AN ANALYTIC HIERARCHY PROCESS BASED RELIABILITY ALLOCATION METHOD (ARAM)

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ABSTRACT

A new method (ARAM) is proposed and evaluated for launch vehicle subsystems reliability allocation. A multiple weighted criterions method called Analytic Hierarchy Process (AHP) is enabled to assess the reliability allocation of a launch vehicle subsystems based on technology, cost, complexity and operation time. These criterions are selected to decide about the optimum reliability of each individual subsystem to achieve reliability goal of the launch vehicle. This is a logical approach because system reliability is product of the subsystem reliabilities, so if they are optimized and compatible with respect to the mentioned criterions, the system reliability will also be optimized and compatible. Thus, it represents an efficient solution method that relies on evaluation of compatibility matrix. This AHP based approach is used for launch vehicle subsystems reliability allocation and results show the efficiency and capability of this method.

Keywords: AHP, Allocation, Reliability, Launch Vehicle.

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1. Introduction

The reliability of a launch vehicle is the probability that a vehicle will complete its mission successfully in a specified period of time [1]. One of the important problems in reliability base design of a system is allocating reliability values to the various components of the system.

Generally, the effort may include cost, complexity, technology, and component obstruction, among others [2]. In this paper, however, we only considered improving the reliability of the constituent components of a system without changing its structure.

There has been some known effort functions mentioned in the literature. In the study, in order to look for a suitable effort function for the allocating purpose, we made a comparison among them first. As a result of the lack of data for creating the parameters, an effort function always cannot be depended on. The Analytic Hierarchy Process (AHP) was then considered to compensate the deficiency. A common used example in the literature was also illustrated for elementary test and verification. To accomplish the reliability allocation procedure, a revised effort minimization method was used for an integral calculation [3].

2. The AHP – Step by Step

The AHP is based on the experience gained by its developer, T.L. Saaty, while directing research projects in the US Arms Control and Disarmament Agency (ACDA). It was developed as a reaction to the finding that there is a miserable lack of common, easily understood and easy-to-implement methodology to enable the taking of complex decisions. Since then, the simplicity and power of the AHP has led to its widespread use across multiple domains in every part of the world. The AHP has found use in business, government, social studies, R&D, defense and other domains involving decisions in which choice, prioritization or forecasting is needed [4].

The AHP provides a means of decomposing the problem into a hierarchy of sub problems which can more easily be comprehended and subjectively evaluated. The subjective evaluations are converted into numerical values and processed to rank each alternative on a numerical scale. The methodology of the AHP can be explained in following steps:

Step 1: The problem is decomposed into a hierarchy of goal, criteria, sub-criteria and alternatives. This is the most creative and important part of decision-making.

Structuring the decision problem as a hierarchy is fundamental to the process of the AHP. Hierarchy indicates a relationship between elements of one level with those of the level immediately below. Figure 1 shows a generic hierarchic structure. At the root of the hierarchy is the goal or objective of the problem being studied and analyzed.

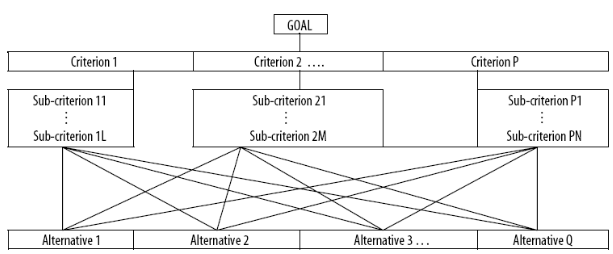

Fig. 1: Generic hierarchic structure [4]

Step 2: Data are collected from experts or decision-makers corresponding to the hierarchic structure, in the pair wise comparison of alternatives on a qualitative scale as described below. Experts can rate the comparison as equal, marginally strong, strong, very strong, and extremely strong. The opinion can be collected in a specially designed format as shown in Figure 2.

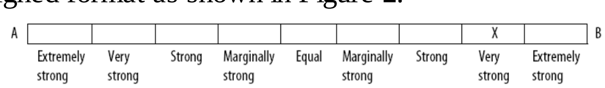

Fig. 2: Format for pair wise comparisons [4]

Step 3: The pair wise comparisons of various criteria generated at step 2 are organized into a square matrix. The diagonal elements of the matrix are 1. The criterion in the i^{th} row is better than criterion in the j^{th} column if the value of element (i, j) is more than 1; otherwise the criterion in the j^{th} column is better than that in the i^{th} row. The (*j*, *i*) element of the matrix is the reciprocal of the (i, j) element.

Step 4: The principal eigen value and the corresponding normalized right eigenvector of the comparison matrix give the relative importance of the various criteria being compared. The elements of the normalized eigenvector are termed weights with respect to the criteria or sub-criteria and ratings with respect to the alternatives.

Step 5: The consistency of the matrix of order n is evaluated. Comparisons made by this method are subjective and the AHP tolerates inconsistency through the amount of redundancy in the approach. If this consistency index fails to reach a required level then answers to comparisons may be re-examined. The consistency index, CI, is calculated as

$$C.I. = \frac{\lambda_{MAX} - n}{n - 1} \qquad (1)$$

Where $\lambda_{\max}$ is the maximum eigen value of the judgment matrix. This CI can be compared with that of a random matrix, RI. The ratio derived, CI/RI, is termed the consistency ratio, CR. Saaty suggests the value of CR should be less than 0.1.

Step 6: The rating of each alternative is multiplied by the weights of the sub-criteria and aggregated to get local ratings with respect to each criterion. The local ratings are then multiplied by the weights of the criteria and aggregated to get global ratings.

The AHP produces weight values for each alternative based on the judged importance of one alternative over another with respect to a common criterion.

3. Launch Vehicle Decomposition

Launch vehicle cab be divided to 6 major segments that are engines, separation, guidance navigation and control (GN&C), payload accommodation, tanks& other equipments, and Electrical Power/Command & Data Handling Cables (see Fig 1).

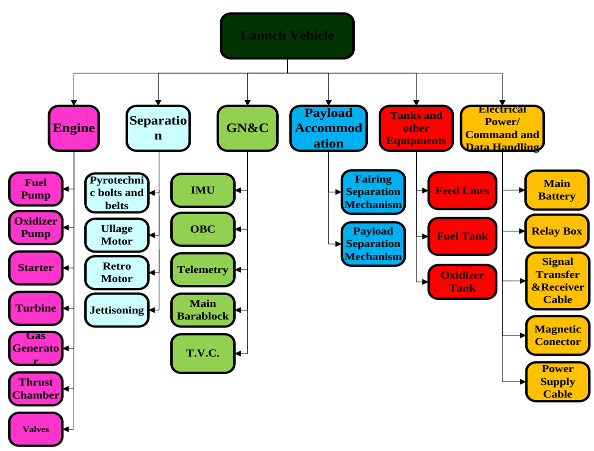

Fig. 1: Launch vehicle decomposition

4. The criterions

The factors of affect on reliability allocation are defined as complexity, technology, duration of operation and cost of subsystems. It is very important to have a deep and clear understanding of these main criterions. To this goal we explain them in this order. *Complexity*, complexity is a general concept that in the proposed method is divided into these factors: Number of independent functional units, Number of functions that the units are done and the mass budget of subsystems. *Technology*, Quantifying of technology is not easy, too. Thus the following factors are considered for this purpose: parts used process of production, equipments, designing experiences and existing technology. *Duration of Operation*, duration of operation of subsystems is another main parameter that is used for calculation of reliability allocation. For example, the engine starter only used for 2 seconds approximately, but turbo-pump used for total engine operation time. *Cost of Subsystems*, the most important parameter that affect on reliability allocation is cost. Cost is influenced by mentioned above parameters (complexity and technology). Here, weight matrix of launch vehicle subsystem is derived independent of other parameters.

5. Launch Vehicle Reliability Allocation Methodology

In this section we will describe the methodology of reliability allocation for launch vehicle. The problem of reliability allocation can be written as

$$h(R_1^*, R_2^*, \ldots, R_n^*) \geq R^* \qquad (2)$$

in which R_i^* is the reliability of each subsystem(component) and R^* is the total reliability of system(here launch vehicle) and h is a the corresponding function that relates reliability of subsystems to total reliability of launch vehicle[5].

As described in section 3 we have decomposed the system of launch vehicle into 6 subsystems and each one has some components. The allocation approach is performed in a hierarchy manner so that we will consider four criterions described in section 4 that are technology, complexity, operation time, and cost. Then the hierarchy diagram for launch vehicles reliability goal is obtained as fig. 2.

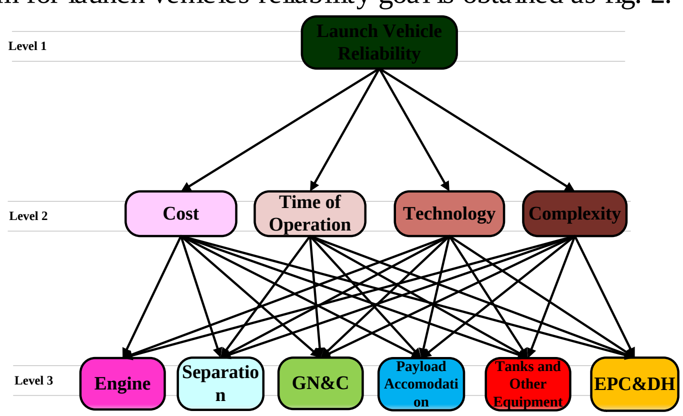

Fig. 2: Levels of reliability allocation improvements

Based on these criterions(level2) and the main goal the relative weights for level 2&3 are obtained by paired comparison as presented in tables 1,3,5,7 and 9. By means of eigenvector method accurately, the normalized weights with respect to upper level criterions are obtained as presented in tables 2,4,6,8,10.

After obtaining the subsystems reliability allocation weights the reliability of each subsystem is apportioned by using following relationship.

$$R_i^*(t_i) = [R^*]^{w_i} \qquad (3)$$

6. Conclusion

In this study we applied AHP as a systematic approach to develop a reliability allocation method for reliability based design process of a typical launch vehicle. In this novel method reliability allocation factors were obtained based on real historical data, experts' knowledge and system configuration that make this method more robust and applicable compared with other optimal allocation methods that may end to unfeasible solutions. Also in our methodology risk of allocating incompatible reliability values to subsystems is reduced to a minimum extent versus before developed reliability allocation methods. So this methodology can be used as a suitable approach for reliability allocation in launch vehicle reliability based design.

Table 1. Matrix of Level 2 with respect to Reliability

	Technology	**Complexity**	**Operation time**	**Cost**
Technology	**1**	**4**	**7**	**3**
Complexity	**0.25**	**1**	**3**	**3**
Operation time	**0.2**	**0.1428**	**1**	**0.25**
Cost	**0.333**	**0.333**	**4**	**1**

Table 2. Normalized matrix of Level2 with respect to Reliability

	Technology	**Complexity**	**Operation time**	**Cost**	**w(level2)**
Technology	**0.560**	**0.730**	**0.4666**	**0.413**	**0.542**
Complexity	**0.140**	**0.182**	**0.2**	**0.413**	**0.234**
Operation time	**0.112**	**0.026**	**0.066**	**0.034**	**0.059**
Cost	**0.186**	**0.060**	**0.266**	**0.137**	**0.163**

Table 3. Matrix of level 3 with respect to Complexity

	engine	***GNC***	***separation***	***Tanks***	***Power***	***PL Accom***
engine	1	4	6	7	5	9
GNC	0.25	1	1.5	1.75	1.25	2.25
separation	0.166	0.666	1	1.166	0.833	1.5
Tanks	0.142	1.75	1.16	1	0.714	1.28
Power	0.2	0.8	1.2	1.4	1	1.8
PL Accom	0.111	0.444	0.666	0.77	0.555	1

Table 4. Normalized matrix of level 3 with respect to Complexity

	engine	***GNC***	***separation***	***Tanks***	***Power***	***PL Accom***	***w(level3)***
engine	0.53	0.46	0.520	0.534	0.534	0.534	0.520
GNC	0.13	0.11	0.130	0.133	0.133	0.133	0.130
separation	0.08	0.076	0.086	0.089	0.089	0.089	0.086
Tanks	0.07	0.202	0.101	0.076	0.076	0.076	0.101
Power	0.10	0.092	0.104	0.106	0.106	0.106	0.104
PL Accom	0.05	0.051	0.057	0.059	0.059	0.059	0.057

Table 5. Matrix of level 3 with respect to Technology

	engine	***GNC***	***separation***	***Tanks***	***Power***	***PL Accom***
engine	1	3	5	7	5	7
GNC	1	1	3	4	3	4
separation	0.333	0.2	1	2	1	2
Tanks	0.142	0.25	0.5	1	0.5	0.5
Power	0.2	0.333	1	2	1	0.75
PL Accom	0.14	0.25	0.5	2	1.33	1

Table 6. Normalized matrix of level 3 with respect to Technology

	engine	***GNC***	***separation***	***Tanks***	***Power***	***PL Accom***	***w(level3)***
engine	0.354	0.596	0.454	0.388	0.422	0.459	0.445
GNC	0.354	0.198	0.272	0.222	0.253	0.262	0.260
separation	0.118	0.039	0.090	0.111	0.084	0.131	0.095
Tanks	0.050	0.049	0.045	0.055	0.042	0.037	0.046
Power	0.070	0.066	0.090	0.111	0.084	0.049	0.078
PL Accom	0.050676	0.049669	0.045455	0.111111	0.112676	0.065574	**0.072526672**

Table 7. Matrix of level 3 with respect to Operation time

	engine	***GNC***	***separation***	***Tanks***	***Power***	***PL Accom***
engine	**1**	**1**	**7**	**1**	**1**	**9**
GNC	**1**	**1**	**7**	**1**	**1**	**9**
separation	**0.142**	**0.142**	**1**	**0.142**	**0.142**	**1.285**
Tanks	**1**	**1**	**7**	**1**	**1**	**9**
Power	**1**	**1**	**7**	**1**	**1**	**9**
PL Accom	**0.111**	**0.111**	**0.777**	**0.111**	**0.111**	**1**

Table 8. Normalized matrix of level 3 with respect to Operation time

	engine	***GNC***	***separation***	***Tanks***	***Power***	***PL Accom***	***w(level3)***
engine	0.235	0.235	0.235	0.235	0.235	0.235	0.235
GNC	0.235	0.235	0.235	0.235	0.235	0.235	0.235
separation	0.033	0.033	0.033	0.033	0.033	0.033	0.033
Tanks	0.235	0.235	0.235	0.235	0.235	0.235	0.235
Power	0.235	0.235	0.235	0.235	0.235	0.235	0.235
PL Accom	0.026	0.026	0.026	0.026	0.026	0.026	0.026

Table 9. Matrix of level 3 with respect to Cost

	engine	***GNC***	***separation***	***Tanks***	***Power***	***PL Accom***
engine	1	3	7	5	5	8
GNC	0.333333	1	2.333333	1.666667	1.666667	2.666667
separation	0.142857	0.428572	1	0.714286	0.714286	1.142857
Tanks	0.2	0.600002	1.399999	1	1	1.6
Power	0.2	0.600002	1.399999	1	1	1.6
PL Accom	0.125	0.375001	0.875	0.625	0.625	1

Table 10. Normalized matrix of level 3 with respect to Cost

	engine	***GNC***	***separation***	***Tanks***	***Power***	***PL Accom***	***w(level3)***
engine	0.499	0.499	0.499	0.499	0.499	0.499	0.499
GNC	0.166	0.166	0.166	0.166	0.166	0.166	0.166
separation	0.071	0.071	0.071	0.071	0.071	0.071	0.071
Tanks	0.099	0.099	0.099	0.099	0.099	0.099	0.099941
Power	0.099	0.099	0.099	0.099	0.099	0.099	0.099941
PL Accom	0.062	0.062	0.062	0.062	0.062	0.062	0.062463

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