Maintainability Allocation assessment in complex systems

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Abstract – **High maintainability becomes a fundamental requirement of most manufacturing products and system maintainability performance represents a key factor in many manufacturing fields. The paper focus on a procedure to obtain maintainability requirements of a complex system and compares the methods to achieve the best fitting.**

The first part of the paper focuses on maintainability allocation procedures: failure rate-based allocation method, trade-off of failure rate and design feature-based allocation method, fuzzy maintainability allocation based on interval analysis and time characteristic-based maintainability allocation models. The second part shows a case study on a generic system containing a redundant architecture with three different MTTR objective of the overall system in order to test the proposed method.

I.   INTRODUCTION

In industrial fields product complexity and miniaturization of components is leading to a huge growth of number and variety of failures, therefore maintainability is one of the most important requirements of a product   [1-2]. The paper focuses on Maintainability Allocation (MA) procedures, in order to analyse how these indicators achieve the best fitting. Maintainability Allocation is performed in the initial phases of a manufacture design. Allocation apportions the overall system objectives, required by a customer, down to component level to provide designers the maintainability requirements of single blocks making up the system[3-4].

The objectives of Maintainability Allocation procedure are:

- Identify the maintainability requirements for subsystems and items in order to guarantee the system maintainability requirements goals;

- Focus on problems of maintainability during the design phase to ensure the realization of very specific requirements.

To realize the requirements some MA procedures are presented in the following paragraph.

The mean corrective maintenance downtime $\bar{M}_{CT}$, also known as MTTR, of a system consisting of n replaceable or repairable items is given by[5-6]:

$$\bar{M}_{CT} = \frac{\sum_{i=1}^{n} \bar{M}_{Ci} \lambda_i}{\sum_{i=1}^{n} \lambda_i} \tag{1}$$

Where:

- $\bar{M}_{Ci}$ is the system active corrective or repair downtime when the i-th item fails

- λ_i is the failure rate for the i-th item.

II.   ALLOCATION METHODS

The Failure rate-based allocation method allows to allocate for each item the optimal mean corrective maintenance downtime values. The principle of this allocation method is the following: the repair time allocated to the item with high failure rate is short and vice versa. The hypothesis of this method is that the failure rate of each item is established. The MTTR distributed to each unit is calculated as [7-8]:

$$\bar{M}_{CT_i} = \frac{\bar{M}_{CT} \sum_{i=1}^{n} \lambda_i}{n \lambda_i} \tag{2}$$

Where:

- $\bar{M}_{CT}$ is the objective MTTR of the overall system
- λ_i is the failure rate of unit i
- n is the total number of unit types

In order to offer more accuracy and allow to calculate the importance of each factor within the MA procedure structure, the trade-off of failure rate method is analyzed. The procedure is similar to the previous one but it introduces some weight factors. The MTTR allocated to each unit is [7]:

$$\bar{M}_{CT_i} = \beta_i \bar{M}_{CT} \tag{3}$$

Where:

- $\beta_i = \frac{\bar{\lambda} k_i}{\lambda_i \bar{k}}$ is the weight coefficient of the repair time for the unit i;

- $\bar{\lambda}$ is the average failure rate of each unit;

- $\bar{k} = \frac{\sum_{i=1}^{n} k_i}{n}$ is the average of each unit weight coefficient;
- $k_i = \sum_{i=1}^{m} k_{ij}$ is the weight coefficient of factor j in unit i.

When this procedure is used, like the previous one, the requirement of maintainability design should be clear.

The human mind logic is introduced, on binary logic system, by using the Fuzzy theory. Human reasoning admits the possibility of switching from one concept to another gradually, while this is not possible in the Boolean logic where an element can only belong or not to a set [9-10]. Factors such as reliability, life cycle cost and product development should also be taken into account [11]. The fuzzy comprehensive evaluation is explained by [12-13]:

$$\tilde{B} = \widetilde{W}^{\circ}\tilde{R} \qquad (4)$$

$$\tilde{B} = [w_1 \quad w_2 \dots w_m] \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix} \qquad (5)$$

$$\tilde{B} = [b_1 \quad b_2 \dots b_n] \qquad (6)$$

Where:
- $\widetilde{W}$ is the weight vector of MA influencing factors;
- $\tilde{R}$ is the matrix of subsystems influencing factors;
- $\tilde{B}$ is the result of maintainability, comprehensive evaluation;
- b₁, b₂, … bₙ express the relative value of maintainability weight factor of each subsystem;
- the symbol "°" is fuzzy composition operator;
- m is the number of influence factors;
- n is the number of subsystems [14].

Lots of methods can be used to determine the element of the vector $\tilde{B}$ and the maintainability allocation can be written as follows:

$$\bar{M}_{CT_j} = \frac{b_j \sum_{j=1}^{n} \lambda_j}{\sum_{j=1}^{n} \lambda_j b_j} \bar{M}_{CT} \qquad (7)$$

To overcome the limit of traditional MA methods and improve the accuracy and effectiveness of the allocated MTTR index in the following paragraph an innovative procedure, based on time characteristics, has been proposed [7].

III. TIME CHARACTERISTICS-BASED MA METHOD

This method classifies the repair time in two categories because different elements are controlled by different design departments in practice [7]:

- Common repair time is determined by the overall system design or the upper design department. This type of time is determined by the overall design or upper level department and it is not directly affected and controlled by product design at this stage;
- Individual repair time is defined as the individual repair time for product units. It is determined by product design, such as assembly, changing, and adjustment time.

Different allocation models are built for different hierarchical level of the system: high level products method for the subsystems and low level products method for the items [15].

For high-level products, we assume that the system consists of n subsystems, each described by the failure rates $\lambda_1, \lambda_2, \dots \lambda_n$. Preparation time T_P, approaching time T_A, and reassembly time T_R compose the common repair time [7].

$$T_{CMN} = T_P + T_A + T_R \qquad (8)$$

The individual repair time, also known as single maintenance time, T_{IDV} is obtained removing the common maintenance time from the MTTR, as follow [16]:

$$T_{IDV} = \bar{M}_{CT} - T_{CMN} \qquad (9)$$

Failure rate-based allocation method is utilized to allocate individual repair time to the lower level of the equipment.

$$\bar{M}_{CTi} = \frac{\sum_{i=1}^{n} \lambda_i}{n\lambda_i} T_{IDV} = \frac{\bar{\lambda}}{\lambda_i} T_{IDV} \qquad (10)$$

Fig. 1. Block diagram of High Level Product Procedure

Fig. 1 shows the most important steps of the MA procedure for the subsystem level (RU group) using the Time Characteristic-based method. The MTTR allocated is calculated with High Level Product procedure.

The maintenance process for low-level components includes isolation, disassembly, and replacement. The total common repair time and individual repair time for all low-level units are the following [7]:

$$T_{RU-CMN} = T_P + T_A + T_R \qquad (11)$$

$$T_{RU-IDV} = \bar{M}_{CTi} - T_{RU-CMN} \qquad (12)$$

Where T_{RU-IDV} is the individual repair time allocated to the single RU (Replaceable Unit); $\bar{M}_{CTi}$ is the time indicator allocated to subsystem i from system level using the high-level product allocation model; T_{RU-CMN} is the common repair time in this level.

The average number of replacements in the alternately replaced RU group consisting of m single RUs is:

$$S_i = \left[\frac{m+1}{2}\right] \qquad (13)$$

Where [x] is a maximum integer not larger than x.

In this study six kinds of maintainability design features are considered: fault detection and isolation, maintenance channel, fasteners, internal assembly, replacement, and scalability. These features may be different for different products depending on specific circumstances. Repair time differs because different maintenance schemes are employed. Coefficient α_i is introduced in the model to correct the weight coefficient and to make the allocation reasonable and accurate. There are three different cases [7]:

- If the failure is isolated to a single RU, the correct coefficient is $\alpha_i = 1$;
- If the failure is isolated to an RU group consisting of m replaced alternately $\alpha_i = S_i = \left[\frac{m+1}{2}\right]$;
- If the failure is isolated to an RU group consisting of r and all are replaced, the correct coefficient is $\alpha_i = r$;

The repair time allocated to each RU is calculated as:

$$\bar{M}_{CTi} = \frac{k_i' \sum_{i=1}^{j+k+l} \lambda_i}{\lambda_i \sum_{i=1}^{j+k+l} k_i'} T_{RU-IDV} \qquad (14)$$

Where $k_i' = \alpha_i k_i = \alpha_i \sum_{j=1}^m k_{ij}$ with m number of weight coefficients and k_{ij} weight coefficient of factor j in unit i; and $i = 1, \dots, j, j+1, \dots, j+k, j+k+1, \dots, j+k+l$
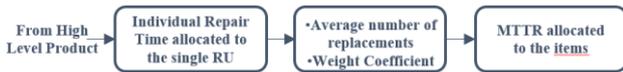

Fig. 2. Block diagram of Low Level Product Procedure

Fig. 2 shows the most important steps of the MA procedure for the element level (LRU group) using the Time Characteristic-based method. The MTTR allocated is calculated with Low Level Product procedure using the results of the High Level Product procedure.

IV.   COMPARISON OF PROCEDURES

There are a lot of advantages from an optimal allocation of maintainability indicators to the various subsystems of a complex system. Once the allocation target is defined a series of system interventions, reconfigurations and corrections are planned in order to optimize maintenance activities, reduce their implementation costs and their impact on people and environment.

In previous paragraphs four MA methods have been analyzed and these procedures are compared to bring out characteristics, strengths and weaknesses of each of them and to identify which is the optimal method for the application under analysis.

The failure rate-based allocation method is easy and fast to apply and is based on resolution of an elementary mathematic equation. Anyway, it shows an intrinsic limit: the failure rates of each single unit must be clear. This procedure is not widely used because it doesn't consider a number of factors which deeply affects the maintenance activities, in fact the method has a low precision and accuracy.

In order to solve the problem, the trade-off of failure rate and design feature-based allocation method is introduced. Influence factors such as complexity, accessibility, scalability and some others are taken into account using dedicated weight coefficients that reflect each role in the maintenance process. Anyway, this solution involves some disadvantages: a huge number of parameters must be known and the final results can profoundly vary if the assessment is not accurate. Furthermore the inability to differentiate the influence factors depending on the nature of their effects involves the unacceptability.

A weight factor, assigned as real number, cannot fully describe the real scenario, therefore the Fuzzy maintainability allocation based on interval analysis method was introduced to solve this problem. The human mind logic, that admits the possibility of switching from one concept to another gradually, is introduced on binary logic system, by using this theory. This MA procedure is characterized by a high implementation complexity and significant waste of budget, resource and time.

The best and the most complete method results the time characteristics-based maintainability allocation method, which succeeds in overcoming the others methods limitations. Indeed this procedure is practical, quick and easy to implement and it provides satisfying results. The repair time is divided in common and individual repair time. The first one is deducted from the total system repair time while the second one is allocated to specific units using one of the traditional methods.

V. CASE STUDY

In order to test and validate the time characteristic-based MA method, a Maintainability Allocation assessment was achieved on a generic system containing redundant blocks (Fig. 3).
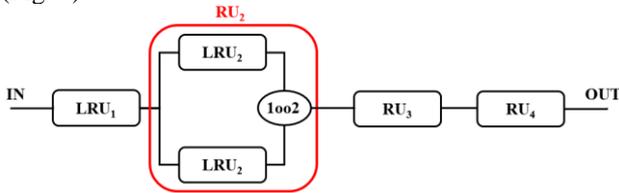

Fig. 3. RBD of the system under test

Figure 3 shows the structure of the analyzed system, in subsystem hierachical level. It is composed by four series subsystem (RU), the first one is an indivisible single block, called LRU_1, the second block is divided in two identical items in parallel configuration, the third and the last block are respectively formed by four and three elements.

Input data is the MTTR target of the system and it can vary between 1 hour and 8 hours, in order to maximize the system availability performance.

Table 1. Input Data for MA procedure

RU	LRU	Input				
		λ [FIT]	S_i	α_i	K_i	K'_i
RU_1	LRU_1	605	1	1	6	6
RU_2	LRU_2	1548	1	1	6	6
RU_3	LRU_3	2027	780	2	16	14	32
	LRU_4		498			16	
	LRU_5		99			20	
	LRU_6		650			12	
RU_4	LRU_7	1535	980	2	12	16	24
	LRU_8		105			12	
	LRU_9		450			12	

Table 1 contains the failure rates of each component of the system as reported in exida documents and all input parameters of the allocation method described in detail in paragraph 3. For the allocation on the LRU level the starting system MTTR is 4h, according with the objective of the analysis.The common repair time of the repairable unit is zero. For the others, according to equation (11-12), the common repair time and the individul repair time are reported in table 2. Moreover the table contains the repair time allocated for each RU subsystem according to equation (14).

Table 2. Common repair time and Individual repair at RU level

	RU_1	RU_2	RU_3	RU_4
T_{CMN}	0h	0h	2h12'	1h12'
T_{IDV}	4h	4h	1h48'	2h48'
$MTTR_i$	3h20'	1h18'	5h18'	5h15'

According to the method previosly described it's possible to calculate the MTTR of each element (LRU).

In order to compare and test the variability of output data due to some deviation involving the input data parameters another two case are analyzed, halving and doubling the MTTR of the overrall system. These simulation times (2h, 4h, 8h) represent a generic working day and its submultiple, in order to provide data output compatible with the industrial standard requirements. This test wants to evidence the relationship between the optimal index allocated and the overral requirement (MTTR) of the system.

Figure 4 shows the MTTR in the different case, the red line evidences the repair time allocated to the elements with the objective MTTR=4h (half working day).

Indeed, the blue and the green columns rapresent the output data with the objective MTTR=2h and MTTR=8h respectively.
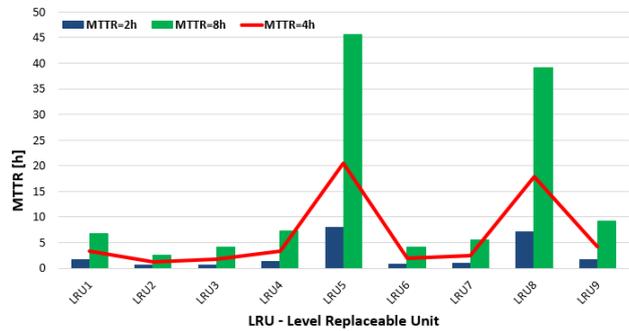

Fig. 4. Comparison of the two cases

Comparing the three cases, it's possible to note that the increase of the MTTR requirement implicates an increase of the maintainability indices allocated to each items. Similarly a decrease of the MTTR goal involves a decrease of the repair time of the elements.

Figure 4 highlights the most critical elements characterized by the highest common repair time, LRU_5 (20 hours and 31 minutes for input MTTR=4h) and LRU_8 (17 hours and 47 minutes for input MTTR=4h). As you would expect from theory and literature, these two items remain the most critical also in the other two simulation.

The least critical elements in all simulations, characterized by the lowest common repair times (around 1 hour for input MTTR=4h) are LRU_2, LRU_3, and LRU_6.

Comparing the failure rates shown in Table 1 and the output data in Figure 4, for the elements with a highest failure rate the procedure allocates the lowest repair time. This type of elements has a higher probability to fail, so it is important that the method allocates a very small repair time because the maintenance operation are frequent, in order to maximize the system availability.

VI.   CONCLUSION

This paper analyzes in detail the Maintainability Allocation procedures. Starting from a study of four allocation methods presented in literature, this paper shows the best procedure to allocate the repair time to each item that composed the overall system. The analysis identifies the time-characteristics based maintainability allocation method due to its simplicity and speed of implementation.

In the proposed case study, a system including redundant block has been analyzed with MTTR requirement for the overall system belongs to the range   1 hour – 8 hours. In the first case the system MTTR is 4h, in the other cases it has been varied, its value is 2h and 8h. The comparisation of the three cases shows that increasing the system MTTR also the maintainability indices allocated to the components increase and vice versa.

Change of the MTTR requirement produces a significant variation of the common repair time for the most critical elements, on the other hand the allocated MTTR endures small deviation for the least critical elements.

Therefore, little variation of the overall MTTR objective produces a big increase of the critical elements repair time with a great demand of hours to fix these issues and repair the elements out of order.

VII.   REFERENCES

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