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Reliability Analysis of C^4ISR Systems Based on Goal-Oriented Methodology

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Abstract: Hard-and-software integrated systems such as command and control systems (C^4ISR systems) are typical systems that are comprised of both software and hardware, the failures of such devices result from complicated common cause failures and common (or shared) signals that make classical reliability analysis methods will be not applicable. To this end, this paper applies the Goal-Oriented (GO) methodology to detailed analyze the reliability of a C^4ISR system. The reliability as well as the failure probability of the C^4ISR system, are reached based on the GO model constructed. At the component level, the reliability of units of the C^4ISR system is computed. Importance analysis of failures of such a system is completed by the qualitative analysis capability of the GO model, by which critical failures of hardware failures like communication module failures and motherboard module failures as well as software failures like network module application software failures and decompression module software failures are ascertained. This method of this paper contributes to the reliability analysis of all hard-and-software integrated systems.

Keywords: command and control system; GO methodology; reliability model; reliability analysis

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1. Introduction

Command and control systems (C^4ISR systems), integrated by both hardware and software, are the core element of battlefield command and dispatch operations, which are designed to reliably and error-freely distribute commends to all stakeholders under the complex, variable and unpredictable battlefield conditions during wartime [1]. Therefore, the reliability of such systems is always one of the core performance features that need to be investigated. However, two characteristics of C^4ISR systems, that are, complicated configurations of systems and large-scale information involved, introduce chaos to the reliable operation of these systems, especially to their failure mechanism identification, reliability analysis, and availability improvement [1,2]. Failure frequency of C^4ISR systems is high under the real battlefield circumstance according to the failure information already mentioned and which reduces significantly the reliability, availability, failure-free operation time of C^4ISR systems [3].

To this end, a thorough and comprehensive reliability analysis of C^4ISR systems is mandatory before its delivery and installation to end-users. System reliability analysis is to discover and determine the risky factors that may lead to malfunctions during the design and actual operation of systems so that to improve the system's reliability by preventing the occurrence of critical failures. However, unlike mechanical, electrical, and software systems that consist of either hardware or software systems, C^4ISR systems were composed of both, which introduces additional difficulties to the reliability analysis of such systems. Each of the system's components could have a more or less complex redundant structure, but we should consider it as a whole. Consequently the system could be considered a minimal serial structure with multiple recovery capacity. The considerations regarding the reliability modeling of combined hardware/software systems had as a starting point the Rome Laboratory's "System and Software Reliability Assurance Notebook" [4]. The document offers a methodology for the reliability assurance study of systems composed both from hardware and software elements, designed for estimation and prediction of its reliability. Moreover, due to the properties already mentioned above, classical reliability analysis methodologies which have been applied maturely for instance Fault Tree Analysis (FTA), Failure Mode and Effect Analysis (FMEA), and Monte Carlo (MC) method, Bayesian network (BN) and so on are not applicable for the analysis of hard-and-software integrated systems such as C^4ISR systems.

The Goal-Oriented (GO) method is directly connected with product structures, functions, and working principles [5]. However, due to its superior features such as easy to model dynamics in reliability modeling scholars are currently began to engage in developing and applying this method theory in various engineering cases [6,7], especially in reliability and safety analysis of weapon and missile systems [4,5], transportation systems [8], and power systems [6,9]. The initial of the GO method can be traced back to 1970s, when the American Electric Power Research Institute (EPRI) highlighted the application of the GO method in the safety and availability analysis of nuclear power plants, by which the failure probability, availability, and maintainability of nuclear power plants are reached [10,11]. The GO method also applied into risk analysis of fuel transportation [10], and post-processing files [12]. At the same time, specific GO software has been developed by companies such as Kaman Company to promote the actual implementation of such a method [12].

From the methodology development point of view, Chu [13] used the GO method to evaluate the availability and risk probability of a 1.1 MW power station that composed of approximately 60 systems and 10,000 components, concluded that the GO method can simulate and analyze the entire nuclear power plant. Yi et al. [14] applied the GO method to complete a reliability analysis of a hydraulic transmission oil supply system (HTOSS) under high-speed conditions and the results show that GO method is suitable for reliability analysis of repairable systems with multiple fault modes. Yin et al. [15] implemented the GO methodology to solve low precision and insufficient efficiency problems in reliability assessment of mechanical equipment, the results indicate that the GO method provides useful reference in addressing the complicated, multiple states and time sequence problems in some engineering cases. Yang et al. [16] analyzed the reliability of a braking system by the GO method, concluded that the GO method is applicable for operation and maintenance investigations of mechanical systems like braking systems. Jia [17] established a GO model for an emergency management system, indicates that the GO method is feasible and efficient for conducting the reliability analysis of social systems. Liu et al. [18] combined the GO method with fuzzy theory, accordingly, established a fuzzy GO model that is proved to be more feasible for reliability analysis.

Overall, the GO methodology is a success-oriented system reliability analysis method with clear structural representation, that is, system configurations can be directly mapped to the GO model without complicated mapping algorithms [19,20]. Compared with the commonly used reliability analysis method such as FTA [21,22], FMEA [23,24], MC [25], and BN [26,27], the GO method has obvious advantages [28–31]: (i) GO models are easy-to-construct, which are able to map from a physical structure of an actual product, by which the functional diagrams are not required; (ii) GO models are easy-to-calculate, quantitative and qualitative analyses of GO models can be obtained through multiple GO operations so that he complicated analysis process (like FTA and BN) can be avoided; (iii) results of GO models are convincing and credible thanks to the specifically designed GO operators. Accordingly, the GO method was selected to represent the failure configuration and structure properties of the C^4ISR system studied in this paper.

The rest of this paper is arranged as follows: Section 2 introduces the modeling and analysis of the GO method. Section 3 presents the case study. Results are demonstrated in Section 4. Discussions are settled at Section 5. The conclusions are listed in Section 6.

2. Methodology

The GO method is the combination of graph theory and probability methodology [32]. The operator of the GO method connects the signal flow to simulate units of a system. Overall, in this method, 17 operators have been defined, as shown in Table 1. The operator type determines characteristics of the operator including operation rules, function, etc. [33] Moreover, signal flow in the GO model represents the logical relationship between input and output operators. State value and state probability are basic attributes of operators and signal flow [34].

Table 1. Standard operators in the GO method.

Operators	Function	Category	Operators	Function	Category
1	Simulate two-state units	Function	10	AND	Logical
2	OR	Logical	11	K-out-of-M	Logical
3	Simulate three state units	Function	12	Choose different output path by input signal	Function
4	Multiple input Unit	Function	13	Multiple inputs and output signals	Function
5	Single input Unit	Function	14	Linear relation of multiple (input) to one (output)	Logical
6	Open after receiving signals	Function	15	Output signal depends on the probability of input signal	Logical
7	Close after receiving signals	Function	16	The unit state resumed close by receiving the control signal	Function
8	Delay state	Function	17	The unit state resumed open by receiving the control signal	Function
9	Output signal depends on two input signals' state	Logical			

The steps of the establishment of reliability GO graph model for a system based on the GO method, generally, are as follows [14,16–18]: (i) System identification and analysis. Identify the system that to be analyzed including its scope, failure mode, function, and relationship among each unit; (ii) Input and output determination. Ascertain the inputs and outputs of the system that already identified in Step (i); (iii) the successful operation criteria determination. A successful state includes the degraded operation of the system and it can give the minimum output signal set; (iv) GO model construction. To create a GO diagram based on the structural diagram of the system by connecting the operators according to the signal flow direction, which includes several steps:

- Select the corresponding operator according to the function of the system unit.
- Connect signal flow to operators selected. Specifically, the essence of the signal flow is the direction of the signal in the system.

- Number the operators and signal flow in the GO diagram.
- Checking the GO model until it complies with the drawing rules of the GO method, otherwise, modify the model (repeat the above steps).

The qualitative analysis of the GO method is to seek the minimum failure unit within the system, while, the quantitative analysis calculates the overall reliability of the system. The state accumulation analysis method is used to quantitatively analyze the system. Accordingly, the state value of the signal flow in the GO method is defined as $0, \cdots, N$, where 0 represents the advanced state and N represents the failure state. Other values correspond to multiple states between 0 and N. Specifically, $P_S(i)$ represents the input signal with the state i, and $P_R(i)$ is the state probability of $P_S(i)$; $A_S(i)$ denotes the cumulative probability of $P_S(i)$, and $A_R(i)$ reflects the cumulative probability of the state of the output signal flow. The calculation of $A_S(i)$ and $A_R(i)$ are listed in Equation (1):

$$\begin{array}{l} A_S(i) = \sum_{j=0}^{i} P_S(j), i = 0, \cdots, N-1, A_S(N) = 1 \\ A_R(i) = \sum_{j=0}^{i} P_R(j), i = 0, \cdots, N-1, A_R(N) = 1 \end{array} \quad (1)$$

The reliability analysis is to find the minimum cut set of the GO model. For a system with M operators, find out the smallest cut set of the system until the states of other operators are 0 and only one operator whose state value is 1, calculate the probability that the system can run successfully according to the probability analysis method. After the first-order minimum failure sets of the system had been ascertained, repeat the above step until the second-order minimum failure set of the system is obtained. The qualitative analysis flowchart of the GO model is shown in Figure 1.

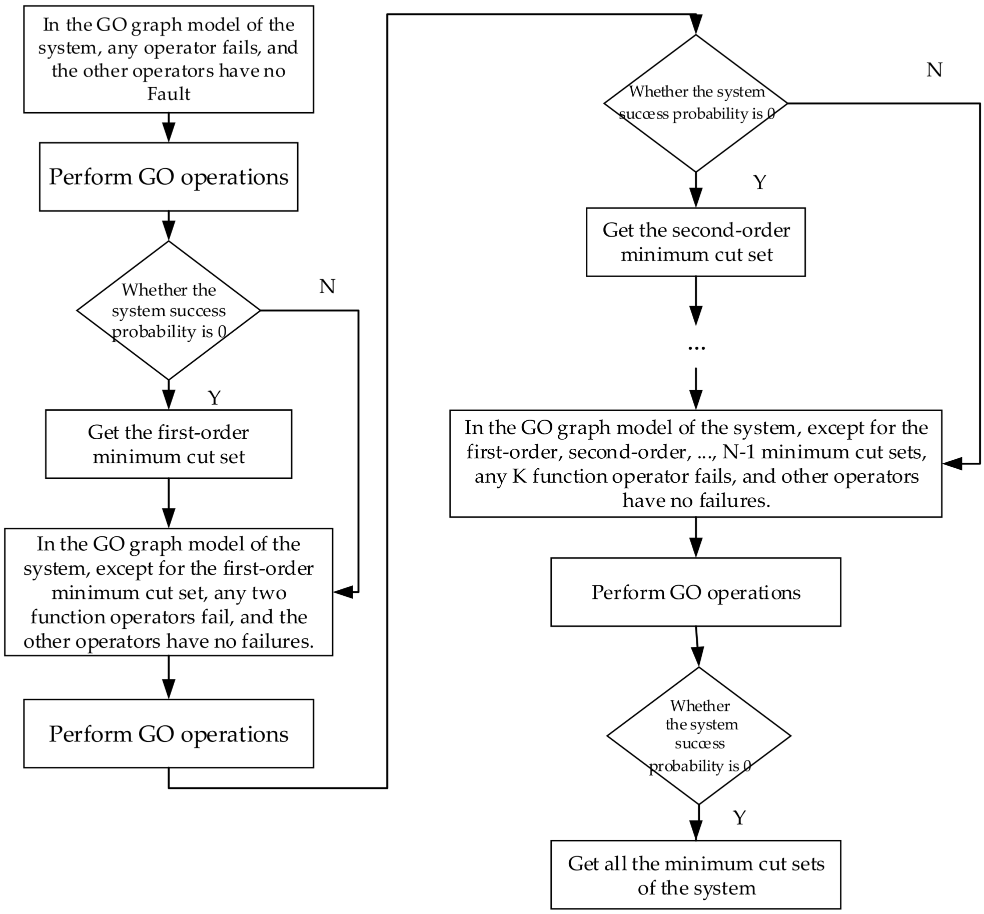

Figure 1. The qualitative analysis flowchart of the GO model.

For a complicated system such as a C[4]ISR system, common cause failures and common signals introduce uncertainty to the results concluded by the GO model. Accordingly, data pretreatments, also known as data corrections, are required. Generally, data correction of GO models, for both common signals and common cause failures, obeys the following rules:

Regarding the correction of reliability data with common signals. The common signal is a signal that the input signal of multiple operators simultaneously. Hence, the state probability of which can be included in all subsequent signal flows related. For a system with M common signals, S_j, $j = 1, 2, \cdots, M$ and only one output signal R. The state probability of the output signal is:

$$P_R = f(P_{S1}, P_{S2}, \cdots, P_{SM}) \tag{2}$$

where, P_R is the success probability of the output signal, $P_{S1}, P_{S2}, \cdots, P_{SM}$ denote M success probabilities of common signals.

For one common signal, denote $P_{S1} = 0$ (The common signal S1 fails) and the success probability of the system output signal P_{R0}, $P_{S1} = 1$ (The common signal S1 succeeds) and the success probability of the system output signal P_{R1}. Hence, the success probability of the output signal is:

$$P_R = (1 - P_{S1})P_{R0} + P_{S1}P_{R1} \tag{3}$$

For two common signals S1 and S2, whose success probabilities of the common signals are P_{S1} and P_{S2}, respectively. The cumulative probability of the state of the output signal R is P_R. According to the GO operation rule, P_R can be calculated by:

$$P_R = c_0 + c_1 P_{S1} + c_2 P_{S2} + c_3 P_{S1} P_{S2} \tag{4}$$

where, c_0, c_1, c_2, c_3 are constant parameters. Furtherly, Equation (4) can be reformed to to:

$$P_R = (1 - P_{S1})(1 - P_{S2})P_{R00} + (1 - P_{S1})P_{S2}P_{R01} + P_{S1}(1 - P_{S2})P_{R10} + P_{S1}P_{S2}P_{R11} \tag{5}$$

In which, $P_{R00} = c_0$, $P_{R01} = c_0 + c_1$, $P_{R10} = c_0 + c_2$, and $P_{R11} = c_0 + c_1 + c_2 + c_3$, and $P_{R00}, P_{R01}, P_{R10}, P_{R11}$ are probabilities of the system output signal in the success state under the condition that the common signals S1 and S2 are in failure-fault ($P_{S1} = 0, P_{S2} = 0$), failure-success ($P_{S1} = 0, P_{S2} = 1$), success-failure ($P_{S1} = 1, P_{S2} = 0$) and success-success ($P_{S1} = 1, P_{S2} = 1$) states, respectively.

For M common signals S_m, $m = 1, 2, \cdots, M$, the success probability of each signal is P_{Sm}, the success probability of the output signal is P_R, The cumulative probability of the state of the output signal can be obtained by:

$$P_R = \sum\nolimits_{K_1=0}^{1} \sum\nolimits_{K_2=0}^{1} \cdots \sum\nolimits_{K_M=0}^{1} P_{RK_1K_2\cdots K_M} \prod_{m=1}^{M} [(1 - P_{Sm})(1 - K_m) + P_{Sm}K_m] \tag{6}$$

where, $P_{RK_1K_2\cdots K_M}$ represents the probability of the success state of the output signal under M common signals; K_m represents the correction coefficient of the m-th common signal, K_m= 0, denotes fault state, while, K_m= 1, reflects success state.

Moreover, the probability of a single signal can be calculated as:

$$\prod_{m=1}^{M} [(1 - P_{Sm})(1 - K_m) + P_{Sm}K_m] \tag{7}$$

As for the reliability data correction with common cause failures. Common cause failures denote that several failures share the same common cause in a system. The β-factor model and the probability algorithm are primary methods handling the data correction of common cause failures in GO models.

The β-factor model uses the β factor to measure the impact of common cause failures. Let λ_1, λ_2, and λ denote failure rates of unit failure, common cause failure, and system failure, respectively. It is obvious that:

$$Q = Q_1 + Q_2 \tag{8}$$

where, Q_1, Q_2, and Q are unit failure probability, common cause failure probability, and system failure probability, separately.

Accordingly, the β factor can be computed by:

$$\beta = \frac{Q_2}{Q} = \frac{Q_2}{Q_1 + Q_2} = \frac{1 - e^{-\lambda_2 t}}{1 - e^{-\lambda t}} = \frac{1 - e^{-\lambda_2 t}}{(1 - e^{-\lambda_1 t}) + (1 - e^{-\lambda_2 t})} \tag{9}$$

In engineering cases, the β factor should be within [0, 0.25], in which, 0 represents no common cause failures. Generally, the more common cause failures involved, the larger the value of β. And, the value can be selected based on the experience of specialists.

Additionally, the probability algorithm assumes the existence of a common cause failure between units $\boldsymbol{A}$ and $\boldsymbol{B}$, thus the following formula can be obtained:

$$R = c_0 + c_1 Q_A + c_2 Q_B + c_3 Q_{A,B} \tag{10}$$

where, Q_A and Q_B are failure probabilities of units A and B, respectively; $Q_{A,B}$ is the probability of units A and B fail simultaneously; The common cause failure probability of units A and B is $C_{A,B}$, then, the failure probability of units A and B can be computed by:

$$\begin{aligned} Q_A &= Q_{AI} + C_{A,B} \\ Q_B &= Q_{BI} + C_{A,B} \\ Q_{A,B} &= Q_{AI,BI} + C_{A,B} \end{aligned} \tag{11}$$

where, Q_{AI} and Q_{BI} are failure probabilities of units A and B. Accordingly, the following equation can be obtained:

$$\begin{gathered} R = c_0 + c_1 Q_{AI} + c_2 Q_{BI} + c_3 Q_{AI,BI} + (c_1 + c_2 + c_3) C_{A,B} \\ R = R_I + (R_{00} - R_{11}) C_{A,B} \end{gathered} \tag{12}$$

where, R_I is the system success probability without common cause failures; R_{00} and R_{11} are system success probabilities under the condition that the success probabilities of units A and B with common cause failures are 0 and 1. Hence, for the situation of the system with M common cause failure units, the following formula is easy to be reached:

$$R = R_I + \sum_{m=1}^{M} (R_{00\cdots} - R_{11\cdots}) C_m \tag{13}$$

3. Case Study

The C^{4}ISR System

This paper analyzes the reliability of the C^{4}ISR system. The C^{4}ISR system is mainly composed of a database, an information desk, a command and control desk, and a commander center. In the database, the signal is the input of the signal receiver, and the outputs are two signal flow paths: the from the input to the server and information exchange module we well as from the input to the RAID control. Then the signal flows into the data storage module, and finally reaches the hard disk; The output of the database is the input of the information editing station. In this device, the signal reaches the data loading module and then goes to the motherboard module; The input of the command console is conducted by the intelligence editing station. The signal passes the USB interface module and motherboard module, then it is distributed in two paths: from the input to the touch display and from the input to the control exterior; After the headquarters receives the signal from the command console it sends the signal to the motherboard module. The schematic diagram of the C^{4}ISR system is demonstrated in Figure 2. According to the C^{4}ISR system, a GO model was constructed, see in Figure 3. The elements of the GO model are introduced in detail in Table 2. The failure rates of each unit are listed in Table 3.

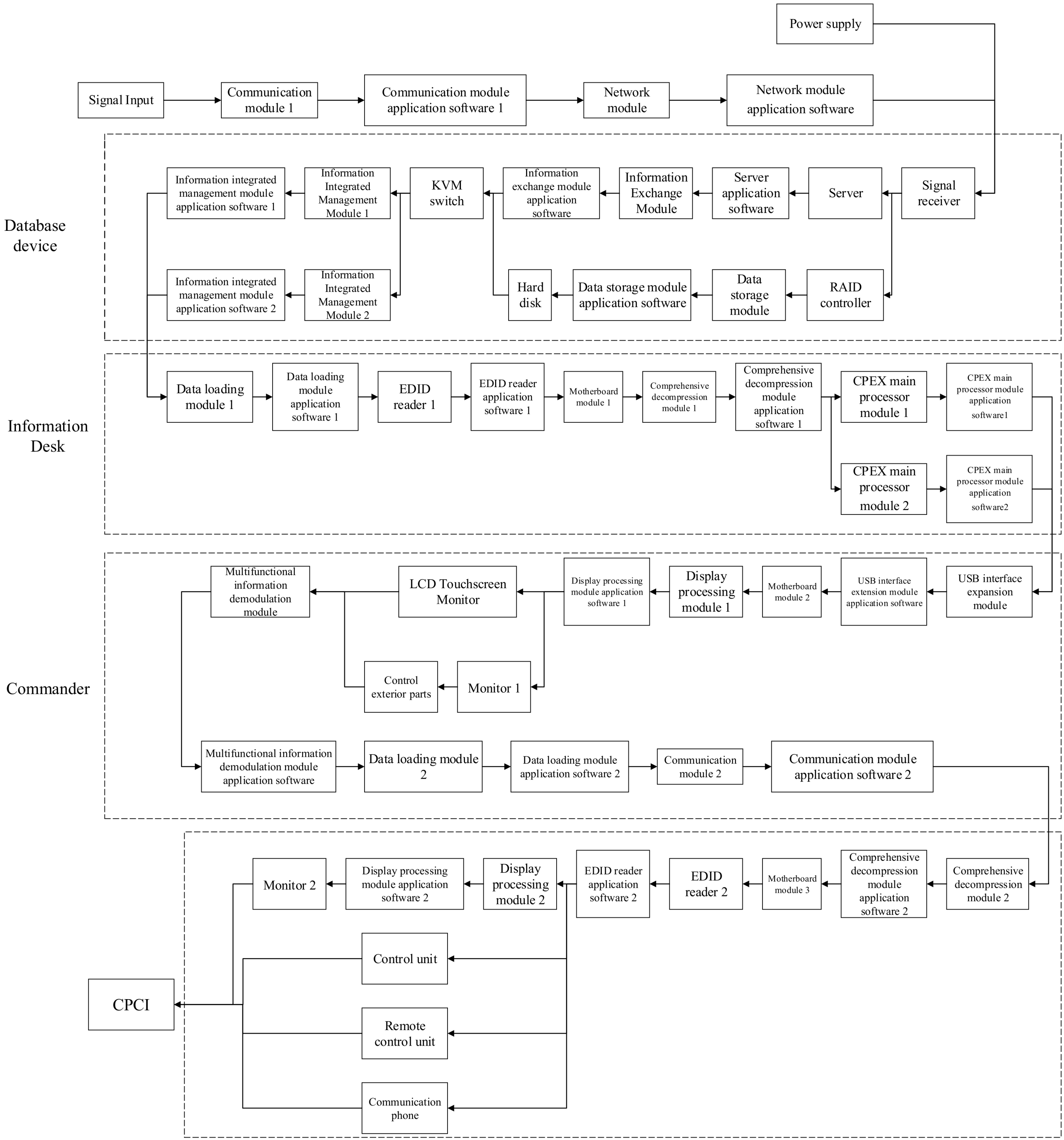

Figure 2. The schematic diagram of the C^{4}ISR system.

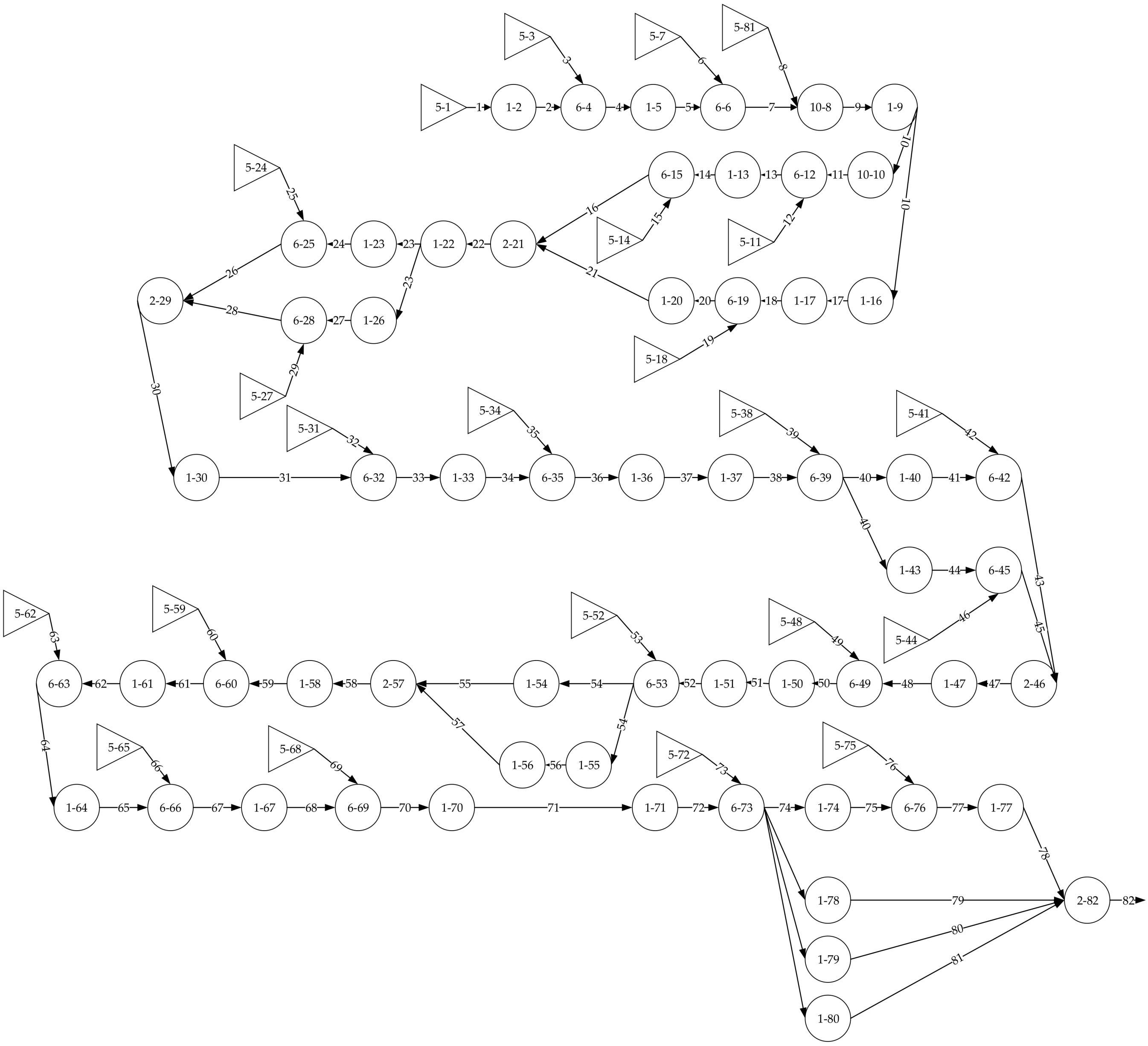

Figure 3. GO graph model for system reliability.

Table 2. The C^4ISR System software and hardware unit and their logical relationships.

Unit	Operator Number	Operator Type	Function Description	Unit	Operator Number	Operator Type	Function Description
Input signal	1	5	Input unit	Monitor_2	77	1	Two-state unit
Communication module_1	2	1	Two-state unit	Control unit	78	1	Two-state unit
Communication module	4	6	Signal-on unit	Remote control	79	1	Two-state unit
Communication module	4	6	Signal-on unit	Communication	80	1	Two-state unit
Network module	5	1	Two-state unit	Signal receiver	9	1	Two-state unit

Table 2. *Cont.*

Unit	Operator Number	Operator Type	Function Description	Unit	Operator Number	Operator Type	Function Description
power supply	81	5	Input unit	Server	10	1	Two-state unit
AND gate	8	10	AND	Server software	12	6	Signal-on unit
Network module software	6	6	Signal-on unit	Information Exchange Module	13	1	Two-state unit
Information exchange module software	15	6	Signal-on unit	Information Management Module Application_1	25	6	Signal-on unit
Data storage module	17	1	Two-state unit	Data load module_1	30	1	Two-state unit
Data storage module software	19	6	Signal-on unit	OR gate	21, 29, 46, 57, 81	2	OR
RAID Controller	16	1	Two-state unit	Hard disk	20	1	Two-state unit
Information Management Module_1	23	1	Two-state unit	Information Management Module_2	26	1	Two-state unit
Data loading module software	32	6	Signal-on unit	Comprehensive decompression module_1	37	1	Two-state unit
KVM switch	22	1	Two-state unit	EDID Reader 1	33	1	Two-state unit
EDID Reader software_1	35	6	Signal-on unit	Motherboard module_1	36	1	Two-state unit
Information Management Module Application_2	28	6	Signal-on unit	Comprehensive decompression module software_1	39	6	Signal-on unit
CPEX main processor module_1	40	1	Two-state unit	CPEX main processor application_1	42	6	Signal-on unit
CPEX main processor module_2	43	1	Two-state unit	CPEX main processor Application_2	45	6	Signal-on unit
USB interface module	47	1	Two-state unit	Motherboard module_2	50	1	Two-state unit
USB interface module application	49	6	Signal-on unit	Display processing module_1	51	1	Two-state unit
Display processing module software_1	53	6	Signal-on unit	Multi-function demodulation module software	60	6	Signal-on unit
Touch display	54	1	Two-state unit	Monitor_1	55	1	Two-state unit
Control exterior parts	56	1	Two-state unit	Data load module 2	61	1	Two-state unit
Multi-function demodulation module	58	1	Two-state unit	Data loading module software_2	63	6	Signal-on unit
Communication module_2	64	1	Two-state unit	Communication module software_2	66	6	Signal-on unit
Comprehensive decompression module_2	67	1	Two-state unit	Comprehensive decompression software 2	69	6	Signal-on unit
EDID reader software_2	73	6	Signal-on unit	Display software_2	76	6	Signal-on unit
Display module_ 2	74	1	Two-state unit	Motherboard module_3	70	1	Two-state unit
EDID reader 2	71	1	Two-state unit	Signal instruction	A	5	Input unit
A: 3, 7, 11, 14, 18, 24, 27, 31, 34, 38, 41, 44, 48, 52, 59, 62, 65, 68, 72, 75							

Table 3. Failure rates of the C^4ISR system units.

Unit	Failure Rate	Unit	Failure Rate
Communication module	0.0001477323	Network module	0.0002001001
Communication module application software	0.0001716049	Network module application software	0.0002684325
Power supply	0.0000079940	Signal receiver	0.0002394779
Server	0.0001998801	Server application software	0.0002251758
Information exchange module application software	0.0002967919	Integrated Information Management Module	0.0002389058
Information Exchange Module	0.0001999200	Data storage module	0.0000800336
RAID controller	0.0001331071	Hard disk	0.0000799472
Data storage module application software	0.0001878982	Data loading module application software	0.0002208103
KVM switch	0.0001598977	Data load module	0.0001596233
EDID reader	0.0001999200	Motherboard module	0.0001335425
EDID reader application software	0.0002357298	Comprehensive decompression module	0.0001595660
Comprehensive information management module application software	0.0002722646	Comprehensive decompression module application software	0.0002160759
CPEX main processor module application software	0.0002077888	USB interface expansion module	0.0001332711
CPEX main processor module	0.0001999500	Display processing module	0.0001335425
USB interface extension module application software	0.0002038553	Display processing module application software	0.0001601643
Touch display	0.0000666867	Monitor	0.0000666867
Multifunctional information demodulation module	0.0001353867	Control exterior parts	0.0001598977
Multifunctional information demodulation module application software	0.0001771930	Control keyboard, Remote control unit, Communication telephone	0.0000266386

4. Results

In this paper, the unit reliability is calculated under the service time of 100 h, see in Table 4. Units of the C^4ISR system in this paper are two-state, that are, working (0) and failed (1). The reliability computation of the GO model follows a designed procedure. First, the success probability of signal flow 7 and 9 can be calculated as:

$$\begin{gathered} A_7(0) = A_1(0)P_2(0)P_4(0)P_5(0)P_6(0) \\ A_9(0) = A_7(0)A_8(0) \end{gathered} \tag{14}$$

According to the system structure, the signal flows to 10 and 16, respectively at the same time. Obviously, the operator is affected by a common cause. Therefore, in combination with the common cause failure, the output signal flow 22 is corrected by the β-factor model. Note that the common cause failure rate is set to be $C = \beta\lambda = 0.000236$. Hence, the success probability of signal flow 10 is reached by:

$$\begin{gathered} A_{10}(0) = A_9(0)P_9(0) \\ A_{22}(0) = A_{10}(0)[P_{10}(0)P_{12}(0)P_{13}(0)P_{15}(0) + P_{16}(0)P_{17}(0)P_{19}(0)P_{20}(0) \\ -P_{10}(0)P_{12}(0)P_{13}(0)P_{15}(0)P_{16}(0)P_{17}(0)P_{19}(0)P_{20}(0)] \\ -A_{10}(0)[P_{15}(0) + P_{20}(0) - P_{15}(0)P_{20}(0)]C \end{gathered} \tag{15}$$

Table 4. C^4ISR System unit Reliability (100 h working time).

Unit	Reliability	Probability of Failure	Unit	Reliability	Probability of Failure
Communication module	0.985335	0.014665	Network module application software	0.973514	0.026486
Communication module application software	0.982986	0.017014	Information exchange module software	0.970757	0.029243
Network module	0.980189	0.019811	Power supply	0.999201	0.000799
Server	0.98021	0.01979	Signal receiver	0.976337	0.023663
Server application software	0.977734	0.022266	Information Exchange Module	0.980207	0.019793
RAID controller	0.986777	0.013223	Hard disk	0.992037	0.007963
Data storage module	0.992029	0.007971	KVM switch	0.984137	0.015863
Data load module	0.984164	0.015836	EDID reader	0.980207	0.019793
Data storage module application software	0.981386	0.018614	Data loading module application software	0.978161	0.021839
Integrated Information Management Module	0.976393	0.023607	Comprehensive information module software	0.973141	0.026859
EDID reader application software	0.976703	0.023297	CPEX main processor module	0.980204	0.019796
Motherboard module	0.986735	0.013265	Control exterior parts	0.984137	0.015863
Comprehensive decompression module	0.98417	0.01583	Comprehensive decompression module software	0.978624	0.021376
CPEX main processor module application software	0.979436	0.020564	USB interface extension module application software	0.979821	0.020179
USB interface expansion module	0.986761	0.013239	Display processing module	0.986735	0.013265
Display processing module application software	0.984111	0.015889	Control keyboard, Remote control unit, Communication telephone	0.99734	0.00266
Multifunctional information demodulation module	0.986553	0.013447	Multifunctional information demodulation module software	0.982437	0.017563
Touch display	0.993354	0.006646	Monitor	0.993354	0.006646

Subsequently, the success probability of the signal flow 23 and 30 are computed, see Equation (16), which are a comment (shared) signal of operators 23 and 26. Accordingly, the output signal 30 needs to be corrected and the common cause rate is set to be $C = \beta\lambda = 0.000236$.

$$\begin{aligned} A_{23}(0) &= A_{22}(0)P_{22}(0) \\ A_{30}(0) &= A_{23}(0)[P_{23}(0)P_{25}(0) + P_{26}(0)P_{28}(0) - P_{23}(0)P_{25}(0)P_{26}(0)P_{28}(0)] \\ &\quad - A_{23}(0)[P_{25}(0) + P_{28}(0) - P_{25}(0)P_{28}(0)]C \end{aligned} \quad (16)$$

Similarly, a common signal 40 and 47 are corrected and the common cause rate is set to be $C = \beta\lambda = 0.000236$ as a basis of that the success probabilities of the signal flow 40, 47, 54, 58, 74, and 82 are computed by Equations (17)–(19):

$$\begin{aligned} A_{40}(0) &= A_{30}(0)P_{30}(0)P_{32}(0)P_{33}(0)P_{35}(0)P_{36}(0)P_{37}(0)P_{39}(0) \\ A_{47}(0) &= A_{40}(0)[P_{40}(0)P_{42}(0)+P_{43}(0)P_{45}(0)-P_{40}(0)P_{42}(0)P_{43}(0)P_{45}(0)] \\ &\quad -A_{40}(0)[P_{42}(0)+P_{45}(0)-P_{42}(0)P_{45}(0)]C \end{aligned} \tag{17}$$

$$\begin{aligned} A_{54}(0) &= A_{47}(0)P_{47}(0)P_{49}(0)P_{50}(0)P_{51}(0)P_{53}(0) \\ A_{58}(0) &= A_{54}(0)[P_{54}(0)+P_{55}(0)P_{56}(0)-P_{54}(0)P_{55}(0)P_{56}(0)] \\ &\quad -A_{54}(0)[P_{54}(0)+P_{56}(0)-P_{54}(0)P_{56}(0)]C \end{aligned} \tag{18}$$

$$\begin{aligned} A_{74}(0) = {} & A_{58}(0)P_{58}(0)P_{60}(0)P_{61}(0)P_{63}(0)P_{64}(0)P_{66}(0)P_{67}(0)P_{69}(0)P_{70}(0) \\ & P_{71}(0)P_{73}(0) \\ A_{82}(0) = {} & A_{74}(0)[P_{78}(0)+P_{79}(0)+P_{80}(0)+P_{74}(0)P_{76}(0)P_{77}(0)+P_{74}(0) \\ & P_{76}(0)P_{77}(0)P_{79}(0)P_{80}(0)+P_{78}(0)P_{79}(0)P_{80}(0)+P_{74}(0)P_{76}(0)P_{77}(0) \\ & P_{78}(0)P_{79}(0)+P_{74}(0)P_{76}(0)P_{77}(0)P_{78}(0)P_{80}(0)-P_{79}(0)P_{80}(0)-P_{74}(0) \\ & P_{76}(0)P_{77}(0)P_{79}(0)-P_{74}(0)P_{76}(0)P_{77}(0)P_{80}(0)-P_{78}(0)P_{79}(0)-P_{78}(0) \\ & P_{80}(0)-P_{74}(0)P_{76}(0)P_{77}(0)P_{78}(0)-P_{74}(0)P_{76}(0)P_{77}(0)P_{78}(0)P_{79}(0) \\ & P_{80}(0)]-A_{74}(0)[P_{78}(0)+P_{79}(0)+P_{80}(0)+P_{77}(0)+P_{77}(0)P_{79}(0)P_{80}(0) \\ & +P_{78}(0)P_{79}(0)P_{80}(0)+P_{77}(0)P_{78}(0)P_{79}(0)+P_{77}(0)P_{78}(0)P_{80}(0)-P_{79}(0) \\ & P_{80}(0)-P_{77}(0)P_{79}(0)-P_{77}(0)P_{80}(0)-P_{78}(0)P_{79}(0)-P_{78}(0)P_{80}(0) \\ & -P_{77}(0)P_{78}(0)-P_{77}(0)P_{78}(0)P_{79}(0)P_{80}(0)]C \end{aligned} \tag{19}$$

With the results above, the reliability of the C^4ISR system under the service time of 100 h is 0.8506. The reliability and failure probabilities of the unit of the C^4ISR system are listed in Table 4.

5. Discussion

With the results of the qualitative analysis, for a system with redundant structures, the not critical failure items of the system are identified to be those whose failure probabilities order (in a decrease order) is 4. Hence, the qualitative analysis is conducted based on the minimum cut sets of remining items. The qualitative analysis results of the C^4ISR system are shown in Table 5, in which, the probabilities of occurrences of minimum cut sets are applied to evaluate their importance.

Table 5. Qualitative analysis results of the C^4ISR System.

Minimum Cut Set	Failure Mode	Corresponding Operator Number	Order	Minimum Cut Set	Failure Mode	Corresponding Operator Number	Order
Power supply	F1	81	1	Network module	F4	5	1
Communication module 1	F2	2	1	EDID reader software 1	F11	35	1
Communication module application software 1	F3	4	1	Network module application software	F5	6	1
Signal receiver	F6	9	1	KVM switch	F7	22	1
Data load module 1	F8	30	1	EDID reader 1	F10	33	1
Data load module software 1	F9	32	1	Motherboard module 1	F12	36	1
Comprehensive decompression module 1	F13	37	1	Comprehensive decompression module software 1	F14	39	1
USB interface expansion module	F15	47	1	Motherboard module 2	F17	50	1
USB interface extension module software	F16	49	1	Display processing module software1	F19	53	1
Data load module 2	F22	61	1	EDID reader 2	F29	71	1

Table 5. *Cont.*

Minimum Cut Set	Failure Mode	Corresponding Operator Number	Order	Minimum Cut Set	Failure Mode	Corresponding Operator Number	Order
Display processing module 1	F18	51	1	Communication module 2	F24	64	1
The multifunctional information demodulation module	F20	58	1	Multi-function demodulation module application software	F21	60	1
Data loading module application software 2	F23	63	1	Communication module application software 2	F25	66	1
Comprehensive decompression module 2	F26	67	1	Comprehensive decompression module software 2	F27	69	1
Motherboard module 3	F28	70	1	Server, RAID controller	F31	10, 16	2
EDID reader application software 2	F30	73	1	Server, data storage module software	F33	10, 19	2
Server, data storage module	F32	10, 17	2	Server application software, hard disk	F38	12, 20	2
Server application software, RAID controller	F35	12, 16	2	Server application software, data storage module	F36	12, 17	2
Server application software, data storage module software	F37	12, 19	2	Information exchange module, data storage module	F40	13, 17	2
Information exchange module, RAID controller	F39	13, 16	2	Information exchange module, hard disk	F42	13, 20	2
Information exchange module, data storage module software	F41	13, 19	2	Information exchange module application software, RAID controller	F43	15, 16	2
Information exchange module application software, data storage module	F44	15, 17	2	Information exchange module software, data storage module software	F45	15, 19	2
Information exchange module application software, hard disk	F46	15, 20	2	Information integrated modules 1 and 2	F47	23, 26	2
Information integrated management module 1 and software 2	F48	23, 28	2	Information integrated management module software 1 and module 2	F49	25, 26	2
CPEX main processor modules 1 and 2	F51	40, 43	2	CPEX main processor module 1 and software 2	F52	40, 45	2
Information integrated management software 1 and 2	F50	25, 28	2	CPEX main processor module software 1 and module 2	F53	42, 43	2
Touch display, Monitor 1	F55	54, 55	2	Touch display, control exterior	F56	54, 56	2
CPEX main processor module application software 1 and software 2	F54	42, 45	2	Display processing module 2, Control unit, Remote control unit, Communication	F57	74, 78, 79, 80	4
Display processing module application software 2, Control unit, Remote control unit, Communication	F58	76, 78, 79, 80	4	Monitor 2, Control unit, Remote control unit, Communication telephone	F59	77, 78, 79, 80	4
Server, Hard disk	F34	10, 20	2				

Table 5 indicates that the criticalities of software and hardware failures of the C^4ISR system are comparable, which demonstrates that for both the design and the operation stage of the mentioned system performance and failure properties of the software and hardware of the C^4ISR system should be focused on. This conclusion also indicates that failure properties of software and hardware integrated systems are consequences of the both software and hardware failures which would be different from the maturely implemented software systems and hardware systems. Additionally, applicability and feasibility of the GO methodology for the reliability analysis of software and hardware integrated systems are valeted. At the component point of view, hardware failures like communication module failures and motherboard module failures as well as software failures like network module application software failures and decompression module software failures are critical than others and which call for special attention of designers and operators. More in detailed conclusions can be reached in Table 5.

Moreover, failure modes are observable consequences (failures) of a system. In this paper, the failure modes' criticality analysis of the C^4ISR system is carried out, as shown in Table 6.

Table 6. Failure mode importance ranking table.

Importance Order	Failure Mode	Probability of System Failure	Importance Order	Failure Mode	Probability of System Failure	Importance Order	Failure Mode	Probability of System Failure
1	F50	0.419885	17	F36	0.263031	33	F10, F29	0.181204
2	F48, F49	0.400207	18	F38	0.262967	34	F21	0.162382
3	F45	0.384112	19	F40	0.244182	35	F3, F25	0.157688
4	F47	0.379861	20	F32	0.244151	36	F19	0.147996
5	F43	0.349425	21	F42	0.244116	37	F7	0.147769
6	F54	0.34004	22	F34	0.244086	38	F8, F22	0.147535
7	F37	0.338387	23	F5	0.235423	39	F13, F26	0.147486
8	F52, F53	0.334847	24	F58	0.213435	40	F2, F24	0.137338
9	F51	0.329612	25	F6	0.212961	41	F59	0.136363
10	F41	0.321465	26	F11, F30	0.210006	42	F20	0.126622
11	F33	0.321437	27	F56	0.202748	43	B	0.12501
12	F44	0.313964	28	F9, F23	0.198131	44	F55	0.124862
13	F46	0.313905	29	F14, F27	0.194326	45	F15	0.124772
14	F35	0.301125	30	F57	0.192215	46	F1	0.007962
15	F39	0.28325	31	F16	0.18442	B: F12, F17, F18, F28		
16	F31	0.283221	32	F4	0.181351			

In Table 6, the criticality rank of each failure mode in a decreased order indicated that: (i) The criticality ranks of application software failures in the system are high such as information integrated management module 1 and software 2 failure (F48), CPEX main processor module application software 1 and software 2 failure (F54), and Information exchange module application software (F43), which means that the application software is the weak link in the entire C^4ISR system; (ii) Failure mode F50, F48, F49, F45 ranks the highest in their importance, addition to application software failures already mentioned, information management application software are critical as well and which needs the particular attention in the C^4ISR system upgrading.

6. Conclusions

This paper applied the GO method to detailed analyze the reliability of a C^4ISR system. In the analysis, the impact of common cause failures and shared signals have been considered, which are common phenomena of hard-and-software integrated systems like the C^4ISR system, and which also makes classical reliability analysis techniques for instance FTA, BN, etc. are not applicable to analysis the reliability such a system. Due to this, this paper constructs a GO method to analysis the reliability of a C^4ISR system. Overall, the reliability of the C^4ISR system is computed to be some 0.85 and the reliability as well as the failure probability of units of the C^4ISR system are reached. Moreover, critical failures of hardware failures like communication module failures and motherboard module failures as well as software failures like network module application software failures and decompression module software failures are ascertained by the GO model as well. The results achieved are in line with the experience accumulated among the historical operations of the C^4ISR system. This paper contributes to the reliability analysis of all hard-and-software integrated systems. However, in the future more practical factors should be considered in the GO model constructions, including the degradation of mechanical elements, human factors, and environmental factors, which are unneglectable for reliability analysis of the C4ISR system and will extend the capability of the GO methodology.

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