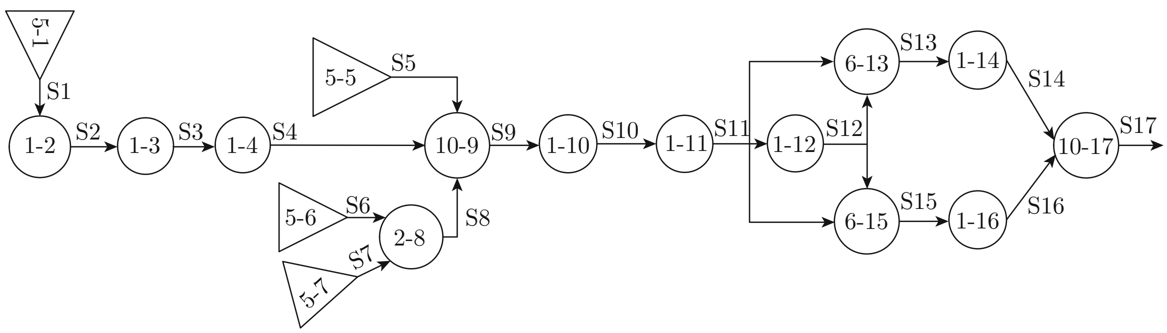

Fig. 4 GO model of the aero-engine main fuel system

Table 1 Operator types and reliability parameters in GO model of the aero-engine main fuel system

Component	Operator serial number	Operator type	Failure rate×10^5/h^{-1}	Maintenance rate/h^{-1}
Fuel from aircraft tank	1	Type 5	0.9	0.2
Transfer tube	2	Type 1	1.2	0.5
Fuel booster pump	3	Type 1	2.5	0.6
Fuel filter	4	Type 1	2.6	0.4
Electronic controller instructions	5	Type 5	1.8	0.5
Temperature sensor	6	Type 5	2.1	0.2
Backup temperature sensor	7	Type 5	2.1	0.2
Logic operator or	8	Type 2	—	—
And gate	9	Type 10	—	—
Fuel pump regulator	10	Type 1	3.6	1.0
Fuel oil heat exchanger	11	Type 1	2.5	0.6
Fuel assignment needle	12	Type 1	1.2	0.8
Fuel tube 1 of main combustion chamber	13	Type 6	1.1	0.6
Fuel needle 1 of main combustion chamber	14	Type 1	2.6	0.8
Fuel tube 2 of main combustion chamber	15	Type 6	1.1	0.6
Fuel needle 2 of main combustion chamber	16	Type 1	2.6	0.8
And gate	17	Type 10	—	—

2.3 Qualitative and Quantitative Reliability Analysis of the Aero-Engine Main Fuel System Based on GO Method

2.3.1 *Qualitative Reliability Analysis*

The state probability formula algorithm is adopted to conduct qualitative reliability analysis of the aero-engine main fuel system. First, a function operator, other than logical operators, is assumed to be in the fault state, its state probability is set to zero, keeping other operators' state unchanged. Then, the success probability of the system is calculated using the state probability formula algorithm. If the success probability of the system obtained is zero, then the fault event of the operator is viewed as a first-order minimum cut set of the system. Similarly, if it is supposed that any two operators, other than logical operators, are in a fault state and the success probability of the system is calculated to be zero. Then, the fault events of the two operators are regarded as a second-order minimum cut set of the system. And so on, one can obtain all kinds of order minimum cut set of the system. According to the GO model shown in Fig. 4, we can obtain 12 first-order minimum cut sets and 1 second-order minimum cut set of the aero-engine main fuel system, as shown in Table 2.

Table 2 Reliability qualitative analysis results of the main fuel system using GO method

Order number of minimum cut set	Operator serial number	Fault unit name
1	1	Fuel from aircraft tank
1	2	Transfer tube
1	3	Fuel booster pump
1	4	Fuel filter
1	5	Electronic controller instructions
1	10	Fuel pump regulator
1	11	Fuel oil heat exchanger
1	12	Fuel assignment needle
1	13	Fuel tube 1 of main combustion chamber
1	14	Fuel needle 1 of main combustion chamber
1	15	Fuel tube 2 of main combustion chamber
1	16	Fuel needle 2 of main combustion chamber
2	6,7	Temperature sensor, Backup temperature sensor

2.3.2 *Quantitative Reliability Analysis*

The probability formula algorithm includes a direct algorithm, a sharing signal correction algorithm and an exact algorithm. When we calculate the output signal S17's success probability, namely availability, we select the exact algorithm based on Eq. (1) to conduct the GO operation of sharing signal S11, S12, and use direct algorithm to conduct the GO operation of non-sharing signals. The quantitative analysis results of the main fuel system are shown in Table 3.

$$A_{\mathrm{R}} = \sum_{K_1=0}^{1} \sum_{K_2=0}^{1} \cdots \sum_{K_L=0}^{1} A_{\mathrm{R},K_1K_2\cdots K_L} \times \prod_{l=1}^{L} [(1 - A_{\mathrm{S},L})(1 - K_l) + A_{\mathrm{S},L} K_l], \tag{1}$$

where A_{R} is the state cumulative probability of the system output signal; $A_{\mathrm{S},L}$ denotes the state cumulative probability of the L sharing signals; $A_{\mathrm{R},K_1K_2\cdots K_L}$ denotes the signal state cumulative probability of the system output in the combination state of the L sharing signals. On the combination state of the l-th sharing signal, $K_l = 0$ represents the fault state and $K_l = 1$ represents the success state.

Table 3 Reliability quantitative analysis results of the main fuel system using GO method

Operation time t/h	Availability
2	0.999 299 91
4	0.999 085 07
6	0.999 009 46
8	0.998 979 88
10	0.998 967 24

3 Reliability Analysis of the Aero-Engine Main Fuel System Using FTA

To validate the correctness and rationality of the reliability analysis results of GO method, this paper also conducts the qualitative and quantitative reliability analysis of the same aero-engine main fuel system using the FTA method.

In quantitative analysis of the aero-engine main fuel system using FTA method, it is assumed that each basic event is independent. The first order approximation algorithm is adopted to calculate the occurrence probability of the fault tree top event. The equation is:

$$Q_{\mathrm{s}} = 1 - \prod_{i=1}^{21} (1 - Q_i), \tag{2}$$

where Q_{s} denotes unreliability of the system; Q_i is the unreliability of l-th basic event. We can obtain $Q_{\mathrm{s}} = 2.789\,642\,7 \times 10^{-4}$ according to the failure rate given in Table 2. So the reliability of this fuel system is $R_2 = 1 - Q_{\mathrm{s}} = 0.999\,721\,03$.

Comparing the analysis results of the FTA with GO method, it can be seen that the minimum cut sets are the same in the qualitative analysis. That is, the reliability qualitative analysis results using these two methods are consistent. In the view of the quantitative analysis result, we also calculate the availability value $R_1 = 0.999\,953\,81$ by GO method with GO software when assuming $t = 0.02\,\mathrm{h}$ as its static reliability, and compare it with the fuel system static reliability above obtained by the FTA method. The comparison result shows the former is slightly larger than the latter, and it is reasonable because the basic events are independent of each other in the FTA method and the reliability of the fuel system obtained by using the first-order approximation algorithm of the FTA method is the minimal. So, we can draw a conclusion that GO method reliability analysis results are reasonable, and GO method can be applied in the reliability analysis of an aero-engine main fuel system. Moreover, the GO method has more advantages than the FTA method in terms of the ease of modeling, consistency and normality of the analysis process.

4 Conclusion

GO method is adopted to conduct quantitative and qualitative reliability analysis of an aero-engine main fuel system in this paper. The general steps and analysis flow of the GO method are summarized. Through the comparison between the analysis results of GO with that of FTA, we verify the rationality and usability of GO method in reliability analysis of the aero-engine main fuel system. Moreover, the GO method has more advantages than the FTA method in terms of the ease of modeling, consistency and normality of the analysis process.

Acknowledgement The authors of this paper wish to thank the China North Vehicle Research Institute and State Key laboratory of Explosion Science and Technology. They provide experimental space, laboratory apparatus and technical support.

References

[1] GAO S L, ZHANG S Y, LUO L, et al. Semi-physical simulation experiment system of fuel control system for an aeroengine [J]. *Advanced Materials Research*, 2012, **468-471**: 2495-2498.

[2] CHEN N T, MA T, WANG J, et al. Aviation engine foil leakage fault analysis based on fuzzy fault tree theory [J]. *Computer Measurement & Control*, 2016, **24**(6): 64-67.

[3] LIU Y, ZHANG T H, ZHOU J. Fault diagnosis and semi-physical simulation for actuator and sensor of aero-engine fuel regulator [J]. *Journal of Propulsion Technology*, 2016, **37**(11): 2165-2172 (in Chinese).

[4] WILLIAMS R L, GATELEY W Y. Use of the GO methodology to directly generate minimal cut sets [C]//*Nuclear System Reliability Engineering and Risk Assessment. Philadelphia*, PA, USA: Society for Industrial and Applied Mathematics, 1977: 825-849.

[5] LI Y Y, YI X J, DENG C L, et al. Reliability analysis of turbocharging system for vehicle engine based on GO method [J]. *Vehicle Engine*, 2016, (5): 38-42 (in Chinese).

[6] YANG J, ZHAO C, ZHU A, et al. Reliability estimation for the braking systems of high-speed electric multiple units based on Bayes inference and the GO method [J]. *Journal of Computational & Theoretical Nanoscience*, 2016, **13**(2): 1314-1322.

[7] LI Z, YANG X M, LU Z X. Failure rate analysis of multi-state repairable system based on GO methodology [J]. *Atomic Energy Science and Technology*, 2011, **45**(11): 1340-1345 (in Chinese).

[8] LIU L L, REN Y, WANG Z L, et al. Algorithm based on Bayesian networks for GO methodology [J]. *Systems Engineering and Electronics*, 2015, **37**(1): 212-218 (in Chinese).

[9] YI X J, DONG H P, SHI J, et al. Reliability analysis of hydraulic transmission oil supply system considering maintenance correlation of parallel structure based on GO methodology [C]//*Proceedings of the 10th International Conference on Reliability, Maintainability and Safety*. Guangzhou, China: IEEE, 2015: 508-513.

[10] CAI G Q, ZHOU L M, LI X, et al. Reliability analysis of urban rail transit vehicle's door system based on GO method [J]. *Journal of Southwest Jiaotong University*, 2011, **46**(2): 264-270 (in Chinese).

[11] YI X J, DHILLON B S, DONG H P, et al. Quantitative reliability analysis of repairable systems with closed-loop feedback based on GO methodology [J]. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 2017, **39**(5): 1845-1858.

[12] YI X J, SHI J, MU H N, et al. Reliability analysis of hydraulic steering system with DICLFL considering shutdown correlation based on GO methodology [C]//*Proceedings of the First International Conference on Reliability Systems Engineering*. Beijing, China: IEEE, 2016: 1-6.

[13] YI X J, DHILLON B S, SHI J, et al. A new reliability analysis method for vehicle systems based on goal-oriented methodology [J]. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 2017, **231**(8): 1066-1095.

[14] ZHOU L G, DONG H P, YI X J, et al. Reliability Analysis of Retracting Actuator with Multi-State Based on Goal Oriented Methodology [J]. *Journal of Shanghai Jiao Tong University*, 2015, **20**(3): 307-311.

[15] YI X J, DHILLON B S, SHI J, et al. Reliability optimization allocation method for multifunction systems with multi-state units based on goal oriented methodology [J]. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering*, 2016, **3**(4): 1-9.

[16] FAN D M, REN Y, LIU L L, et al. Algorithm based-on dynamic Bayesian networks for repairable GO methodology model [J]. *Journal of Beijing University of Aeronautics and Astronautics*, 2015: **41**(11): 2166-2176 (in Chinese).

[17] YI X J, SHI J, MU H N, et al. Reliability analysis of repairable system with multiple-input and multifunction component based on goal-oriented methodology [J]. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering*, 2017, **3**(1): 1-6.

[18] SHEN Z P, HUANG X R. Principle and application of GO methodology [M]. Beijing: *Tsinghua University Press*, 2004 (in Chinese).