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A New Life Expectancy Assessment Method for Complex Systems With Multi-Characteristics: Case Study on Power-Shift Steering Transmission Control System

XIAO-JIAN YI[1,2,3], YUE-FENG CHEN[4], HUI-NA MU[1], JIAN SHI[3,5], AND PENG HOU[1]

[1]School of Mechatronical Engineering, Beijing Institute of Technology, Beijing 100081, China
[2]Department of Overall Technology, China North Vehicle Research Institute, Beijing 100072, China
[3]Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing 100190, China
[4]The Seventh Research Laboratory, Beijing Special Vehicle Institute, Beijing 100072, China
[5]School of Mathematical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

Corresponding author: Hui-Na Mu (mhnzhy@126.com)

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ABSTRACT Life is an important monitoring index for prognostic and health management systems. This paper proposes a new life expectancy assessment method for high-value complex systems with multi-characteristics based on goal-oriented (GO) method. First, the new life expectancy assessment method is expounded in detail, and its process is formulated. Then, the control system of power-shift steering transmission for a heavy vehicle, which is a typical mechatronics control system with multi-characteristics, such as multi-state, multi-function, and correlations, is taken as an example to evaluate its life expectancy by this paper's method. In order to verify the advantages, feasibility, and rationality of the new life expectancy assessment method, the results are compared with the results by Monte Carlo method. All in all, this life expectancy assessment method not only improves the theory of GO method, so that GO method is applied to evaluate the life expectancy of complex systems with multi-characteristics first, but also provides a new approach for life expectancy assessment of complex systems, which can take into consideration various system characteristics and only use unit life data, so that it is low evaluation cost, higher estimating efficiency and accuracy, and a more stable assessment result.

INDEX TERMS Reliability assessment, complex systems, GO method, life expectancy, system characteristics, prognostic and health management.

I. INTRODUCTION

With the development of technology in electronics, communication and networking etc. rapidly in recent years, the systems applied in various engineering areas become more and more complex and integration because of complex structure, complex characteristics, complex working conditions, and so on. And their costs become more and more expensive. Quality and reliability are key attributes of economic success of a system because they result in an increase in productivity at little cost and vital for business growth and enhanced competitive position. Reliability assessment plays an important role in life cycle of systems, as follows:

(1) In design phase, the reliability assessment can evaluate whether the system reliability meets the design requirements, so that it can provides product improvement suggestions effectively.
(2) In production phase, the reliability assessment can judge whether the product is qualified, so that it contribute to controlling the product quality.
(3) In usage phase, the reliability assessment can show the system reliability level, so that it can guidance the optimization maintenance and mission decision-making.

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Life is an important monitoring index for Prognostic and Health Management systems. The Life Expectancy is a key reliability index of complex systems. The Life Expectancy assessment of complex systems is a quantitative estimation by using probabilistic method and reliability data. Because the cost of complex system is more and more valuableness, the test sample of system for evaluating its Life Expectancy is less or even none in the practical engineering. Thus, the accuracy of Life Expectancy assessment by using the test data of system itself is very low, and the assessment result cannot meet the engineering requirements. Until now, a large number of researchers focus on the Life Expectancy assessment by using small sample size and test data of unit. There are four kinds of system reliability assessment methods to evaluate the Life Expectancy [1], [2], which are exact methods, approximate methods, Bayesian methods, and Monte Carlo methods. While, the above methods have the following disadvantages:

(1) The existing exact methods have high requirements for system structure, data type, etc., so it is not easy to establish modeling, and conduct computing so that it is difficult to apply in engineering.
(2) The approximation methods adopt the data conversion among different data types, so the assessment result is relatively conservative. Moreover, the precision of assessment result is hard to control.
(3) The Bayesian methods are conducted by the step-by-step conversion according to pyramid model, whose two key steps are calculating system prior moment and calculating system prior distribution, respectively. Because the above two key steps of Bayesian methods usually adopt the second-moment method and Markov Chain Monte Carlo simulation method, it is not easy to control the accuracy and bias of assessment results.
(4) The Monte Carlo methods, which are most common Life Expectancy assessment method, use the sample technology to evaluate system Life Expectancy, so the simulation times affects the operation efficiency and accuracy of assessment result directly. Moreover, the assessment result is very unstable.
(5) The information of system structure, function constitutes, and system characteristics for the reliability models of above assessment methods are ignored, so it is hard to obtain the accurate assessment result for a limited testing time and samples. Especially, the high value complex systems often operate the units' life test without system's life test.

Thus, how to avoid above disadvantages of system reliability assessment methods to conduct Life Expectancy assessment of complex systems considering the system structure, function constitutes and system characteristics quickly, steadily and accurately has been a point of concern. Goal Oriented (GO) methodology [3], [4] is a system reliability analysis method by using unit reliability data according to GO model to conduct GO operation to obtain the quantitative analysis result and qualitative analysis result. Moreover, GO method is especially suitable for reliability analysis of complex systems with complex correlations [5]–[9], multifunction [9], [10], multi-fault modes [11], [12], multistate [13], [14], closed-loop feedback link [15]–[17], and so on. Nowadays, GO method has been applied in reliability analysis of defense systems, water, oil and gas supply systems, manufacturing systems, transportation systems, power systems, etc., and it has become increasingly popular in recent years because of its advantages in terms of its ease of creating a model and of its representational and analysis power [3], as follows:

(1) GO model is directly established according to system structure, working principle and function constitutes, and it can visually reflects the system characteristics. Moreover, GO model is easy to check, and can avoid the influence of human factors for reliability model.
(2) Both quantitative analysis result and qualitative analysis result of system are obtained by multiple GO operations, which is easy to operate efficiently and quickly. Moreover, the reliability analysis results have high-level consistency by different engineer(s). And it can avoid the complex analysis process and the influence of sampling.
(3) The development space of GO methodology is larger, so that it can be improved to solve various kinds of practical engineering problems, such as safety analysis [18], reliability optimization allocation [19], [20], and so on.

In view of above advantages of GO method, this paper proposes a new system reliability assessment method for complex systems taking into consideration various system characteristics to evaluate system Life Expectancy firstly. This paper also aims to fill this gap. The main contributions of this study are as follows:

(1) We propose a new Life Expectancy assessment method for complex systems based on GO method by using reliability data of unit and taking into consideration various system characteristics.
(2) We formulate the process of this paper's Life Expectancy assessment method.
(3) The power-shift steering transmission control system (PSSTCS) of a heavy vehicle is taken as a case study for the first time to evaluate its Life Expectancy by the new Life Expectancy assessment method.

The remainder of the paper is organized as follows. The Life Expectancy assessment method for complex system based on GO method is expounded in detail in Section 2. In Section 3, in order to illustrate the usage of the new Life Expectancy assessment method, a PSSTCS is taken as a case study. In order to verify the advantages, feasibility and rationality of the new Life Expectancy assessment method, the results are compared with the results by Monte Carlo methods in Section 4. Section 5 provides some conclusions on the findings of the research.

II. LIFE EXPECTANCY ASSESSMENT METHOD FOR COMPLEX SYSTEMS WITH MULTI-CHARACTERISTICS BASED ON GO METHOD

In this section, a new Life Expectancy assessment method for complex systems with multi-characteristics based on GO method is proposed by only using reliability data of unit in aspect of expounding its evaluating steps in detail, and formulating its process.

A. NEW LIFE EXPECTANCY ASSESSMENT METHOD

GO model can directly reflects the system structure, working principle, function constitutes and system characteristics, and GO operation can obtain the system minimum cutset and system reliability by taking into considering system characteristics. Thus, in view of advantages of GO model, qualitative analysis and quantitative analysis of GO method, the Life Expectancy of complex systems with multi-characteristics is obtained by using reliability data of selecting life test unit, whose evaluating steps are as follows:

1) CONDUCTING SYSTEM ANALYSIS OF COMPLEX SYSTEMS

The system analysis is base of GO method, and it directly affects the establishing GO model and conducting GO operation. It mainly includes:

(i) To analyze system structure and system function constitutes according to the principle diagram, engineering drawing or function flowchart of system.

(ii) To determine system characteristics, such as complex correlations, multifunction, multi-state, and so on.

(iii) To define the success rule of system according to system analysis result.

2) ESTABLISHING GO MODEL OF COMPLEX SYSTEMS

GO model is a key element of GO method. It is developed according to the system principle diagram, the engineering drawing, and the function flowchart directly. The qualitative analysis and quantitative analysis are conducted by GO operation according to GO model. GO operators and signal flows are fundamental elements of GO model. GO operator represents unit itself and logical relationship, and signal flow represents specific fluid flow or a logical process. Establishing GO model of complex systems has two steps, as follows:

(i) To select GO operator. GO operator has function GO operator, logical GO operator, and auxiliary GO operator, which are used to describe the unit itself, the logical relationship in system, and auxiliary operation. There are 17 basic GO operators [3] and 10 developed GO operators, as presented in Table I. For the non-system units, such as action signal, they are used to establish GO model of system, but such units do not affect the system Life Expectancy, so they are described by visual Type 5 operator whose reliability is 1.

(ii) To develop GO model. According to system analysis result, the GO model is developed through the signal flow to connect GO operator. And the GO operation is done along the direction of signal flow.

TABLE 1. Description of frequently-used GO operators.

Operator Type	Description
1	Two state unit with failure state and operating state
2	Logical "OR"
4	Unit with multiple input signals
5	Unit with single input signal
6	Unit state turning into open by receiving control signal
7	Unit state turning into close by receiving control signal
10	Logical "AND"
11	Logical "K-out-of-M"
15B	Multiple signal conditions control signal converted into a multi-conditions control signal
16	Unit state resumed close by receiving control signal
17	Unit state resumed open by receiving control signal
18A	Logical relation "standby structure in any place"
19	Multi-state unit
20	Signal flow of conditional operating mode
21	Units without control signal
22	Units with multi-conditions control signal
23	Logical relation of "multi-function integration"
24	Multi-inputs Closed-Loop Feedback Link
25	Convert between multiple scalar signal flows and a vector signal flow

3) SELECTING LIFE TEST UNIT OF COMPLEX SYSTEMS

The new Life Expectancy assessment method is conducted by using reliability data of unit. Thus, selecting life test unit is one key step of evaluating Life Expectancy for complex system, which can be obtained by multiple GO operations. It has three steps, as follows:

(i) To obtain the minimum cut sets of system by qualitative analysis of GO method. And the minimum cut sets of system can provides the guidance for selecting life test unit. Its steps are as follows:

a) To obtain the one-order minimum cut set of system. Setting the reliability of a function GO operator in GO model is 0, and the reliabilities of other GO operators are kept constant; in this case, if system reliability is 0 by GO operation, this GO operator will be a one-order minimum cut set, as shown in Fig. 1(A).

b) To obtain the two-order minimum cut set of system. Setting the reliabilities of two function GO operators in GO model are 0 except one-order minimum cut set, and the reliabilities of other GO operators are kept constant; in this case, if system reliability is 0 by GO operation, the two GO operators will be a two-order minimum cut set, as shown in Fig. 1(B).

c) To obtain the higher-order minimum cut sets of system in above same way.

(ii) To classify the units according to unit type, i.e. the units belonging to the same unit type as a classification.

(iii) To determine the life test unit according to the following rules:

a) To conduct life test for all classifications of units if conditions allow, such as enough testing expenses and testing facilities.

b) To conduct life test for part classifications of units belonging the minimum cut sets of system if condition does not allow.

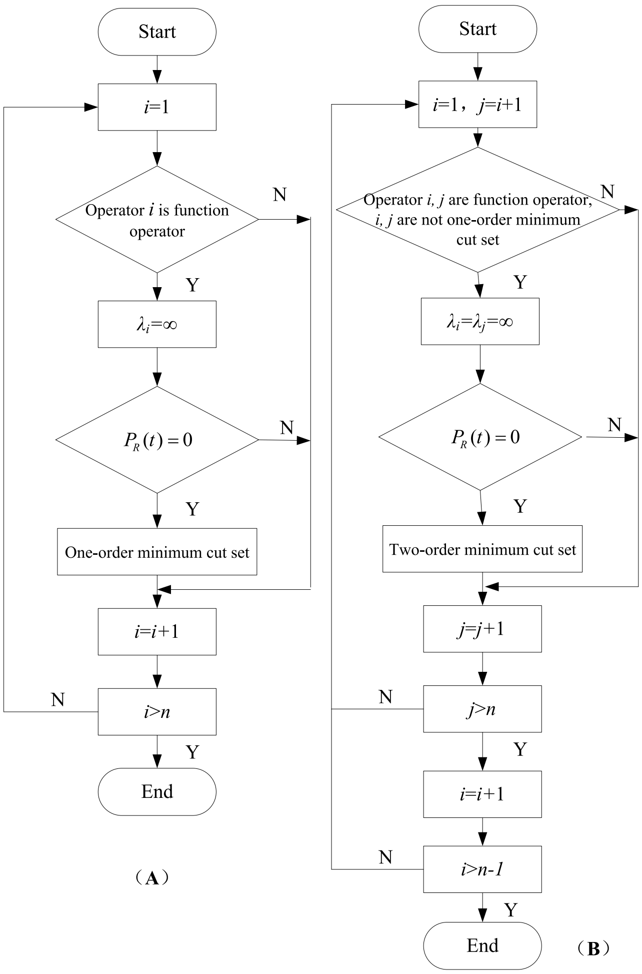

FIGURE 1. **Process of One-order minimum cut set and Two-order minimum cut set.**

4) COLLECTING DATA OF LIFE TEST UNIT FOR COMPLEX SYSTEMS

Collecting data of life test unit is another key step of evaluating Life Expectancy for complex system, which is of crucial importance, and it includes:

(i) To determine test type of life test unit. There are five test types, i.e. complete samples life test, fixed time censoring with replacement life test, non-substitute time tac-tail life test, fixed number censoring with replacement life test, and non-substitute number tac-tail life test. The principles of determining test type of life test unit are as follows:

a) To conduct complete samples life tests if condition allow, such as enough testing expenses and testing facilities.

b) To conduct fixed failure number test and fixed time test if condition does not allow.

(ii) To conduct unit test according to test type of life test unit.

(iii) To collect test data. According to test type of life test unit, the life data of each sample should be collected.

5) EVALUATING FAILURE RATE OF UNIT FOR COMPLEX SYSTEMS

The failure rate of unit is used to calculating the reliability of unit at different time point. There are two kinds of units, which are non-life test unit and life test unit, respectively. For non-life test unit, it needs not to evaluate its failure rate, and its failure rate is set 0. For life test unit, according to the test type of life test unit to evaluate its failure rate, the corresponding steps are as follows:

(i) To select evaluation method of failure rate for life test unit. For the large sample of life test unit, the evaluating method by using test data can be selected. Because the Bayes method can evaluate the failure rate of life test unit by making the most of its prior information, and using a small number of its test data. Thus, for the small sample of life test unit, it needs to select the Bayes method.

(ii) To evaluate the basic failure rate of life test unit. The steps of the evaluating method by using test data are as follows:

a) To determine the total time test according to selecting data of life test unit.

b) To develop the likelihood function according to test data of test sample.

c) To obtain the point estimation of basic failure rate for life test unit by solving the likelihood equation, which is obtained by using logarithm derivation for likelihood function.

The steps of the Bayes method are as follows:

a) To determine the total time test according to selecting data of life test unit.

b) To develop the likelihood function according to test data of test sample, as shown in Eq. (1).

$$L(X\,|\lambda) = L(x_1, x_2, \cdots, x_n; \lambda) \tag{1}$$

where, $X = (x_1, x_2, \cdots, x_n)$ is the test data of test sample, x_i is the test data of *ith* test sample, λ is the basic failure rate of life test unit, $L(X\,|\lambda)$ is the likelihood function.

c) To determine the prior distribution $\pi(\lambda)$ of the basic failure rate for life test unit.

d) To determine the posteriori distribution $\pi(\lambda\,|X)$ of the basic failure rate for life test unit, as shown in Eq. (2).

$$\pi(\lambda\,|X) = \frac{h(X,\lambda)}{m(X)} = \frac{L(X\,|\lambda)\pi(\lambda)}{\int_\Theta L(X\,|\lambda)\pi(\lambda)d\lambda} \tag{2}$$

where, $m(X)$ is the marginal density function of X, $h(X, \lambda)$ is the joint distribution of X and λ.

e) To obtain the point estimation of basic failure rate for life test unit by calculating the expectation of $\pi(\lambda\,|X)$, as shown in Eq. (3).

$$\widehat{\lambda} = E\,(\lambda|\,X) \tag{3}$$

where, $\widehat{\lambda}$ is the point estimation of basic failure rate for life test unit, $E\,(\lambda|\,X)$ is the expectation of $\pi(\lambda\,|X)$.

(iii) To evaluate the failure rate of life test unit by Eq. (4).

$$a = \lambda \cdot \alpha_W \cdot \pi_Q \cdot \pi_E \tag{4}$$

where, a is the point estimation of failure rate for life test unit; α_W is the correction factor of life test unit and time dependent functions, and it is equal to specific value of average lifetime and rated operating time of unit; π_Q is the quality rank coefficient of life test unit; π_E is the environmental influence coefficient of life test unit. For life test unit obeying exponential distribution, α_W, π_Q and π_E are 1, respectively; For life test unit obeying non exponential distribution, α_W, π_Q and π_E should be determined according to the experimental data and historical data of life test unit, respectively.

6) EVALUATING LIFE EXPECTANCY OF COMPLEX SYSTEMS

The Life Expectancy of system is evaluated by using test data of unit based on GO method. The evaluating steps are as follows:

(i) To determine the time points for fitting system reliability function. In order to fit system reliability function accurately, the time point should be throughout the whole system life cycle for Life Expectancy assessment as much as possible.

(ii) To calculate the unit reliability at different time points by using the failure rate of unit according to Eq. (5).

$$R(t) = e^{-at} \tag{5}$$

where, $R(t)$ is the reliability of unit at time t.

(iii) To calculate the system reliability at different time points based on the quantitative analysis of GO method by using the unit reliability. For the GO model without shared signals, the quantitative analysis of GO method adopts the direct algorithm [21]. And for the GO model with shared signals, the quantitative analysis of GO method adopts the exact algorithm with shared signals [22], otherwise the system reliability at different time points will have a large bias [16].

(iv) To evaluate system Life Expectancy by Eq. (6).

$$\text{MTTF} = \int_0^{T_0} R(t)dt \tag{6}$$

where, $R(t)$ is the system reliability function T_0 is the upper limitation of system estimation life,.

B. PROCESS OF THE NEW LIFE EXPECTANCY ASSESSMENT METHOD

The process of the new Life Expectancy assessment method for complex systems with multi-characteristics based on GO method is the operation standard in order to guide the Life Expectancy assessment accurately. In this study, we formulate the new Life Expectancy assessment method proposed in this paper according to Section II-A, as shown in Fig. 2.

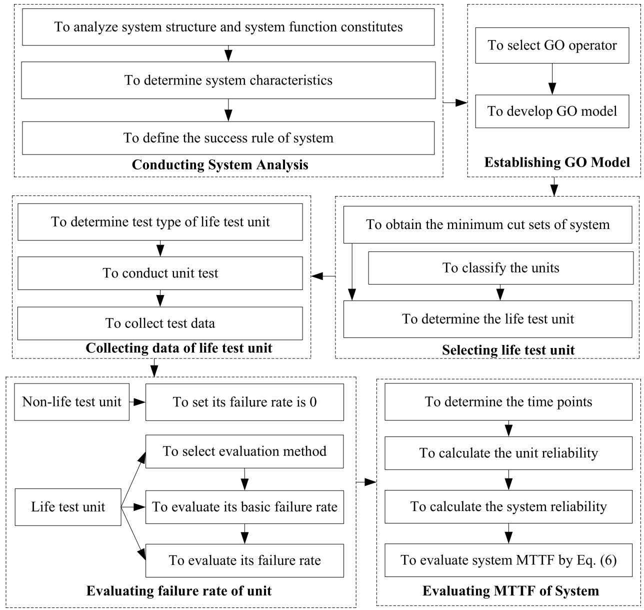

FIGURE 2. Process of new life expectancy assessment method for complex system based on GO method.

III. EXAMPLE

The power-shift steering transmission control system (PSSTCS) is a typical mechatronics control system with multi-characteristics, such as multi-state, multi-function, one system for multi-conditions, and correlations. Usually, in real project, because the value of PSSTCS is more than one million dollars, the life-test of system for PSSTCS is rarely conducted. Thus, taking the power-shift steering transmission control system (PSSTCS) as a case study, it is used to illustrate the usage method, advantages, feasibility and reasonability of the new Life Expectancy assessment method for complex system based on GO method. In order to present this example and compare with Monte Carlo method conveniently, we assume the following.

(1) The oil tubes and interfaces of the PSSTCS are not considered.
(2) In Eq. (4), α_W is set 1.
(3) The testing expenses and testing facilities cannot support all units to conduct life test.
(4) In this case, the Life Expectancy of PSSTCS operating 500 hours, which is an overhaul period, is evaluated.

A. CONDUCTING SYSTEM ANALYSIS OF PSSTCS

The power-shift steering transmission control system (PSSTCS) is a key complex subsystem with multi-characteristics of heavy vehicle to achieve the control of the steering, speed changing, fan driving, and lubricating.

1) TO ANALYZE STRUCTURE AND FUNCTION CONSTITUTES OF PSSTCS

The PSSTCS is composed of a hydraulic oil supply system, an integration pump-motor system, a fan control system, an electronic control system, and hydraulic control system. And the hydraulic oil supply system consist of a fill oil and constant pressure system of pressure oil tank, a pump group, and a fill oil system of transmission control and fan control.

The function constitutes and the structure principle drawing of PSSTCS are shown in Fig. 3 and Fig. 4, respectively.

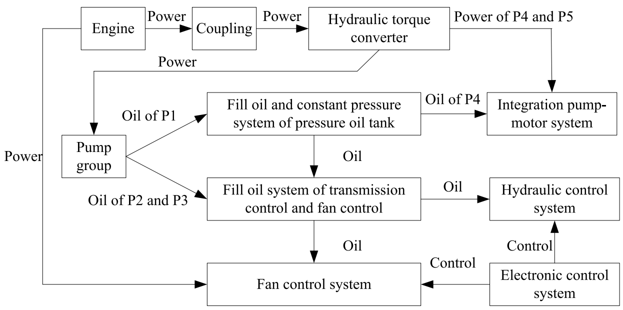

FIGURE 3. Function constitutes of PSSTCS.

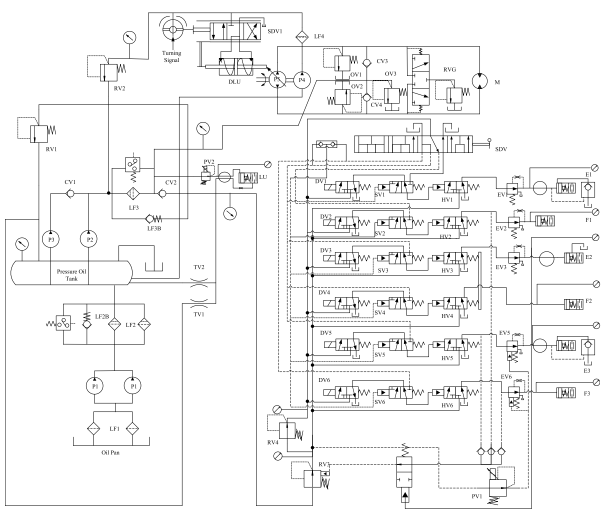

FIGURE 4. Structure principle drawing of PSSTCS.

2) TO DETERMINE SYSTEM CHARACTERISTICS OF PSSTCS

According to engineering practice, the PSSTCS is a complex system with multi-characteristics, which are standby correlation, multi-state, multi-function and one system for multi-conditions. The system characteristics of PSSTCS are analyzed, as follows:

(i) To analyze the standby correlation structure of PSSTCS

When LF2 group is obstructed and pressure between input and output becomes more than 0.5 mega Pascal, oil will be injected into pressure oil tank via LF2B. LF3 and LF3B are same like LF2 group and LF2B. Thus, the LF2 group and LF2B, LF3 and LF3B are standby correlation structures.

(ii) To analyze the multi-state unit of PSSTCS

Pump group often output oil with unstable oil pressure, and RV1 and RV2 are constant pressure valve of hydraulic control system and integration pump-motor system, respectively. They can turn unstable oil pressure of system into the goal oil pressure, so that they make system normal operating and improve the system reliability.

(iii) To analyze the multi-function and one system for multi-conditions of PSSTCS

The PSSTCS can adjust the speed of left and right fans at the same time by the fan control system, control left and right turnings by the integration pump-motor system, and achieve various speed thresholds under electronic control condition and manual emergency condition by the hydraulic control system, respectively. The hydraulic control system achieves Gear 1L, 1, 2, 3, 4, R1 and R2 under electronic control condition, and achieves Gear 1, 3 and R1 under manual emergency condition. The shifting strategy of the hydraulic control system is presented in Tab. II. In Tab.1, E1, E2 and E3 are clutches, and F1, F2 and F3 are brakes. Different combination of clutches and brakes achieve different gears.

TABLE 2. Shifting strategy of hydraulic control system for PSSTCS.

Gear	E3	E2	E1	F1	F2	F3
1L	×			×		×
1		×		×		×
2	×	×		×		
3		×	×			×
4	×	×	×			
R1	×			×	×	
R2	×		×		×	

3) TO DEFINE THE SUCCESS RULE OF PSSTCS

According to above analysis of PSSTCS, the success rule can be defined as that system can achieve the control of the steering, speed changing, fan driving, and lubricating.

B. ESTABLISHING GO MODEL OF PSSTCS

1) TO SELECT GO OPERATOR IN GO MODEL OF PSSTCS

According the system analysis result and the types of GO operator, the function GO operators, logical GO operators and auxiliary GO operator are selected to describe the units itself, logical relationships, auxiliary GO operation in PSSTCS, respectively, as presented in Tab. III and Tab. IV.

2) TO DEVELOP GO MODEL OF PSSTCS

The GO model of PSSTCS is developed by using the signal flows to connect above GO operators, as shown in Appendix I. The type and numbering of GO operator are represented by the first number and the second number in GO operator, respectively. The numbering of signal flow is represented by the number on signal flow. And the signal flow 124 is the system output of PSSTCS.

C. SELECTING LIFE TEST UNIT OF PSSTCS

1) TO OBTAIN THE MINIMUM CUT SETS OF PSSTCS

The minimum cut sets of PSSTCS are obtained according to Section II-A, as presented in Tab. V. And they are used to provide the guidance for selecting life test unit.

2) TO CLASSIFY THE UNITS

Because the testing expenses and testing facilities cannot support all units to conduct life test, the life test units are

TABLE 3. Function GO operator in GO model of PSSTCS.

Unit	NO. (Operator)	Type (Operator)	Description
Oil pan	1	5	Input unit
Filter LF1	2, 3	1	Two-state unit
Pump P1	5, 6	6	Unit controlled by two signals
Power of P1, P2 and P3	7	Virtual 5	Input unit whose reliability is 1
Filter LF2	9, 10	1	Two-state unit
Bypass-valve LF2B	13	1	Two-state unit
Pressure oil tank	15	1	Two-state unit
Pump P3	16	6	Unit controlled by two signals
Pump P2	17	6	Unit controlled by two signals
One-way valve CV1	18	1	Two-state unit
Filter LF3	20	1	Two-state unit
One-way valve CV2	21	1	Two-state unit
Bypass-valve LF3B	23	1	Two-state unit
Constant pressure valve RV1	25	19	Steady pressure unit
Power P4 and P5	26	Virtual 5	Input unit whose reliability is 1
Pump P4	27	6	Unit controlled by two signals
Filter LF4	28	1	Two-state unit
Constant pressure valve RV2	29	19	Steady pressure unit
Steering wheel signal	30	Virtual 5	Input unit whose reliability is 1
Valve body of SDV1	31	6	Unit controlled by two signals
Piston valve block	32	1	Two-state unit
Hydraulic cylinder DLU	33	1	Two-state unit
Swash plate pump of P5	34	1	Two-state unit
Two-way variable displacement pump P5	35	6	Unit controlled by two signals
Overflow valve OV1	36	1	Two-state unit
One-way valve CV4	37	1	Two-state unit
Overflow valve OV2	39	1	Two-state unit
One-way valve CV3	40	1	Two-state unit
Group valve RVG	42	21	Multifunction unit
Reversing motor M	43	21	Multifunction unit
Power of electronic control system	45	5	Input unit
Control panel	46	6	Unit controlled by two signals
Panel switch	47	5	Input unit
Handle signal	48	Virtual 5	Input unit whose reliability is 1
State signal sensor	49	5	Input unit
Switch D1	51	1	Two-state unit
Switch D2	52	1	Two-state unit
Pilot valve PV2	54	22	Multifunction unit
Liquid viscous clutch cylinder of left fan	55	1	Two-state unit
Active friction plate of left fan	57	6	Unit controlled by two signals
Friction plate of left fan	58	1	Two-state unit
Power of liquid viscous clutch	59	Virtual 5	Input unit whose reliability is 1
Liquid viscous clutch cylinder of right fan	60	1	Two-state unit
Active friction plate of right fan	62	6	Unit controlled by two signals
Friction plate of right fan	63	1	Two-state unit
Overflow valve OV3	66	1	Two-state unit
Throttle valve TV1	67	1	Two-state unit
Throttle valve TV2	68	1	Two-state unit
Overflow valve RV3	70	1	Two-state unit
Overflow valve RV4	71	1	Two-state unit
Signal of SDV	72	Virtual 5	Input unit whose reliability is 1
Hand valve SDV	73	6	Unit controlled by two signals
Electric controllable valve DV1	74	6	Unit controlled by two signals
Manual hydraulic control valve SV1	76	22	Multifunction unit

TABLE 3. *(Continued.)* Function GO operator in GO model of PSSTCS.

Liquid control valve HV1	77	21	Multifunction unit
Constant pressure throttle valve EV1	78	21	Multifunction unit
Oil cylinder E1	79	21	Multifunction unit
Electric controllable valve DV2	80	6	Unit controlled by two signals
Manual hydraulic control valve SV2	82	22	Unit controlled by two signals
Liquid control valve HV2	83	21	Two-state unit
Constant pressure throttle valve EV2	84	21	Two-state unit
Oil cylinder F1	85	21	Two-state unit
Electric controllable valve DV3	86	6	Unit controlled by two signals
Manual hydraulic control valve SV3	88	22	Unit controlled by two signals
Liquid control valve HV3	89	21	Two-state unit
Constant pressure throttle valve EV3	90	21	Two-state unit
Oil cylinder E2	91	21	Two-state unit
Electric controllable valve DV4	92	6	Unit controlled by two signals
Manual hydraulic control valve SV4	94	22	Unit controlled by two signals
Liquid control valve HV4	95	21	Two-state unit
Oil cylinder F2	96	21	Two-state unit
Electric controllable valve DV5	97	6	Unit controlled by two signals
Manual hydraulic control valve SV5	99	6	Unit controlled by two signals
Liquid control valve HV5	100	1	Two-state unit
Constant pressure throttle valve EV5	101	6	Unit controlled by two signals
Oil cylinder E3	102	1	Two-state unit
Electric controllable valve DV6	104	6	Unit controlled by two signals
Manual hydraulic control valve SV6	106	6	Unit controlled by two signals
Liquid control valve HV6	107	1	Two-state unit
Constant pressure throttle valve EV6	108	6	Unit controlled by two signals
Oil cylinder F3	109	1	Two-state unit
Pilot valve PV1	111	6	Unit controlled by two signals

selected in minimum cut sets of PSSTCS. And the units of minimum cut sets for PSSTCS are classified according to unit type, as presented in Tab. VI.

3) TO DETERMINE THE LIFE TEST UNIT

In this case, although the testing expenses and testing facilities cannot support all units to conduct life test, they can support 10 samples for each classification presented in Tab. VI to conduct life test.

D. COLLECTING DATA OF LIFE TEST UNIT FOR PSSTCS

1) TO DETERMINE TEST TYPE OF LIFE TEST UNIT

In this case, all life test units are conduct to the complete samples life tests.

2) TO CONDUCT UNIT TEST

According to complete samples life tests, 10 samples of each classification are conduct unit test until failures of them.

TABLE 4. Logical GO operator and auxiliary GO operator in GO model of PSSTCS.

Logical relationship	NO. (Operator)	Type (Operator)	Description
OR	4	2	Logical relationship of LF1group
OR	8	2	Logical relationship of P1 group
OR	11	2	Logical relationship of LF2 group
Condition signal flow	12	20	Signal flow describing failure probability of LF2 group
Standby	14	18A	Standby relationship of LF2group and LF2B
OR	19	2	Oil supply of LF3
Condition signal flow	22	20	Signal flow describing failure probability of LF3
Standby	24	18A	Standby relationship of LF3 and LF3B
AND	38	10	Logical of left steering
AND	41	10	Logical of right steering
One system for multi-conditions	44	23	System output of steering control
AND	50	10	Control signal of control panel
Auxiliary operator for combination signal	53, 75, 81, 87, 93	15B	Control signal of fan drive
AND	56	10	Oil of friction plate of left fan
AND	61	10	Oil of friction plate of right fan
AND	64	10	System output of fan drive
OR	65	2	System output of hydraulic control system
OR	69	2	Lubrication oil
Auxiliary operator for GO operation	98, 105	25A	Signal flow conversion
Auxiliary operator for GO operator	103, 110	25B	Signal flow conversion
AND	112	10	Gear L1 of electronic control condition
AND	113	10	Gear 1 of electronic control condition
AND	114	10	Gear 2 of electronic control condition
AND	115	10	Gear 3 of electronic control condition
AND	116	10	Gear 4 of electronic control condition
AND	117	10	Gear R1 of electronic control condition
AND	118	10	Gear R2 of electronic control condition
AND	119	10	Gear 3 of manual emergency condition
AND	120	10	Gear 1 of manual emergency condition
AND	121	10	Gear R1 of manual emergency condition
One system for multi-conditions	122	23	System output of electronic control condition
One system for multi-conditions	123	23	System output of manual emergency condition
AND	124	10	System output of PSSTCS

TABLE 5. Minimum cut sets of PSSTCS.

Order	NO. (Operator)	Order	NO. (Operator)	Order	NO. (Operator)
1	1	1	54	1	101
1	7	1	55	1	102
1	15	1	57	1	106
1	20	1	58	1	107
1	25	1	59	1	108
1	26	1	60	1	109
1	27	1	62	1	111
1	28	1	63	2	2, 3
1	29	1	66	2	5, 6
1	30	1	70	2	21, 23
1	31	1	71	2	67, 68
1	32	1	76	2	72, 74
1	33	1	77	2	73, 74
1	34	1	78	2	80, 72
1	35	1	79	2	80, 73
1	36	1	82	2	86, 72
1	37	1	83	2	86, 73
1	39	1	84	2	92, 72
1	40	1	85	2	92, 73
1	42	1	88	2	97, 72
1	43	1	89	2	97, 73
1	45	1	90	2	104, 72
1	46	1	91	2	104, 73
1	47	1	94	3	9, 10, 13
1	48	1	95		
1	49	1	96		
1	51	1	99		
1	52	1	100		

TABLE 6. Classifications of minimum cut sets for PSSTCS.

NO. (Classification)	Name (Classification)	NO. (Operator)
1	Oil pan	1
2	Pressure oil tank	15
3	Rough filter	2, 3
4	Refined filter	9, 10, 20, 28
5	Constant pressure valve	25, 29, 36, 39, 66, 70, 71
6	Pressure pump	5, 6, 27
7	Steering wheel	30
8	Valve body of SDV	31
9	Valve blocks of SDV	32
10	Oil cylinder	33, 55, 60, 79, 85, 91, 96, 102, 109
11	Swash plate of pump	34
12	Two-way variable displacement pump	35
13	One-way valve	21, 37, 40
14	Hand valve	73
15	Group valve	42
16	Reversing motor	43
17	Control panel	46
18	Panel switch	47
19	Handle signal	49
20	Switch	51, 52
21	Pilot valve	54, 115
22	Friction plate	57, 58, 62, 63
23	Manual hydraulic control valve	76, 82, 88, 94, 99, 106
24	Liquid control valve	77, 83, 89, 95, 100, 107
25	Constant pressure throttle valve	78, 84, 91, 101, 108
26	Bypass-valve	13, 23
27	Throttle valve	67, 68
28	Electric controllable valve	74, 81, 88, 95, 97, 104

3) TO COLLECT TEST DATA

According to the complete samples life tests, the life data of each sample for all classifications are collected, as presented in Appendix II.

E. EVALUATING FAILURE RATE OF UNIT FOR PSSTCS

For non-life test units, their failure rates are set 0. And for life test units, their failure rates are evaluated, as follows:

1) TO SELECT EVALUATION METHOD FOR EVALUATING BASIC FAILURE RATE OF LIFE TEST UNIT

Because the samples of each life test units are very small, whose number is 10, the Bayes method is adopted to evaluate the basic failure rates of life test units in this case.

2) TO EVALUATE THE BASIC FAILURE RATE OF LIFE TEST UNIT

According to Section II-A, the deducing processes of the point estimation formula of the basic failure rate for life test unit are as follows:

(i) To determine the total time test according to selecting data of life test unit, as Eq. (7).

$$T_j = \sum_{i=1}^{10} t_{ji} \tag{7}$$

where, T_j is the total time of jth classification, $j = 1, 2, \cdots, 28$; t_{ji} is the test date of ith life test unit for jth classification, $i = 1, 2, \cdots, 10$.

(ii) To develop the likelihood function, as shown in Eq. (8).

$$\begin{aligned} L\left(T_j \left|\lambda\right.\right) &= \prod_{i=1}^{10} P\left(t_{ji} \left|\lambda\right.\right) \\ &= \lambda^{10} \exp\left\{-\lambda \sum_{i=1}^{10} t_{ji}\right\} = \lambda^{10} \exp\left\{-\lambda T_j\right\} \end{aligned} \tag{8}$$

where, $L(T_j\left|\lambda\right.)$ is the likelihood function.

(iii) In this case, $\pi(\lambda)$ is adopted the Jeffery's prior distribution.

(iv) To determine the posteriori distribution $f\left(\lambda \left|T_j\right.\right)$ of the basic failure rate for life test unit, as shown in Eq. (9). It obeys the Gamma distribution with two parameters $\Gamma\left(\lambda \left|10, T_j\right.\right)$.

$$f\left(\lambda \left|T_j\right.\right) = \frac{L(T_j\left|\lambda\right.)\pi(\lambda)}{\int_{\Theta} L(T_j\left|\lambda\right.)\pi(\lambda)d\lambda} = \frac{T_j^{10}\lambda^9 e^{-\lambda T_j}}{\Gamma(10)} \tag{9}$$

(v) To obtain the point estimation of the basic failure rate for life test unit by calculating the expectation of $f\left(\lambda \left|T_j\right.\right)$, as shown in Eq. (10).

$$\begin{aligned} \widehat{\lambda} &= E\left(\lambda \middle| T_j\right) = \int_0^{+\infty} \lambda \cdot \frac{T_j^{10}}{\Gamma(10)} \lambda^{10-1} e^{-T_j\lambda} d\lambda \\ &= \int_0^{+\infty} \frac{T_j^{10}}{\Gamma(10)} \cdot \frac{\Gamma(10+1)}{T_j^{10+1}} \\ &\quad \cdot \frac{T_j^{10+1}}{\Gamma(10+1)} \lambda^{10+1-1} e^{-T_j\lambda} d\lambda \\ &= \frac{T_j^{10}}{\Gamma(10)} \cdot \frac{\Gamma(11)}{T_j^{11}} = \frac{10\Gamma(10)}{\Gamma(10)\, T_j} = \frac{10}{T_j} \end{aligned} \tag{10}$$

where, $E\left(\lambda \middle| T_j\right)$ is the expectation of $f\left(\lambda \left|T_j\right.\right)$.

TABLE 7. Failure rate of life test unit.

NO. (Classification)	Point estimation of failure rate	NO. (Classification)	Point estimation of failure rate
1	7.5620e-04	15	2.0173e-04
2	3.2985e-04	16	7.5466e-04
3	0.0058	17	5.0886e-05
4	2.2947e-04	18	5.9953e-05
5	2.0157e-04	19	8.0725e-05
6	7.4884e-04	20	5.0548e-05
7	1.0138e-06	21	1.3050e-04
8	1.0280e-04	22	5.0109e-05
9	5.7710e-04	23	2.5035e-04
10	1.0208e-04	24	2.5038e-04
11	5.0767e-05	25	5.8059e-04
12	9.2464e-04	26	2.4582e-04
13	7.4582e-04	27	2.3949e-04
14	1.3058e-04	28	2.6263e-04

TABLE 8. Reference value of π_Q.

Quality grade	π_Q	Quality grade	π_Q	Quality grade	π_Q	Quality grade	π_Q
Grade A	0.3	Grade B	0.6	Grade C	1	Grade D	3

TABLE 9. Reference value of π_E.

Work environment	Mechanical units and hydraulic units in oil medium under a closed condition	Operating units in closed shell	Operating units in open environment
π_E	1.0	1.8	2.5

3) TO EVALUATE THE FAILURE RATE OF LIFE TEST UNIT BY EQ. (4), AS PRESENTED IN TAB. VII. π_Q AND π_E REFER TO TAB. VIII AND TAB. VIIII, RESPECTIVELY [29].

F. EVALUATING LIFE EXPECTANCY OF PSSTCS

1) TO DETERMINE THE TIME POINTS FOR FITTING SYSTEM RELIABILITY FUNCTION OF PSSTCS

In this case, the 500 hours are averagely divided into 100 time points in order to fitting system reliability function of PSSTCS greatly.

2) TO CALCULATE THE UNIT RELIABILITY AT DIFFERENT TIME POINTS

According to Eq. (5), the reliabilities of units can be obtained by using their failure rates, which for the non-life test units and the life test units are 0 and the data presented in Tab. VII, respectively.

3) TO CALCULATE THE RELIABILITY OF PSSTCS AT DIFFERENT TIME POINTS

The signal flow 1, 4, 7, 8, 15, 19, 20, 25, 29, 46, 59, 69, 70, 71, 73 and 115 are shared signals in Fig. 4, so the exact algorithm with shared signals is adopted to calculate the system reliability. The reliabilities of PSSTCS at different time points are presented in Tab. X.

G. TO EVALUATE LIFE EXPECTANCY OF PSSTCS

The system reliability function is fitted by using the data of Tab. X, as Eq. (11). And according to Eq. (6), the Life

TABLE 10. Reliability of PSSTCS at different time points.

NO. (time point)	System reliability	NO. (time point)	System reliability
1	0.9676	26	0.2651
2	0.9341	27	0.2488
3	0.8999	28	0.2334
4	0.8652	29	0.2188
5	0.8304	30	0.2051
6	0.7956	31	0.1921
7	0.7611	32	0.1798
8	0.7270	33	0.1682
9	0.6934	34	0.1574
10	0.6605	35	0.1471
11	0.6283	36	0.1375
12	0.5970	37	0.1284
13	0.5666	38	0.1199
14	0.5372	39	0.1119
15	0.5088	40	0.1045
16	0.4815	41	0.0974
17	0.4552	42	0.0909
18	0.4299	43	0.0847
19	0.4057	44	0.0789
20	0.3826	45	0.0735
21	0.3605	46	0.0685
22	0.3395	47	0.0638
23	0.3194	48	0.0593
24	0.3004	49	0.0552
25	0.2823	50	0.0514
51	0.0478	76	0.0073
52	0.0444	77	0.0068
53	0.0413	78	0.0063
54	0.0384	79	0.0058
55	0.0357	80	0.0054
56	0.0331	81	0.0050
57	0.0308	82	0.0046
58	0.0286	83	0.0043
59	0.0265	84	0.0040
60	0.0246	85	0.0037
61	0.0229	86	0.0034
62	0.0212	87	0.0031
63	0.0197	88	0.0029
64	0.0183	89	0.0027
65	0.0169	90	0.0025
66	0.0157	91	0.0023
67	0.0146	92	0.0021
68	0.0135	93	0.0020
69	0.0125	94	0.0018
70	0.0116	95	0.0017
71	0.0108	96	0.0015
72	0.0100	97	0.0014
73	0.0092	98	0.0013
74	0.0085	99	0.0012
75	0.0079	100	0.0011

Expectancy of PSSTCS can be obtained, as Eq. (12).

$$R(t) = e^{-0.01009t}, 0 \leq t \leq 500hours \tag{11}$$

$$MTTF = \int_0^{500} R(t)dt = \int_0^{500} e^{-0.01009t}dt = 98.4696hours \tag{12}$$

IV. RESULTS AND ANALYSIS

Monte Carlo method is widely used to evaluate system Life Expectancy. Thus, in order to verify the advantages, feasibility and rationality of the new Life Expectancy assessment method for complex systems proposed in this paper, its result is compared with the results by Monte Carlo methods simulating 100,000 times and 1,000,000 times. And this paper's Life Expectancy assessment method and Monte Carlo method simulating 1,000,000 times operate 3 times. In addition to evaluating the failure rates of units, the Life Expectancy assessment steps by Monte Carlo method are mainly

(1) To establishing Monte Carlo Simulation model according to the logical relationship of units and systems.
(2) To calculate the unit reliability at the *ith* time point by using the data of Tab. VII and Eq. (5), $i = 1, 2, \cdots, 100$.
(3) To generate random number according to unit reliability at the *ith* time point.
(4) To simulate a given number of simulation times according to Monte Carlo simulation model to obtain system reliability at the *ith* time point.
(5) To repeat step (2) and step (4), the system reliabilities at all-time points are obtained.
(6) To fit system reliability function by using the data of step (5).
(7) To evaluate system Life Expectancy by Eq. (6)

Above all, the Life Expectancies of PSSTCS by Monte Carlo methods and this paper's method are presented in Tab. XI and Tab. XII.

TABLE 11. Comparison I: assessment result and evaluation efficiency.

Index	Monte Carlo method		This paper's method
	100,000	1,000,000	
System LIFE EXPECTANCY *hours*	96.3678	98.0573	98.4696
Operation time *Seconds*	2871.6	5174.2	262.336

TABLE 12. Comparison II: Stability.

NO. (operation)	System Life Expectancy *hours*	
	Monte Carlo method (1,000,000)	This paper's method
1	97.4278	98.4696
2	98.0573	98.4696
3	97.9628	98.4696

According to Tab. XI, the Life Expectancy of PSSTCS by this paper's method is in close proximity to the result by Monte Carlo method simulating 1,000,000 times, so it indicates that the new Life Expectancy assessment method proposed in this paper is feasible and reasonable. Furthermore, the Monte Carlo simulation model does not connect the system structure, function constitutes, and system characteristics closely, and it is not easy to check. And the Monte Carlo method does not take into consideration the system characteristics of PSSTCS, which can improve the system reliability, so that the Life Expectancies of PSSTCS by Monte Carlo methods are less than the result of this paper's method. Moreover, the operation time of this paper's method is much less than the operation times of Monte Carlo method simulating 100,000 times and 1,000,000 times. Thus, it shows that this paper's method has obvious advantages in aspects of establishing reliability model, evaluation accuracy and operation efficiency.

According to Tab. XII, the Life Expectancies of PSSTCS by Monte Carlo method at different operation number are

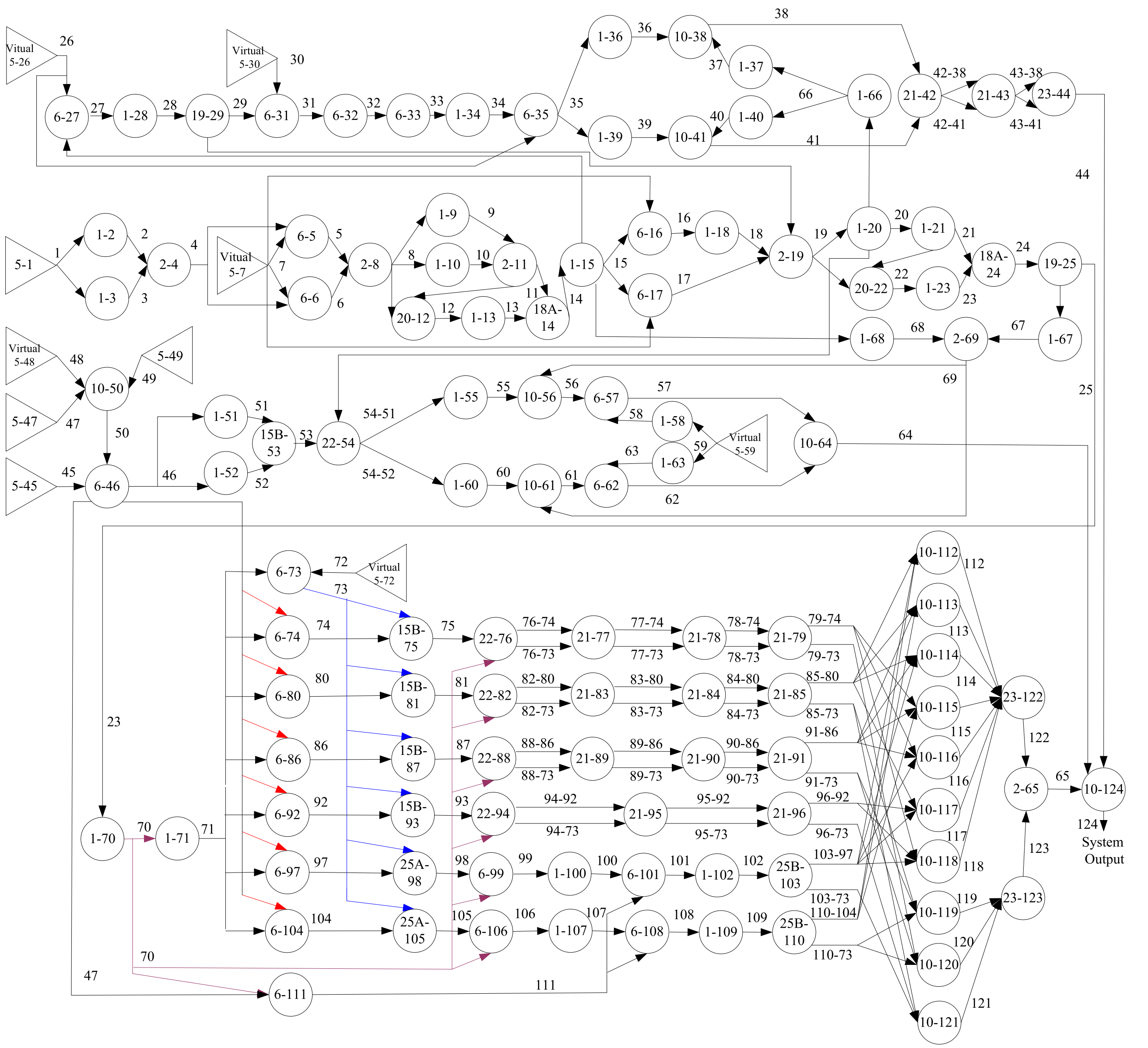

FIGURE 5. Structure principle illustration of the PSSTCS.

fluctuant because of the influence of sampling, but the Life Expectancies by this paper's method at different operation number are same. Clearly, it indicates that this paper's method can avoid the complex sampling process and the influence of sampling, so that it can obtain a stable and unique assessment result.

The process of this paper's method shows that it has some obvious advantageous, as follows:

(1) Only the reliability data of unit is used to evaluate the system Life Expectancy, so that it can save evaluation cost.
(2) GO model is closely linked to system structure, function constitute and system characteristics, so it is easy to check for complex systems with multi-characteristics. And GO operation can avoid the influence of sampling effectively.
(3) The evaluation process of this paper's method is easy to operate.

V. CONCLUSION

This study proposes a new Life Expectancy for complex systems with multi-characteristics based on GO method. First, the new Life Expectancy assessment method is expounded in detail from conducting system analysis of complex systems, establishing GO model of complex systems, selecting life test unit of complex systems, collecting data of life test unit for complex systems, evaluating failure rate of unit for complex systems, and evaluating Life Expectancy of complex systems. On this base, its process is formulated. Then, the control system of power-shift steering transmission for a heavy vehicle, which is a typical mechatronics control system with multi-characteristics, such as multi-state, multi-function,

TABLE 13. Test data of PSSTCS.

NO. (Classification)	Sample Date *hours*										T_j /*hours*
1	2358	2391	2463	2277	2414	2377	2381	2305	2503	2334	23803
2	2934	3155	3085	3168	3029	2868	2848	3155	3010	3065	30317
3	189	201	199	195	142	156	166	163	157	167	1735
4	8700	8562	8354	8991	8853	8726	8635	8977	8546	8812	87156
5	4852	4823	4956	4978	5100	5103	4978	4721	5103	4997	49611
6	1280	1356	1305	1319	1456	1279	1357	1285	1345	1372	13354
7	1000000	987000	992300	977090	991894	987030	995200	978913	987059	967092	9863578
8	9710	9568	9384	9991	9835	9762	9685	9977	9546	9821	97279
9	1667	1783	1725	1698	1801	1754	1739	1684	1621	1856	17328
10	9810	9588	9884	9791	9878	9736	9985	9877	9599	9816	97964
11	19810	19568	19784	19794	19873	19732	19975	19827	19399	19216	196978
12	1111	1013	1245	1019	980	1078	1034	1123	1118	1094	10815
13	1310	1323	1305	1319	1456	1322	1423	1347	1345	1258	13408
14	7692	7789	7523	7921	7653	7895	7712	7625	7314	7458	76582
15	5000	4892	4945	4878	4963	5103	5058	4978	5002	4753	49572
16	1316	1423	1315	1219	1356	1289	1333	1387	1315	1298	13251
17	19110	19268	20784	19344	19893	19252	19965	19817	19299	19786	196518
18	16667	15892	16689	17125	17002	16987	16782	17211	16653	15789	166797
19	12500	11589	11387	12670	12543	12131	13451	12478	11987	13141	123877
20	20000	19872	19568	20157	20365	19782	19145	18987	19956	20001	197833
21	7692	7726	7456	7812	7796	7523	7845	7536	7915	7325	76626
22	20012	19856	19785	19453	20121	20068	19975	19456	20058	20781	199565
23	4001	3978	4012	4123	3879	3945	3987	4109	3945	3965	39944
24	3901	4078	3913	4312	3789	3867	3889	4078	4201	3912	39940
25	1667	1523	1789	1669	1871	1712	1703	1903	1725	1662	17224
26	4101	4278	4013	4112	3989	4167	3989	4012	4101	3918	40680
27	4167	4325	4215	4123	4019	4156	4112	4325	4216	4098	41756
28	3825	3789	3910	3789	3980	3678	3812	3789	3845	3659	38076

one system for multi-conditions, and standby correlation, is taken as an example to evaluate its Life Expectancy by this paper's method. Finally, in order to verify the advantages, feasibility and rationality of the new Life Expectancy assessment method, the results are compared with the results by Monte Carlo method. Moreover, compared with the evaluation results by Monte Carlo methods, it shows that this paper's method has the following outstanding advantages:

(1) This paper's method can take into consideration various system characteristics to evaluate Life Expectancy of complex systems, so that its evaluation accuracy is higher.
(2) This paper's method uses the GO model as system reliability model, so that it can connect the system structure, function constitutes, and system characteristics directly and closely, and it is easy to check.
(3) This paper's method uses the GO operation to obtain the system reliability at different time points, so that it can avoids the influence of sampling for result to obtain the stable evaluation result, but it also has higher efficiency.
(4) This paper's method uses only the reliability data of unit to evaluate the system Life Expectancy, so that it can save evaluation cost.
(5) This paper' method has a brief and clear assessment process, and it is easy to make program to operate. Moreover, the Life Expectancy assessment results have high-level consistency by different engineer(s).

All in all, this Life Expectancy assessment method not only improves the theory of GO method, so that GO method is applied to evaluate the Life Expectancy of complex systems with multi-characteristics firstly; but it also can overcome the disadvantages of the existing system Life Expectancy evaluation methods efficiently. Furthermore, this paper provides a new approach for Life Expectancy assessment of complex systems, which can takes into consideration various system characteristics, and only uses unit life data, so that it is low cost, higher estimating efficiency and accuracy, and a more stable assessment result.

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APPENDIX I

See Fig. 5.

APPENDIX II

See Table 13.

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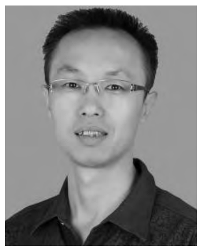
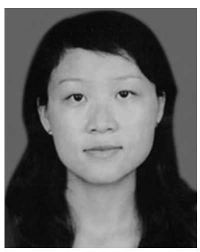
XIAO-JIAN YI was born in 1987. He received the B.S. degree in control technology from the North University of China, in 2010, and the M.S. and Ph.D. degrees in reliability engineering from the Beijing Institute of Technology, in 2012 and 2016, respectively. During 2015–2016, he was a Joint Training Ph.D. Student with the University of Ottawa to study on robot reliability and maintenance. From 2016 to 2018, he was an Associate Professor with the China North Vehicle Research Institute, the Beijing Institute of Technology, and the Academy of Mathematics and Systems Science, Chinese Academy of Sciences. He has authored one book, more than 50 articles, and holds eight patents. His research interests include system reliability analysis, system reliability assessment, optimization design, maintainability engineering, fault diagnosis, point process theory, and statistical learning theory. He is a Technical Committee Member of the IEEE PHM 2018, the Program Chair of PHM-Chongqing 2018 and SDPC 2018, and a Reviewer for ten international journals and conferences, such as the IEEE Transactions on Reliability, *Reliability Engineering and System Safety*, and *Quality and Reliability Engineering International*. He was a member of ASME and SAE, China. He was a recipient of the Science and Technology Progress of NORINCO, in 2015.



YUE-FENG CHEN is currently with the Armed Force Research Institute, Army Institute of Research, Beijing, China. He is mainly engaged in the research in the field of fault diagnosis, prediction, and health management of special equipment and integrated electronic information system of vehicles. He has published one monograph, one translation, and more than 30 papers. He was a recipient of a number of science and technology progress awards.



HUI-NA MU was born in 1981. She received the B.S. degree in information and computing science from Shandong University, Shandong, China, in 2004, and the Ph.D. degree in military chemistry and pyrotechnics from the Beijing Institute of Technology, Beijing, China, in 2009. From 2009 to 2010, she held a Postdoctoral position with the Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing. From 2015 to 2016, she was a Visiting Scholar with the University of Connecticut, Connecticut, USA. Since 2011, she has been an Assistant Professor with the School of Mechanical Engineering, Beijing Institute of Technology. She has published over 50 articles. Her research interests include the reliability and safety theory, and analysis and assessment for complex systems. She is a member of ASME and the Director of the Reliability Engineering Branch, China Field Statistical Research Association. Her awards and honors include the First Military Progress Prize in Science and Technology, in 2013, and the Excellent Paper of the Academic Annual Conference of the Chinese Association for Applied Statistics of Reliability Society, in 2015.

JIAN SHI was born in 1966. He received the B.S. degree from the Department of Mathematics, Peking University, in 1988, and the M.S. and Ph.D. degrees from the Department of Probability and Statistics, Peking University, in 1994. From 1994 to 1996, he held a Postdoctoral position with the Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing, China. In 1996 and 1998, he held a Postdoctoral position with the Department of Statistics, The Chinese University of Hong Kong, Hong Kong. From 2000 to 2001 and from 2003 to 2004, he was a Visiting Scholar with the Department of Statistics and Actuarial Science, The University of Hong Kong, Hong Kong. From 2001 to 2002, he was a Visiting Scholar with the Department of Epidemiology and Public Health, Yale University. Since 2007, he has been a Professor with the Academy of Mathematics and Systems Science, Chinese Academy of Sciences. He has published over 50 articles. His research interests include reliability and industrial statistics, biomedicine statistics, and statistical inference. He has been the Managing Director and the Deputy Secretary General of the China Association of Probability Statistics, since 2006, was the Director of the Chinese Association for Applied Statistics, from 2009 to 2013, has been a Vice Chairman of the China Standardization Committee, Technical Committee for Standardization of the Application of National Statistical Methods, and Technical Committee on Data Processing and Interpretation, since 2005, was an Editorial Board Member of System Science and Mathematics, from 2009 to 2013, and has been an Editorial Board Member of *Mathematical Reviews*, since 2007.

PENG HOU was born in 1986. He received the B.S. degree in theoretical physics from Jinzhong University, in 2010, and the M.S. degree in law from the Shanxi University of Finance and Economics, in 2013. He is currently pursuing the Ph.D. degree majoring in reliability engineering with the Beijing Institute of Technology. He has authored one book and published over 10 articles. His research interests include fault diagnosis, point process theory, and statistical learning theory.