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MEAN FAILURE MASS AND MEAN FAILURE REPAIR TIME: PARAMETERS LINKING RELIABILITY, MAINTAINABILITY AND SUPPORTABILITY

ŚREDNIA MASA USZKODZENIA I ŚREDNI CZAS NAPRAWY USZKODZENIA: PARAMETRY ŁĄCZĄCE NIEZAWODNOŚĆ, OBSŁUGIWALNOŚĆ I UTRZYMYWALNOŚĆ

Up to now, no parameters linking reliability, maintainability and supportability directly are available in reliability engineering. Index such as availability can be used to check the compatibility of those RAM features only after individual index of every characteristic is obtained such as MTBF, MTTR, etc. Thus available methods to balance those three features are not efficient and direct during the product design phase. In this paper, concepts of mean failure mass and mean failure repair time are presented. By investigating the relationship of the failure probability and the mass of a product, a feature linking reliability and supportability is obtained. Similarly, by studying the relationship of the failure probability and the mean time to repair of a product, a feature linking reliability and maintainability is obtained. Based on above definitions, an approach of reliability, maintainability and supportability trade-off during design phase is achieved. Effectiveness of both of the new concepts is demonstrated by an example of balancing the maintainability and supportability of a subsystem of a space station.

Keywords: *mean failure mass, mean failure repair time, reliability, maintainability, LRU.*

Jak dotąd w inżynierii niezawodności nie istniały parametry łączące niezawodność, obsługiwalność i utrzymywalność. Wskaźniki takie jak gotowość mogą być stosowane w celu sprawdzenia zgodności tych cech RAM (Reliability, Availability, Maintainability – Niezawodność, Gotowość, Obsługiwalność) dopiero po uzyskaniu indywidualnego wskaźnika każdej charakterystyki, takich jak MTBF, MTTR, itp. W ten sposób dostępne metody równoważenia owych trzech cech nie są wystarczająco skuteczne i bezpośrednie w fazie projektowania produktu . Niniejszy artykuł przedstawia pojęcia średniej masy uszkodzenia i średniego czasu naprawy uszkodzenia. Badając zależność prawdopodobieństwa uszkodzenia i masy produktu, uzyskuje się cechę łączącą niezawodność i utrzymywalność. Podobnie, badając zależność prawdopodobieństwa uszkodzenia i średniego czasu naprawy produktu, uzyskuje się cechę łączącą niezawodność i obsługiwalność. Na bazie powyższych definicji osiągnięto kompromisowe podejście do niezawodności, obsługiwalności i utrzymywalności podczas fazy projektowania. Skuteczności obu nowych koncepcji dowodzi przykład równoważenia niezawodności i obsługiwalności podsystemu stacji kosmicznej.

Słowa kluczowe: *średnia masa uszkodzenia, średni czas naprawy uszkodzenia, niezawodność, obsługiwalność, LRU*

1. Introduction

Modern equipments or systems are becoming more dependent on system engineering methods to ensure the life cycle availability and reliability. RAM (reliability, availability and maintainability) features are more and more essential to systems such as atomic energy plants, space stations and aeroplanes [1, 2].

Assessment of RAM parameters, methodologies for RAM analysis and simulation or modeling for RAM are the major issues on RAM studies [3]. As an approach which affects the product design deeply, methodology for RAM analysis plays the most important role in the life cycle RAM work. By the view of applications, RAM analysis should be a synthesis way which will deal with reliability, availability and maintainability at the same time. Unfortunately the methods presented in literature are not able to analyze RAM features simultaneously. Many analysis methods deal with RAM feature individually [4–7]. Other methods perform analysis of reliability, maintainability and supportability in a serial way [1, 8]. The reason is that no direct parameters linking reliability, maintainability and supportability are available [9–11]. Index such as availability can be used to check the compatibility of those RAM features only after individual index of every characteristic is obtained such as MTBF, MTTR, etc.

Above situation leads to that methods used to balance RAM features are not efficient and direct during the product design phase. For some systems such as space station or expeditionary warships, support issue plays an important role for mission accomplishment. Spares supply is expensive and crucial herein. During the design phase, trade-off of reliability, maintainability and spare plan is much necessary. Indirect methods such as multidiscipline domain optimization (MDO) approach and RAM simulation have been employed for RAM trade-off [12–13]. As these methods are not able to point out what issues affect the RAM parameters and how to affect RAM parameters, direct analysis methods are needed for RAM features trade-off, so are the parameters which can link reliability, maintainability and supportability directly.

So far, existent RAM parameters are not able to link reliability, maintainability and supportability directly [9-10]. This paper aims to give two parameters. One directly links reliability and supportability, another directly links reliability and maintainability. As we know, supportability and maintainability are two concepts which depend on the usage and maintenance scenario. Failure-maintenance and failure-spare delivery schedule affect the product supportability and maintainability profoundly. Once the usage and maintenance scenario is confirmed, the failure-maintenance and failure-spare delivery relationships will express objective characteristics of the designed product. Naturally, there is a need to study the relationship of the failure probability and the mass of a product. Similarly, the relationship of the failure probability and the mean time to repair of a product is also an interesting target.

In this paper, concepts of mean failure mass and mean failure repair time are presented. Effectiveness of both of the new concepts is demonstrated by an example of balancing the maintainability and supportability of a subsystem of a space station.

2. The concept of mean failure mass

Failure of a product is its inherent property. When a failure occurs, some units (LRU and SRU, namely line replaceable unit and shop replaceable unit) in the product need to be maintained or to be replaced directly. For a matured product, a unit locates in a fixed location. For units in a product, a failure and a unit replacement relationship contains the product structural information and the maintenance information. Once the maintenance scenario is confirmed, the failure-replacement relationship of the unit is fixed.

For organizational-level maintenance or intermediate-level maintenance, failure of a LRU or a SRU can result in a replacement of another LRU or SRU. Hence, the following concept is presented.

Definition 1: suppose some failure of unit A will result in a replacement of unit *B*. Let the set of failures of unit *A* which will result in replacement of unit *B* be Ω. Under the given conditions and given time, the total failure probability of unit *A* in Ω is named $F_a(t)$. The mass of unit *B* is named M_b. Define the product of $F_a(t)$ and M_b as: mean failure mass of unit *B* brought by unit *A* which is expressed by $MFM_{a\text{-}b}$:

$$MFM_{a\text{-}b}\,(t)=F_a(t)\cdot M_b \tag{1}$$

Definition 2: suppose some failure of unit *A* will result in a replacement of itself. Let the set of failures of unit *A* which will result in replacement of itself be Ω. Under the given conditions and given time, the total failure probability of unit *A* in Ω is named $F_a(t)$. The mass of unit *A* is named M_a. Define the product of $F_a(t)$and M_a as: mean failure mass of unit *A* which is expressed by MFM_a:

$$MFM_a(t)=F_a(t)\cdot \mathrm{Ma} \tag{2}$$

By definition 1 and definition 2, it is obvious that MFM is a variable of time *t* with a dimension of mass (for instance, kilogram). It can be seen as how much mass has been lost by failure in average which in most cases can also be regarded as the delivery burden of spares. For example, suppose there are 100 LRU *A*s and 100 LRU *B*s in service. LRU *A* has a failure probability of 0.25 in 6 months and a mass of 10 kg. LRU *B* has a failure probability of 0.50 in 6 months and a mass of 6 kg. Calculation shows that in 6 months, 25 LRU *A*s and 50 LRU *B*s will fail. For LRU *A*, 25 spares with 250 kg are needed, meanwhile for LRU *B*, 50 spares with 300kg are needed. Under this circumstance, on the view of weight, LRU *B* has a greater support burden than LRU *A* with a ration of 300 to 250. Actually, by definition 2, this ratio can be obtained direct. By definition 2, MFM_a is the product of 0.25 and 10 kg, that is 2.5; MFM_b is the product of 0.5 and 6 kg, that is 3. MFM_b/MFM_a is exactly the ratio of 3/2.5 which means the ratio of support burden of spares weight of LRU *A* to LRU *B*. It can be seen mean failure mass can be a useful parameter in the case where the spares delivery is difficult and expensive such as accommodation of a Space Station.

3. The concept of mean failure repair time

As mentioned above, for a matured product, a unit locates in a fixed location. Once the maintenance scenario is confirmed, the failure-maintenance relationship is fixed. Under given conditions, the time consumed for a unit repair is of an objective value named as mean time to repair. If every failure results in an immediate repair, then next concept will be objective.

Definition 3: suppose some failure of unit *A* will result in a repair of unit *B*. Let the set of failures of unit *A* which will result in repair of unit *B* be Ω. Under the given conditions and given time, the total failure probability of unit *A* in Ω is named $F_a(t)$. The *MTTR* (mean time to repair) of unit *B* is named $MTTR_b$. Define the product of $F_a(t)$ and $MTTR_b$ as: mean failure repair time of unit *B* brought by unit *A* which is expressed by $MFRT_{a\text{-}b}$:

$$MFRT_{a\text{-}b}\,(t)=F_a(t)\cdot MTTR_b \tag{3}$$

Definition 4: suppose some failure of unit *A* will result in a repair of itself. Let the set of failures of unit *A* which will result in repair of itself be Ω. Under the given conditions and given time, the total failure probability of unit *A* in Ω is named $F_a(t)$. The *MTTR* (mean time to repair) of unit *A* is named $MTTR_a$. Define the product of $F_a(t)$ and $MTTR_a$ as: mean failure repair time of unit *A* which is expressed by $MFRT_a$:

$$MFRT_a\,(t)=F_a(t)\cdot MTTR_a \tag{4}$$

By definition 3 and definition 4, it is obvious that MFRT is a variable of time t with a dimension of time (for instance, hour). It can be seen as how much repair time has been spent by failure in average which in most cases can also be regarded as the maintenance burden. Example can be simply given similarly as section 2.

4. Applications

Definition 1 to 4 implies that the object is a unit. A unit is a replacement or repair target, so above definitions have no doubt in reality usage. But if the object is a module or a system which consists of several units, then the average support burden and average maintenance burden cannot be obtained from above definitions directly. Although definition 1 to 4 are not suitable to a module or a system, we can still borrow MFM and MFRT to express total spares delivery burden and total maintenance burden of a module or a system, which are the total spares mass need to be delivered and the total maintenance time need for every failure repair. Once MFM and MFRT can be calculated directly, RAM trade-off analysis can be easily accomplished.

4.1. Failure-replacement correlative matrix and failure-maintenance correlative matrix

A failure-replacement correlative matrix can be employed to express failure-replacement relationship of LRUs in a system:

Table1. Failure-replacement correlative matrix Σ

	unit 1	unit 2	…	unit n
failure of unit 1	m_{11}	m_{12}	…	m_{1n}
failure of unit 2	m_{21}	m_{22}	…	m_{2n}
…	…	…	…	…
failure of unit m	m_{n1}	m_{n2}	…	m_{nn}

If failure of unit *i* results in replacement of unit *j*, set m_{ij} as 1. If failure of unit *i* doesn't result in replacement of unit *j*, then set m_{ij} as

0. Note that matrix Σ depends on the structure of the system and LRU selection plan. Similarly, A failure-maintenance correlative matrix can be similarly defined as Φ. In most cases, Σ and Φ have the same expression, so we treat them as the same one. Once Σ is known, the MFM and MFRT of a system can be calculated by following equations:

$$MFM_s(t) = \left[F_1(t) \quad F_2(t) \quad \cdots \quad F_n(t)\right]\Sigma \begin{bmatrix} M_1 \\ M_2 \\ \cdots \\ M_n \end{bmatrix} = \mathrm{F\Sigma M}$$

$$MFRT_s(t) = \left[F_1(t) \quad F_2(t) \quad \cdots \quad F_n(t)\right]\Sigma \begin{bmatrix} MTTR_1 \\ MTTR_2 \\ \cdots \\ MTTR_n \end{bmatrix} = \boldsymbol{F\Sigma T} \qquad (6)$$

where F is a vector consists of failure probability of every unit. $\boldsymbol{M}$ is a vector consists of mass of every unit. $\boldsymbol{T}$ is a vector consists of MTTR of every unit. Obviously, when all the units of a system are independent in the view of failure-replacement and failure-maintenance, matrix Σ is diagonal:

$$\begin{aligned} MFM_s(t) &= \textstyle\sum_{i=1}^{n} MFM_i(t) \\ MFRT_s(t) &= \textstyle\sum_{i=1}^{n} MFRT_i(t) \end{aligned} \qquad (7)$$

Formula (5) to (7) are reasonable only if the failures of every unit are independent which means the elements of $\boldsymbol{F}$ are independent.

4.2. Corrective and preventive maintenance

Above concepts are induced from corrective maintenance where failure is the only reason for units replacement or repair. But actual cases are more complicated where preventive maintenance is also a major issue. As preventive maintenance is more regular, one can simply add its affect on corresponding parameters of corrective maintenance. Suppose during time t, the system support burden and maintenance burden resulting from failures are $\boldsymbol{F\Sigma M}$ and $\boldsymbol{F\Sigma T}$. We also suppose during time t, there are n times scheduled replacement for unit A. Suppose corrective repair doesn't affect scheduled preventive replacement and the time consumed of other preventive maintenances is negligible, then the total the system support burden and maintenance burden can be written as:

$$\begin{gathered} MFM_s(t)=\boldsymbol{F\Sigma M}+nM_a \\ MFRT_s(t)=\boldsymbol{F\Sigma T}+nMTTR_a \end{gathered} \qquad (8)$$

The ratio is reasonable which can be showed simply as follows. Suppose there are m unit A. Then for time t, mass of $m \cdot F_a(t) \cdot M_a$ will be replaced for corrective maintenance. At the same time, for preventive maintenance every unit A will be replaced n times. Then mass of $m \cdot n \cdot M_a$ will be replaced for preventive maintenance. Total replaced mass is $m \cdot F_a(t) \cdot M_a + m \cdot n \cdot M_a$. It is obvious that for defined MFM, replaced mass for preventive maintenance can directly added as $n \cdot M_a$.

4.3. Trade-off analysis by MFM and MFRT.

When MFM and MFRT are achieved, trade-off analysis can be done efficiently. As MFM and MFRT are deeply dependent on the product structure and the LRU selection results, this trade-off can be used for LRU selection optimization. In general, a product structure can be expressed as a tree. Following is an example:

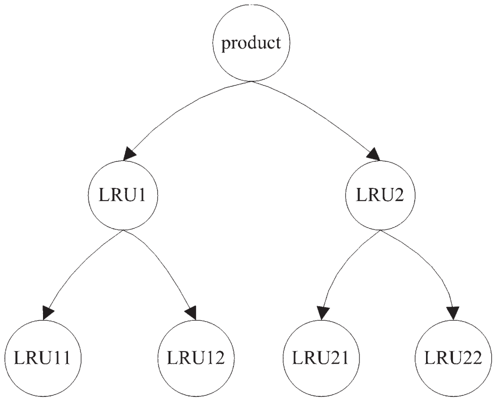

Fig. 1. A product structure tree

The LRU selection can be (1) LRU1 and LRU2, or (2) LRU11, LRU12, LRU21 and LRU22. Normally, selection (1) results in greater MFM, as spare defined as bigger item will lead to uneconomical spares delivery. Selection (1) also leads to a smaller MFRT, as maintenance for bigger item will consume smaller dismantlement time. At the same time, selection (2) results in smaller MFM and greater MFRT, as spares defined as smaller item will lead to economical spare delivery and consume greater replacement time.

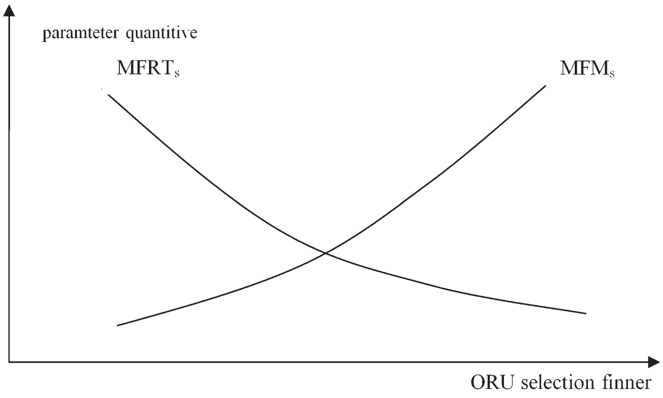

Fig. 2. ORU selection trade-off

Above figure shows that MFM and MFRT are contradictory with regard to different LRU selection level. By a unification ration, an optimization point can be found for the total cost function of MFM and MFRT.

5. Case study

MFM and MFRT represent the mean spares delivery burden and maintenance burden which are contradictory in some sense. As they both are relative to LRU selection plan, they are suitable for RAM trade-off in product design phase. Following is an example of LRU selection by RAM trade-off on CDRA (Carbon Dioxide Removal Assembly) of ECLSS (Environmental Control and Life Support Systems). Here the concept of ORU(Orbit Replaceable Unit) is employed instead of LRU.

In following study, 7 ORU selection plans are given. The first approach is to compute MFM and MFRT directly and employ a resulted synthetical objective function to carry on ORU selection. The first approach is called direct calculation method. In next step, a Monte Carlo method is used to simulate the failure occurence in a time range. Real spares mass delivered and maintenance time consumed are calculated by accumulation approach. The second way is called simulation

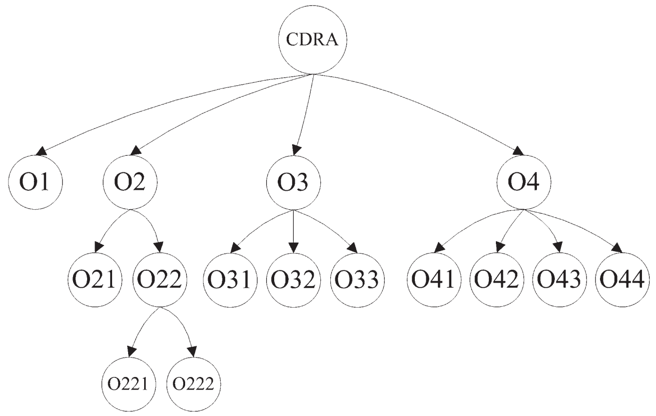

Fig. 3. Structural tree of CDRA

Table 2. Name of ORUs

O1	AIR I/O Selector Valve Module	O32	Open Loop Vent Valve
O2	Desiccant and Sorbent module	O33	AIR Save Pump
O21	Desiccant Bed	O4	AIR Blower and Precooler Module
O22	CO2 Sorbent Module	O41	Selector Valve 4
O221	CO2 Sorbent Bed	O42	AIR Blower
O222	Check Valve	O43	Precooler
O3	AIR Save Pump Module	O44	Selector Valve 5
O31	Selector Valve 3		

Table 3. Basic data of ORUs

ORU or Module	Failure rate(1/y)	MTTR(h)	Mass(kg)	Maintenance plan
AIR I/O Selector Valve Module 1	0.0815	0.92	10	Corrective maintenance
Desiccant and Sorbent module 2	0.3879	1.23	52	Preventive maintenance
Desiccant Bed 21	0.2827	2.21	19	Preventive maintenance
CO2 Sorbent Module22	0.3052	1.26	26	Preventive maintenance
CO2 Sorbent Bed221	0.1594	1.90	24	Preventive maintenance
Check Valve222	0.1458	2.22	5	Corrective maintenance
AIR Save Pump Module3	0.4099	1.55	25	Corrective maintenance
Selector Valve 3 31	0.1730	2.58	4	Corrective maintenance
Open Loop Vent Valve 32	0.1601	2.63	4	Corrective maintenance
AIR Save Pump 33	0.0768	2.84	18	Corrective maintenance
AIR Blower and Precooler Module 4	0.7078	1.38	30	Corrective maintenance
Selector Valve 4 41	0.2230	3.38	4	Corrective maintenance
AIR Blower42	0.0733	2.92	20	Corrective maintenance
Precooler43	0.1885	2.96	4	Corrective maintenance
Selector Valve 5 44	0.2230	3.32	4	Corrective maintenance

Table 4. ORU Selection Scheme

Selection	Number of ORU	ORU
1	5	01,021,022,03,04
2	6	01,021,0221,0222,03,04
3	7	01,021,022,031,032,033,04
4	8	01,021,0221,0222,031,032,033,04
5	9	01,021,0221,0222,03,041,042,043,044
6	10	01,021,022,031,032,033,041,042,043,044
7	11	01,021,0221,0222,031,032,033,041,042,043,044

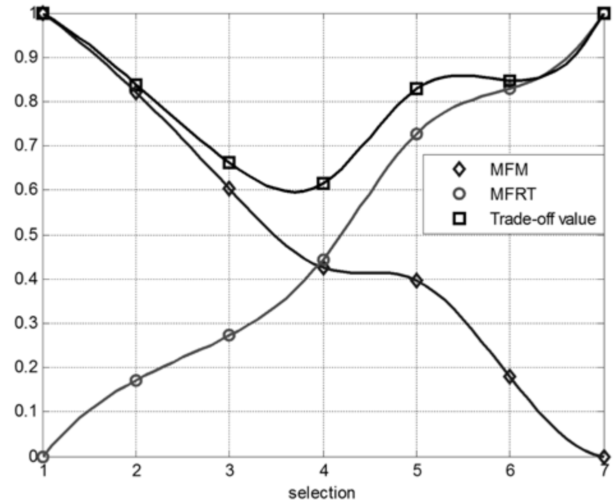

Fig. 4. plot of objective function of direct calculation method

method. Finally, the effectiveness of new definitions can be verified by comparison of above results obtained in different ways.

CDRA of ECLSS has 4 modules, the AIR I/O Selector Valve Module, Desiccant and Sorbent module, AIR Save Pump Module and AIR Blower and Precooler Module. The structure tree of CDRA is shown in Fig. 3, and the names of ORU in CDRA are given in Table 2. In addition, the basic reliability, mass and MTTR of ORUs are given in table 3. According to structure tree of CDRA, there are 7 ORU selection scheme as shown in table 4.

Some assumptions are given for MFM and MFRTcomputation:

(1) For simplicity, suppose the ORU's reliability is of exponential distribution.

(2) Failure and replacement of every unit doesn't affect each other.

The MFM and MFRT are computed as ORU selection indices by formulas (2), (4), (7), (8). For synthesis trade-off analysis, MFM and MFRT are normalized as :

$$x_i = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \tag{9}$$

Where X_{min} is the minimum value of MFM or MFRT, X_{max} is the maximum value of MFM or MFRT. Let the synthetical objective function be:

$$\min\left\{\sqrt{MFM^2 + MFRT^2}\right\} \tag{10}$$

Results are shown in Table 5 and Fig. 4. The selection (4) is the optimal solution from the curve of trade-off value.

In another approach, Monte Carlo method is used to simulate failure occurance of the ORUs of CDRA in a time range. The real spares

Table 5. MFM and MFRT

Selection	Number of ORU	MFM(kg)	MFRT(h)	MFM (normalized)	MFRT (normalized)	Trade-off value
1	5	147.7801	10.1655	1	0	1
2	6	143.9708	12.8225	0.8212	0.1713	0.8389
3	7	139.3280	14.3858	0.6034	0.2721	0.6619
4	8	135.5187	17.0428	0.4246	0.4435	0.6140
5	9	134.9192	21.4509	0.3965	0.7278	0.8288
6	10	130.2764	23.0141	0.1787	0.8286	0.8476
7	11	126.4671	25.6712	0	1	1

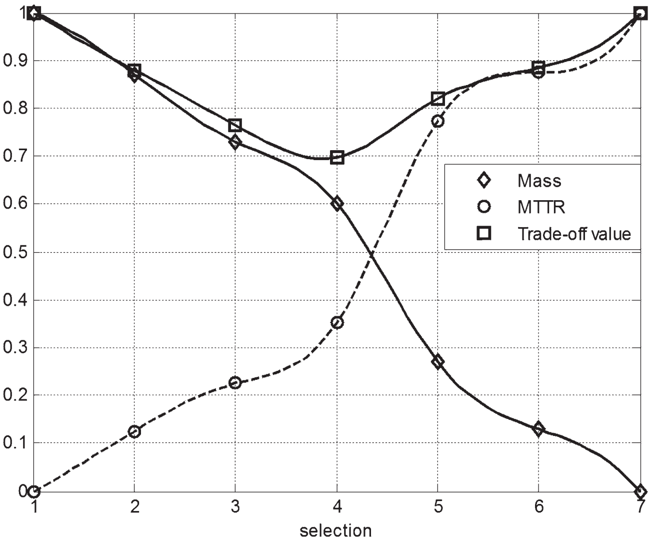

Fig. 5. Plot of objective function of simulation method

mass and maintenance time are achieved by accumulation computation. Here the ORU's failure rate is assumed to be of exponential distribution. The spares delivery burden and maintenance burden are achieved by employing Monte Carlo method and normalization method shown in Table 6 and Fig. 5.

The selection (4) is also the optimal solution by Monte Carlo simulation.

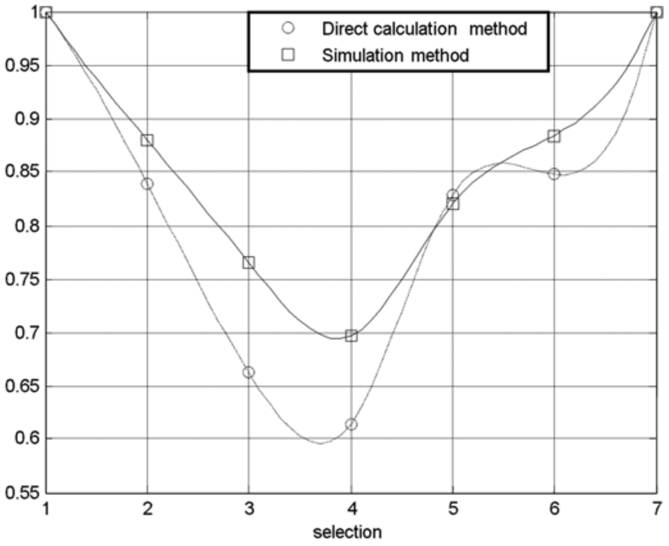

Fig. 6. Trade-off value of two methods

Finally, the results of two different trade-off ways are compared in Fig.6. The trade-off objective function value of direct calculation method and classical Monte Carlo simulation method shows the same tendency and the same optimal ORU selection point. This case study shows that the concepts of mean failure mass and mean failure repair time are much useful for RAM trade-off analysis.

6. Conclusions

Because of some restriction during the design phase of products, the traditional methods used to balance RAM are not efficient and direct. In this paper, an approach of reliability, maintainability and supportability trade-off during design phase is achieved using the concepts of mean failure mass and mean failure repair time both of which are firstly presented. The article uses the concepts of MFM and MFRT to express total spares delivery burden and total maintenance burden of a module or a system, which are the total spares mass need to be delivered and the total maintenance time needed for every failure repair. Once MFM and MFRT of a system can be calculated directly, the system RAM trade-off analysis can be easily accomplished. A case of a Carbon Dioxide Removal Assembly (CDRA) of space station showed that the concepts of MFM and MFRT are very useful for a simple calculation of the support and maintenance burden which leads to a direct trade-off of RMS. The trade-off results of direct computation and simulation are same which shows the new concepts and relative computation method are effective. From above paper, one can see that MFM and MFRT are the parameters linking reliability, maintainability and supportability.

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