The Method of Mission Reliability Allocation for Complex System Based on Simulation

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Abstract—**Reliability has become a greater concern in recent years, because high-tech industrial processes with ever increasing levels of sophistication comprise most engineering systems today. Reliability Allocation Method currently used has corresponding advantages in different aspects, but there are still some limitations in practical engineering applications. It is difficult to establish the mission reliability models for large and complex system while facing the degradation use in function, dynamic correlation between structural composition and faults not meeting the independent assumptions, and other cases. Based on the analysis of the advantages and disadvantages of the traditional reliability allocation methods, this paper described in details the mission reliability allocation method of complex system by applying simulation. It can not only conduct a great deal of iteration calculation but also can weigh different allocation schemes without adding additional work, using simulation calculations after the initial establishment of system simulation models. This is suitable for the mission reliability allocation of complex systems in engineering projects. Finally, this paper provided practical cases applying this method into achieving mission reliability allocation of a warship system.**

Keywords- Reliability Allocation; Complex System; Simulation; Model.

I. INTRODUCTION

Reliability has become an ever greater concern in recent years, because high-tech industrial processes with ever increasing levels of sophistication comprise most engineering systems today. Reliability allocation is an important link of system reliability design. Reliability allocation is to allocate reliability indicators provided by the system to subsystems, parts and components according to certain principles and procedures so as to enable designers at all levels to identify its reliability design requirements, accurately estimate manpower, time and resources according to the requirements and study the possibility of achieving this requirement and methods. It is a decomposition process from the integral to part, from big to small and from top to bottom. Reliability allocation can be used in the design of both hardware system and software. While most of literatures present how to do the reliability allocation for hardware design a method of reliability allocation for software and network is described in [1, 2].

Reliability allocation includes basic reliability allocation and mission reliability allocation. Currently, reliability allocation is carried out mainly by constrained system reliability allocation method and unconstrained reliability allocation method. The former mainly includes Lagrange multiplier method, dynamic programming method, and direct search method; while the latter mainly includes equal allocation method, combination in proportion technique and score allocation method [3], and it also includes some methods deriving from above for the score is more rational, such as Fuzzy Decision Method [4,5], AHP [6], using the maximal entropy ordered weighted averaging method [7], Analytical Target Cascading Method [8], sensitivity evaluation method [9] and so on. Unconstrained allocation method is frequently used in engineering. The use of all these methods often needs to establish the reliability model. It is very easy to build the basic reliability model of the system, such as series model; However, it is often difficult to establish the mission reliability model for large and complex system due to complexity of its structure, complexity in functions to be achieved, degradation use in function and dynamic correlation between structural composition, faults not meeting the independent assumptions, and other cases. This results in difficulties in the use of above methods. In this case, this paper, based on simulation ideas [10,11], puts forward the simulation-based reliability allocation method in order to achieve the mission reliability allocation for complex system. This method establishes not the mission reliability model but the simulation logic model of the system by defectively using functional logical relationship between product units, which can be widely applied in engineering.

In this paper, Section Ⅱ introduces the overview of reliability allocation method frequently used. And then the simulation-based mission reliability allocation for complex system, including allocation idea and allocation process are detailed in Section Ⅲ. At last, it is a case study.

II. RELIABILITY ALLOCATION METHOD FREQUENTLY USED

Reliability allocation is the process of decomposing reliability indicators of the top-level system to the underlying unit step by step in the product design phase. In the course of the reliability allocation process, various methods should follow some common basic principles [12,13], such as:

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TABLE I. FREQUENTLY-USED RELIABILITY ALLOCATION METHODS AND CHARACTERISTICS

Allocation method	Applicable stage	Applicable Scope	Applicable Conditions	Advantages	Disadvantages
Equal allocation method	demonstration stage	Basic reliability allocation and mission reliability allocation	When the product definition is not very clear	Simple calculation and convenient for use	Not giving considerations to the actual differences between various subsystems
Combination in proportion technique	Preliminary design stage	Conventional combination in proportion technique applies only to basic reliability allocation	With a similar physical model available for reference, requiring that model shall have certain data basis	Using the original actual user-defined data	High dependence on the reference model
Score allocation method	Preliminary design stage and detailed design stage	Basic reliability allocation and mission reliability allocation of series systems	With scarce reference data, with certain quality basis of technical personnel	The initiative and engineering experience of personnel can be given into full play, and score results has a certain convergence	Only scoring a few aspects of indicators, the results cover incomplete information

- Allocate lower reliability value to higher-complexity subsystems and equipment;
- Allocate lower reliability value to equipment with immature technology;
- Allocate lower reliability value to the equipment working in difficult environmental conditions;
- Allocate lower reliability value to products in service for long term;
- Allocate relatively higher reliability value to products with higher importance;
- Allocate relatively higher reliability value to products difficult to repair and replace;
- On-shelf products that have reliability value or systems that have been used sophisticatedly will not be allocated with new reliability value in design phrase, while it is required to remove the reliability value of these units from the total index then allocate the remnant reliability value to other systems.

Mainly due to different considerations and different premise of data application, different reliability allocation methods have different accuracy of their results. Frequently-used reliability allocation methods and their characteristics [14,15] are as shown in Table 1.

Although these above methods have corresponding advantages in different aspects, but there are still limitations in practical engineering applications:

1) Logical complexity of system functions. Owing to the interconnect, backup, timing and other related relations between functions of various system component units, the underlying units could not meet the fault independence assumption. Therefore the existing series, parallel, by-pass, bridging and voting and other reliability models could not describe the whole system mission reliability;

2) System reliability could not be calculated by the existing formula due to system and component unit life expectation does not obey the exponential distribution. Analytic deduction of other types of distributions is too complicated;

3) Each result of reliability allocation needs to be verified, the reliability allocation work can be put to an end if only the requirements are satisfied. But this process is too long for complex systems which require iterative calculation [16].

III. SIMULATION-BASED MISSION RELIABILITY ALLOCATION OF COMPLEX SYSTEMS

A. Allocation ideas

Reliability allocation and reliability prediction are two inverse processes, while the latter is used to validate the reasonableness of the results of reliability allocation. Simulation-based reliability allocation method of complex systems just uses this idea, i.e. in the case of a known initial value of reliability allocation, using the prediction method to obtain the simulation-based system reliability value and determine whether the initial requirements of allocation can be meet; if not so, it is required to regulate the values obtained in the current allocation according to the equipment importance or system weaknesses and other factors obtained from the simulation analysis, and then conduct prediction again until system requirement can be satisfied. This method does not require establishing the mission reliability model of the system while directly employs the criterion for system failure to building simulation models for the complex functional logic relationship and timing relationship between systems, which is applicable to any allocation types including exponential allocation. As a result of simulation-based calculations, after the initial establishment of system simulation models, we can conduct a lot of iterations and also weigh different allocation schemes without adding additional work. Therefore, it is suitable for the use in reliability allocation of complex systems in the engineering project.

B. Allocation process

Simulation-based reliability allocation mainly complies with the following steps:

First, make clear the definition of the system mission and establish fault criteria, which is the basis of the entire simulation. Simulation model can be established accurately only different missions have been given a clear definition of fault criteria. Therefore, the definition of fault criteria must be clear enough: what unit works on what time phase, what is the influence of unit fault on the mission—the system fault or functional degradation, as well as what kind of combination and what kind of timing of each unit fault will lead to system fault.

Secondly, build simulation models based on the system functional logical relationship and fault criteria.

Thirdly, obtain the initial allocation value of the underlying unit by using conventional reliability allocation method. At this stage, if there is a known basic reliability requirements of the system, the result of basic reliability allocation can be used as the initial value assigned, so that the mission reliability allocation can be conducted under the premise of guaranteeing the basic reliability requirements so as to reduce the number of iterations.

Then, use the initial allocation value as an input of simulation model to run the simulation, and thereby compute the reliability of top system.

Finally, determine whether the top system reliability can meet the requirements; if not so, it is required to re-regulate reliability values of the underlying unit and then continue the simulation by iteration method until the requirement can be satisfied. In the process of values regulation, take importance factors into account so as to efficiently and rationally complete reliability allocation process [17].

Using the device as the underlying unit, the specific simulation algorithm is as shown in Figure 1.

(1) Build simulation models;
(2) Read the database to obtain the initial value of Mean Time Between Critical Fault (MTBCF) of each device, the number of device and other input parameters;
(3) Give simulation times, the maximum simulation time and time intervals between statistics;
(4) Running the simulation. Initializing, making all devices be from free faults;
(5) Generate random numbers; conduct random sampling on the life expectation of n device by using Monte Carlo method according to life expectation of device and MTBCF.

In the simulation running at J time, the fault time of the i^{th} device is:

$$t_{ij} = F_i^{-1}(\eta_{ij}) \quad (1)$$

In the formula, $F_i(t_{ij})$ is the fault distribution function of the i^{th} device; η_{ij} refers to the random number of random sampling of the i^{th} device at J time of simulation.

(6) Sequence by the order of the time of device fault occurring, let the fault first occur to the device with short fault time;
(7) According to the established simulation model, using traversal search method, sequentially determine whether the device fault results in system fault until the system fault occurs, identify system fault time t_j ;
(8) Record current fault time of the system and the serial number of devices to which faults have occurred;
(9) If the current simulation times are greater than the set simulation times, then go to step 10; otherwise, go to step 4;
(10) Using the interval statistical method to carry out system fault distribution statistic analysis for all data obtained by simulation to get the system MTBCF

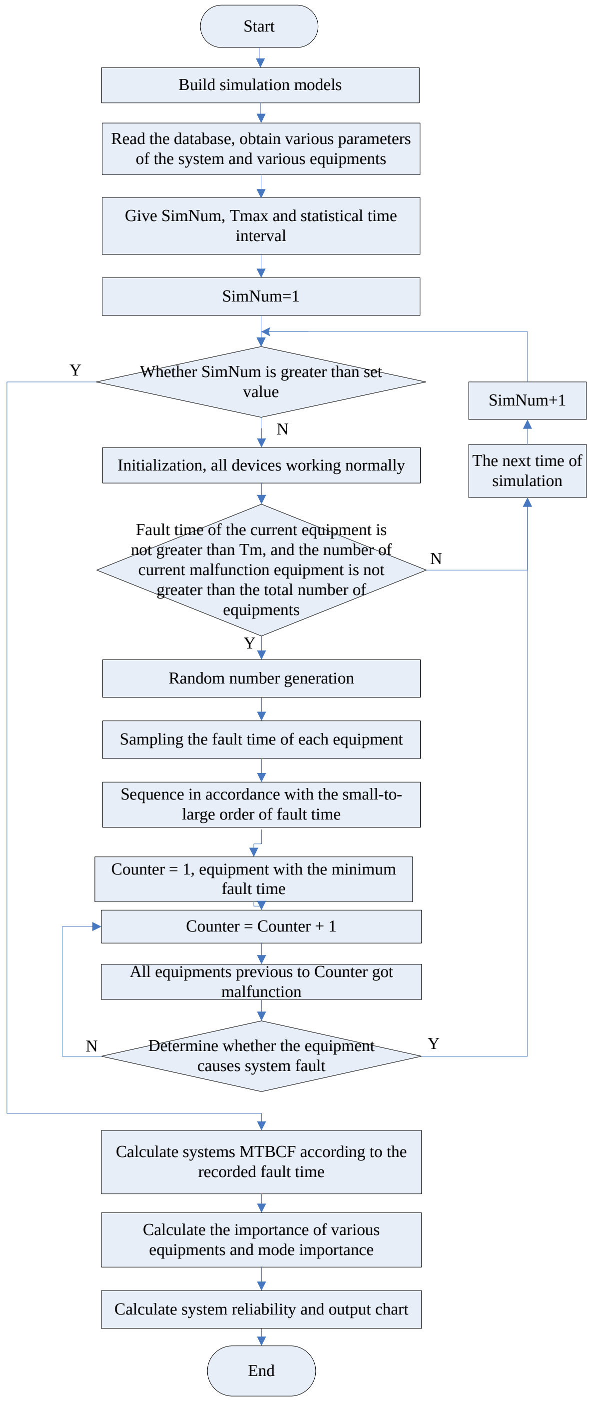

Figure 1. simulation algorithm

value, reliability, device importance and the mode importance. Importance reflects the importance degree of device in system. Mode importance is used to identify the weakness in system.

As the system fault time values are generated by random sampling, it is necessary to conduct statistical analysis for these values after N times of simulation. Suppose the maximum working hours of the system is T_{max} and equally divide it into several intervals (setting as m), then each time interval ΔT is:

$$\Delta T = \frac{T_{max}}{m} \quad (2)$$

Relevant reliability indicators can be obtained by placing the system fault time of each simulation on its corresponding time interval, such as MTBCF and fault distribution function are respectively as follows:

$$MTBCF = \sum_{r=1}^{m} [t_r \cdot p_s(t_r)] \quad (3)$$

$$F_s(t_r) = \frac{m_r}{N} = \sum_{r=1}^{m} p_s(t_r) \quad (4)$$

In the formula, t_r refers to the biggest moment in the time interval r, $p_s(t_r)$ refers to the probability of placement in the time interval r, i.e. $p_s(t_r) = \Delta m_r / N$. In which, the importance of device is:

$$W(Zi) = \frac{\text{times of system in fault caused by equipment Zi in fault}}{\text{times of equipment Zi in fault}} \quad (5)$$

Mode importance of the device is:

$$W_N(Zi) = \frac{\text{times of system in fault caused by equipment Zi in fault}}{\text{times of system in fault}} \quad (6)$$

IV. APPLICATION OF WARSHIP SYSTEMS CASES

Take Warship Integrated Platform Management System as an example to do the reliability allocation.

A. System description and mission failure criterion

1) System Description

Warship Integrated Platform Management System is a very important system in warships, which is mainly used for warship implementing real-time monitoring, control and management over main systems (equipment) on the platform. This system contains eight sub-systems including 16 types and 82 equipments in total. Among them, one is a ship-borne computer which does not need to be allocated new reliability value and four equipments can be used as backup units for backup related equipments in all sub-systems. Thus between the different sub-system does not conform to the faults independent assumptions. There are series, parallel, n out of r and some fault correlation between interior equipments of different sub-systems. Therefore, it is very difficult to establish the system reliability models using conventional methods. We can describe the system in simulation method presented in 3.2.

2) Mission reliability requirements

MTBCF of Integrated Platform Management System is required to be 2000 hours.

3) Mission fault criterion

Warship working process will have different mission profiles. Under the corresponding different mission profiles, warship integrated platform management system has different working condition and fault criteria. For a typical mission profile, each sub-system will respectively achieve different functions. As a result, if any sub-system was in fault, the entire system functions could not be achieved. In the interior of sub-systems, some equipments fault will not lead to complete loss of functions of sub-systems but lead to functional degradation; fault relation exists between some equipments.

Taking No. 6 sub-system as an example, which includes No.75~No.79 equipment, No.17, No.51, No.52 and No.80 are four general-purpose backup units mentioned above, they are in other sub-systems and can backup No.75 equipment. Then, the fault criterion of No.6 subsystem is as follows: one of No.75~No.79 equipment is in fault, or No.75, No.17, No.51, No.52 and No.80 all get malfunctions.

B. Establish the simulation model of mission reliability

System mission reliability simulation model could be established according to the mission criteria. Functional faults correlations in No. 2 and No.6 subsystems are as shown in Figure 2 and Figure 3. In the graphics, the figure in box respectively represents equipment serial number. No. 51, No. 52 and No. 80 equipment do not belong to No. 2 sub-systems, but they can achieve backup for No. 17 equipment in the sub-system, so we can consider that they follow 1out of 4 relationship. After identifying functional fault correlations between various sub-systems, by following the series relationship between sub-systems, we can create reliability simulation model of the entire system, that is, the combination of functional faults and timing between what equipment can lead to system fault. System simulation model could be established according to the functional faults correlations in system, and then simulated program could be compiled according to the algorithm shown in figure 1. The partial codes are as follows.

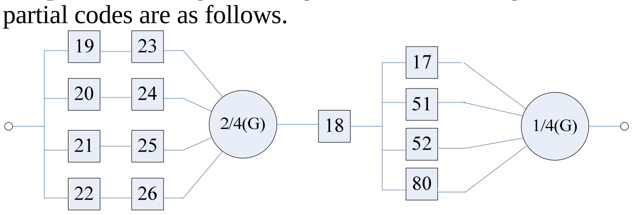

Figure 2. Functional faults correlation in No. 2 sub-system

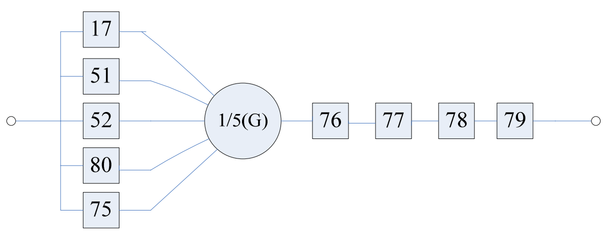

Figure 3. Functional faults correlation in No. 6 sub-system

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    …
(Get fault time and Sequence in accordance with the small-to-large order)
For j = 1 To 81
   E(j) = False  'Initialization, all equipments working normally
Next
For j = 1 To 81
    E(TTF(j).SerialNumber) = True   'the equipments are in fault according to the fault time order
     (Determine whether the equipment fault cause system fault)
    …
    S-S6_status = E(76) Or E(77) Or E(78) Or E(79) Or (E(17) And E(51) And E(52) And E(80) And E(75))
    'No.6 subsystem status
    …
    System_status = S-S1_status Or S-S2_status Or S-S3_status Or S-S4_status Or S-S5_status Or S-S6_status Or S-S7_status Or S-S8_status   'The whole system status
    …
     (fault data statistics and compute MTBCF, importance and mode importance)
    …
    Next j
    …
```

C. *Obtain the initial value by series model allocation*

MTBCF of No. 82 equipment can be up to 100,000 hours, after removing No. 82 equipment with the known fixed value from the system reliability indicator, the reliability allocation can be carried out in series model using score allocation method, and the result shall be taken as the initial value of simulation-based mission reliability allocation. Considering the complexity and working hours, the result of reliability allocation in series model is as shown in Table 3. The same type of equipment could be allocated with the same value.

TABLE II. SEQUENCE OF EQUIPMENT IMPORTANCE

Sequence number	Equipment Number	Importance	Mode importance
1	81	1.0000	0.0706
2	82	1.0000	0.0697
3	49	1.0000	0.0559
4	7	1.0000	0.0520
5	9	1.0000	0.0508
6	11	1.0000	0.0481
7	13	1.0000	0.0469
8	12	1.0000	0.0461
9	10	1.0000	0.0460
10	8	1.0000	0.0455
11	78	1.0000	0.0449
12	76	1.0000	0.0439
13	14	1.0000	0.0437
14	77	1.0000	0.0420
15	79	1.0000	0.0412
16	18	1.0000	0.0338
17	16	1.0000	0.0323
18	50	1.0000	0.0316
19	15	1.0000	0.0306
20	48	1.0000	0.0261
21	47	1.0000	0.0223
22	41	0.1490	0.0062
23	42	0.1313	0.0052
…	…		…

D. *Run the simulation to obtain the final value of reliability allocation*

Substitute initial reliability allocation values of various equipments into simulation model and run the simulation, and then obtain the system MTBCF up to 6630.548 hours, which is far greater than 2,000 hours as required by the system, so it is required to appropriately reduce the reliability index of some equipment. The main principles of adjustment: equipment with high importance, weakness links in systems shall reserve relatively higher reliability index; equipment assigned with unduly high reliability index probably could not be achieved in the project, so the reliability index should be appropriately reduced based on the actual situation.

According to the sequence of equipment importance and vulnerability in the system obtained in the first round of simulation (see Table 2), based on the practical application of actual engineering projects, we can regulate MTBCF values of some equipment and obtain system MTBCF 2247.826 hours after several rounds of iterations, so the current initial value can meet the requirements of mission reliability allocation, then reliability allocation work can be ended. The final allocation results are as shown in Table 4.

V. CONCLUSION

Using existing common methods to conduct system reliability allocation will be constrained in different aspects to varying degrees; especially in the case of complex system mission reliability allocation, some methods even could not solve the practical problems. However, in the case of using digital simulation ideas to conduct complex system mission reliability allocation, as long as the system mission and functions are identified, we can establish a system simulation model and further conveniently conduct verification on the results of complex system mission reliability allocation by using the initial allocation index of various underlying units, and meanwhile acquire the information of importance of various units, mission reliability and MTBCF of the whole system and various subsystems. In addition, this method can guarantee the correctness of multiple iterations testing and applies to application in practical engineering.

Using simulation-based complex system reliability allocation method is required to established corresponding simulation models for different application objects, which requires that engineering staff shall not only have a deep understanding of system functions prior to the establishment of simulation model, but also certain programming capabilities so as to ensure the correctness of establishing logic simulation models. Therefore, the research on general-purpose modeling simulation of complex systems can be further carried out in order to better apply to engineering projects.

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TABLE III. INITIAL ALLOCATION RESULT

type	n	r_{i1}	r_{i2}	r_{i3}	r_{i4}	w_i	n* w_i	$C_i = w_i / w$	$MTBCF_i$
A	16	10	1	7	1	70	1120	0.0163284	124985.4
B	21	6	1	10	1	60	1260	0.0139958	145816.3
C	2	7	1	6	1	42	84	0.0097971	208309
D	4	6	1	8	1	48	192	0.0111966	182270.4
E	4	6	1	8	1	48	192	0.0111966	182270.4
F	1	6	1	8	1	48	48	0.0111966	182270.4
G	3	6	1	10	1	60	180	0.0139958	145816.3
H	1	10	1	8	1	80	80	0.0186611	109362.2
I	1	4	1	7	1	28	28	0.0065314	312463.6
J	1	7	1	5	1	35	35	0.0081642	249970.9
K	1	8	1	9	1	72	72	0.016795	121513.6
L	1	7	1	6	1	42	42	0.0097971	208309
M	14	6	1	6	1	36	504	0.0083975	243027.2
N	10	6	1	6	1	36	360	0.0083975	243027.2
O	1	10	1	9	1	90	90	0.0209937	97210.88
Sum	81						w =4287		

Note: n refers to the number of equipment of the same type; refers to the complexity; technical level; working hours; environmental conditions; score of various devices; coefficient of scoring for each unit; score of the system.

TABLE IV. FINAL ALLOCATION RESULT

type	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
MTBCF (ten thousand hours)	4	4.5	4.5	3	3	4.5	3.5	3	4.5	4.5	4.5	4.5	3	3	4.5