SIMPLIFIED F.M.E.C.A. ON PUMA HELICOPTERS

Petru-Eduart DODU[1]

The aim of this article is to analyze the causes which conducted into an aeronautical organization to lack of availability of helicopters (availability rate between 40% and 45%) in the same time with increasing of rate of cannibalization (cannibalization rate between 55% and 60%) and number of not available spare parts. An original method is proposed, one widely used in USA industry - Simplified Failure Mode and Effects Analysis – for which it is used an increased number of parameters specifics to the aviation domain to identify possible problems in maintenance activity and to set priority in allocating resources.

Key Words: aviation, failure, risk priority number, risk, airframe and engines, electrical and automation systems, radio and navigation systems

1. Introduction

Maintenance costs are an important part of aircraft's life cycle costs. The total amount can reach five times the ownership cost, and 10%-20% of direct operating cost. When designing a product, it is very hard to estimate the worst conditions that the product will experience throughout its life time. A primary responsibility of the maintenance specialist is to assess technical systems failures and deviations from optimum performance. Failure analysis is a powerful tool in an organization's effort to improve its maintenance effectiveness. The results of failure analysis should be reviewed in weekly meetings [1].

The term *failure* may be defined as the incapability of a material, device, structure or machine to satisfactorily perform its intended function within the specified limits under specified conditions due to, for example, a change in dimensions, shape and/or material properties [2]. Especially in the Air Force it is common occurrence, because they are posing a potential safety problem, aircraft malfunctions are recorded and analyzed very carefully [3]. Failure of an aircraft's structural component can have catastrophic consequences, resulting in loss of human life and destruction of the aircraft. Thus the investigation of malfunctions and failures in aircraft structures is of vital importance, in order to prevent further incidents [4]. The organization safety manager should arbitrate the maintainability requirements in order to perform preventive, corrective, service, and configuration management [5]. Hazard analysis considers failure occurrences, operating procedures, human factors, and transient conditions, all to be included in the list

[1]Aircraft Engineer, Ministry of Defence, Otopeni, Romania, e-mail: eduartaero@yahoo.com

of hazard causes [6]. The procedures for accomplishing reliability analysis are: the creation of a system functional model, the execution of a failure “mode and effect” analysis, and the identification of critical items (those items whose failure or inability to achieve a required function would significantly affect the capability, reliability, or safety of a system) [5].

A common concept in reliability and failure analysis is the FMEA (Failure Modes and Effects Analysis). FMEA process was originally developed by the US military in 1949 to classify failures “according to their impact on mission success and personnel/equipment safety” and has been used since 1960s Apollo space missions [7].

FMEA provides a lot of valuable qualitative information about the system design and operation, since its goal is to exactly identify the failure modes and mechanisms of interest [8]. Aircraft malfunctions are investigated by using different methods, reaching from the simplest to the most complex, specific to aeronautics or taken from other technical fields. Their goal is to improve reliability, or even to re-design the aircraft and its parts [9].

The RPN (Risk Priority Number) method requires the analysis team to use past experience and engineering judgment, in order to rate each potential problem according to three rating scales:

♦ **Severity**, which rates the severity of the potential effect of the failure, is represented in table 1.1 [10]:

Table 1.1

Severity of the potential effect of the failure

Effect	**Criteria: Severity of the Effect**	**Ranking**
Hazardous without warning	Very high severity ranking when a potential failure mode affects safe operation and/or involves noncompliance with government regulation without warning.	10
Hazardous with warning	Very high severity ranking when a potential failure mode affects safe operation and/or involves noncompliance with government regulation with warning.	9
Very High	Item inoperable, with loss of primary function.	8
High	Item operable, but at reduced level of performance.	7
Moderate	Item operable, but Comfort/Convenience item(s) inoperable.	6
Low	Item operable, but Comfort/Convenience item(s) operable at reduced level of performance.	5
Very Low	Fit & Finish/Squeak & Rattle item does not conform.	4
Minor	Fit & Finish/Squeak & Rattle item does not conform.	3
Very Minor	Fit & Finish/Squeak & Rattle item does not conform.	2
None	No effect.	1

Severity is a term widely used in safety handbooks. A classification of the severity in safety management is:

-category I: catastrophic - a failure which may cause death or weapon system loss (i.e. aircraft, tank, missile, ship, etc.);

-category II: critical - a failure which may cause severe injury, major property damage, or major system damage, which will result in mission loss;

-category III: marginal - a failure which may cause minor injury and system damage, which will result in a delay, loss of availability, or mission degradation;

-category IV: minor - a failure not serious enough to cause injury or system damage, but which will result in unscheduled maintenance [11].

♦ **Occurrence**, which rates the likelihood that the failure will occur is represented in table 1.2 [12]:

Table 1.2

Probability of Failure	Possible Failure Rates	Ranking
Very High: Failure is almost inevitable;	1 in 2	10
	1 in 3	9
High: Repeated failures;	1 in 8	8
	1 in 20	7
Moderate: Occasional failures;	1 in 80	6
	1 in 400	5
	1 in 2.000	4
Low: Relatively few failures;	1 in 15.000	3
	1 in 150.000	2
Remote: Failure is unlikely.	< 1 in 500.000	1

♦ **Detection**, which rates the likelihood that the problem will be detected, is represented in table 1.3:

Table 1.3

Rating	Meaning
1	Certain - fault will be caught on test
2	Almost certain
3	High
4	Moderate
5	Low
6	Fault is undetected by Operators or Maintainers

The RPN only defines priority, where no specific value is required, but it can be set as a target value. When the RPN at 125 is achieved, the effort to reduce the risk priority number must be continuously performed by looking at each of the above mentioned factors: Occurrence (O), Severity (S) and Detection (D).

Risk is the combination of End Effect Probability and Severity, where probability and severity include the effect of non-detectability (dormancy time).

This may influence the End Effect Probability of failure, or the worst case effect Severity. In Risk Management, risk is the combination of severity of the harm and probability that it will occur. For medical equipment manufacturers, the relevant standard is ISO 14971:2007 which uses this definition of risk. The traditional method develops a two dimensional table in which the cells represent risk acceptability (unacceptable, undesirable, tolerable, acceptable).

A FMEA is a detailed document that identifies ways in which a process or product cannot succeed in meeting critical requirements. From here a list of items can be generated to determine appropriate types of controls or where changes in the procedures should be made, in order to reduce or mitigate risk [13]. Risk mitigation can be done by individually reducing one of the two factors: probability of occurrence and severity.

For some products, government agencies (such as the military and those agencies involved in aviation and space exploration), are responsible for ensuring that users receive a system that is reliable, safe, cost-effective, and easy to maintain and to use [14].

The FMEA process, originally developed by the US military in 1949 to classify failures "according to their impact on mission success and personnel/equipment safety," is nowadays used in many formal quality systems, such as ISO 16949 /2.4-6/ [2].

2. Simplified failure modes and effects analysis

Simplified Failure Modes and Effects Analysis (SFMEA) is a top-down method to analyze the design, widely used in American industry, but also fully applicable to evaluate maintenance processes on Puma helicopters. SFMEA is an ideal tool that can be used to establish or enhance preventive and predictive maintenance programs. With the right team, consisting in knowledgeable and reliable engineers, skilled operators, and maintenance experts, the process will identify most, if not all, of the probable failure modes and significant functions that could occur. This information can be used afterwards, to develop specific preventive or predictive maintenance tasks, which will eliminate or substantially reduce the potential for such problems to take place [15]. SFMEA provides a method for determining which failures can be prevented. Necessary inputs are: the frequency of occurrence for each problem, the cause combination, and what happens if a failure occurs. Such method is used under the following circumstances: a) each component part is a “block” within a technical system; b)“block” malfunction leads to the whole system failure, and each malfunction is a distinct malfunction; c) each malfunction has an effect of a certain degree upon the system; d) risk priority number (RPN) is being used

$$RPN = Severity \times Occurrence \times Detection \quad (1)$$

and corrective actions, that may reduce gravity or increase detection, are applied.

The analysis begins with a certain RPN and calculations are being done to reach a lower value. A simplified pattern is in use, similar to table 2.1;

The simplified analysis pattern assesses three criteria: 1.The impact of the malfunction on the technical system’s capacity to function; 2.The probability for a specific malfunction to occur, given by the previous experience or by statistics and 3.The probability to detect malfunction before its occurrence, with the means at hand at that particular moment. For each malfunction, a potential effect is anticipated. For each malfunction and effect, the severity the malfunction has for the system is being identified as a whole which interferes with accomplishing a mission.

It is well known that, when addressing High Severity values regardless of RPN, the Criticality is neglected. Most templates don't have a column to calculate/evaluate criticality. It is important to assess Severity, **but also Criticality** (sometimes named Risk) and RPN separately (RPN is a derivative of Severity, Occurrence, and Detection). Criticality means the failure probability of the equipment is very high. The minor failure of critical equipment may lead to severe impact on equipment/platform performance [16].

$$Criticality = Severity \times Occurence \tag{2}$$

Table 2.1

Simplified analysis

Simplified Failure Modes and Effects Analysis					Severity		Probability		Detection	RPN		New RPN	Cause of malfunction	Type of preparation	Risk (Criticality)
Process	Asset	Component	Failure Mode	Effect Of Failure		Cause of Failure		Current Control			Improv-ement				

The simplified analysis, as presented in table 2.1, has been developed by introducing 3 columns of supplementary data.

The analysis of maintenance activity will use the following terms regarding the type of work performed:

- *Preliminary check (P.C.): aviation maintenance basic procedure, mainly preventive. It occurs periodically and it is comprised of daily/regular/high frequency inspections, minor repairs, protective works, lubrication, and other activities such as aircraft taxi to the parking spots, make ready for inspection, post-flight check, troubleshooting for pilot/check revealed failures, re-fuelling, lubrication, fluid/gas servicing, and technical documentation fill-ins;*
- *Pre-flight check (Pr.F.C.): all maintenance activities performed before flight, as specified by maintenance instructions,. It is connected with activities such as aircraft towing, battery and ordnance check-ups (depending on the type of mission), equipment and engine checks and special systems power-up;*

- *Post-flight check (Po.F.C.): all maintenance activities performed after flight as specified by maintenance instructions, particular to aircraft type. Performed by aircraft technician/crew chief and maintenance personnel;*
- *Scheduled checks: aviation maintenance works performed after a particular number of flight hours. In case of Puma helicopters, they are performed at 50 (100, 300) flight hours. Also known as L.R. 50, L.R. 100, etc.;*
- *P2 inspection: maintenance inspection after 400 flight hours;*
- *On ground (G.): represents the period when the aircraft is into a static posture, going through a receiving-delivering procedure between the new flight crew and the old flight crew, or in a taxi procedure;*
- *In flight (F.): represents the period when the aircraft is flying and the pilot/crew discovers a fault, signaled or not by the affected equipment.*

Qualitative Scale for Severity, Occurrence and Detection is represented, in table 2.2 (l.o.c. means "loss of capacity" and p. means "probability") [17].

Table 2.2

Qualitative Scale for Severity, Occurrence and Detection

Rank	Severity	Occurrence	Detection
1	None (l.o.c. <10%)	Almost Never (p. <10%)	Almost Certain (p. 91-100%)
2	Very Minor (l.o.c. 11-20%)	Remote (p. 11-20%)	Very High (p. 81-90%)
3	Minor (l.o.c. 21-30%)	Very Slight (p. 21-30%)	High (p. 71-80%)
4	Very Low (l.o.c. 31-40%)	Slight (p. 31-40%)	Moderately High (p. 61-70%)
5	Low (l.o.c. 41-50%)	Low (p. 41-50%)	Moderate (p. 51-60%)
6	Moderate (l.o.c. 51-60%)	Medium (p. 51-60%)	Low (p. 41-50%)
7	High (l.o.c. 61-70%)	Moderately High (p. 61-70%)	Very Low (p. 31-40%)
8	Very High (l.o.c. 71-80%)	High (p. 71-80%)	Remote (p. 21-30%)
9	Serious (l.o.c. 81-90%)	Very High (p. 81-90%)	Very Remote (p. 11-20%)
10	Hazardous (l.o.c. 91-100%)	Almost Certain (p. 91-100%)	Almost Impossible (p. <10%)

The next step is to establish the probability for each cause to happen. Based on previous experience, this parameter is given by the probability of occurrence.

A scale from 1 to 10 is being used, representing RPN associated with malfunction - a small number gives the information that the method is accurate for detection and vice versa. At the end, RPN is calculated, and the possibility to lower it through better preventive maintenance and superior monitoring system is analyzed. Analysis of RPN contributes to the development of control plans, testing requirements, optimum maintenance work plans, reliability growth analysis and related activities [18].

A survey on the most complicated malfunctions discovered during 6 months on Puma helicopters has been performed. This survey may be described by taking into account the following aspects:

– malfunctioning technical components cannot be subject for delayed maintenance;

– maintenance works on discrepancy repair must be performed only by highly trained maintenance personnel;
– at least two people are required for execution/control and approval of maintenance performance;
– maintenance may be done only by using high complexity tools and devices to be found only in suitable maintenance facilities;
– maintenance labor requires more than 18 hours, and the aircraft is not available for flight for at least 2 days.

Table 2.3

Criticality (risk) data

OCCURENCE \ SEVERITY	1		2		3		4		5		6		7		8		9		10	
1										2										
2		1	2			1		2				3			4	3				
			1				10		1	10				6	3					
3				5		3	1	4		5	1	8	4	3	17	8				
			5		1		5			12					2					
4				7	5				3	2	7	4	2		6	10				
							4			17				50	1	6				
5				1		2	2				9		6		11	1				
			3		3		12				8			3	1					
6									5		5		9		2					
					3		4							3	15					
7													5		9					
8																				
9																				
10																				

The table 2.3 presents Criticality: the blue color represents the airframe and engine domain; the brown color represents the electrical and automation systems (IESA) domain, the yellow color represents radio domain and the green color represents the navigation domain.

The number on every square represents the analyzed faulty components of each specified domain. This risk (criticality) table identifies whether corrective action is required in the case of columns with severity 9 and 10.

There is no malfunction characterized by 9 and 10 severity and because of this immediately corrective actions are not needed.

Reduction of occurrence probability and the detection increase are chosen as solutions to alter RPN (it is not suitable to change severity because in the case of helicopter study everything that comes into consideration is very important). Causes of malfunctions are: wear and tear, fatigue, corrosion and so on.

The synthetic and analytic data conducts to the following results:

The results are presented in the tables below; where number 1 represents the Airframe and Engine systems; number 2 represents the Electrical and Automation systems (IESA), number 3 represents Radio systems and number 4 represents the Navigation systems.

- The types of operations and maintenance actions, where malfunctions were discovered, are illustrated in table 2.4:

Table 2.4

Operations and maintenance

	G	**F**	**P.P.**	**Pr.F.C.**	**Po.F.C.**	**L.R. 50**	**L.R. 100**	**L.R. 200**	**L.R. 300**	**P2**
1	6.14	10.53	32.46	1.75	38.60		4.39	1.75		4.39
2			13.33	13.33		0	30.67		40	2.67
3			44.58	13.25	42.17					
4			63.89	2.78	33.33					

- Description of RPN and changed RPN, are displayed in table 2.5:

Table 2.5

Description of RPN and changed RPN

<table>
<tr><td colspan="2"></td><td colspan="2">1</td><td colspan="2">2</td><td colspan="2">3</td><td colspan="2">4</td></tr>
<tr><td rowspan="3">RPN Changed</td><td>severity</td><td rowspan="3">73.91</td><td>-</td><td rowspan="3">66.67</td><td>-</td><td rowspan="3">71.08</td><td>-</td><td rowspan="3">65.74</td><td>-</td></tr>
<tr><td>occurrence</td><td>89.71</td><td>53.33</td><td>92.22</td><td>74.71</td></tr>
<tr><td>detection</td><td>10.29</td><td>46.67</td><td>7.78</td><td>25.29</td></tr>
<tr><td colspan="2">RPN
Unchanged</td><td colspan="2">26.09</td><td colspan="2">33.33</td><td colspan="2">28.92</td><td colspan="2">34.26</td></tr>
</table>

- Causes of malfunctions are in accordance with table 2.6:

Table 2.6

Causes of malfunctions

	1	**2**	**3**	**4**
Wear &Tear	70.18	29.33	79.52	65.74

Fatique	6.14	64.00	20.48	20.37
Corossion	6.14	0.00	0.00	11.11
Other Causes	17.54	6.67	0.00	2.78

2.1.RPN on airframe and engine technical systems.

Two types of mechanical failures can cause the aircraft accidents: fatigue failure and corrosion failure. Fatigue failure on aircraft parts can be predicted through serial testing on aircraft prototype at design/development and certification stages. Corrosion failure on aircraft components may not be predicted, and a remote likelihood of detection takes place, especially when corrosion failure rate of aircraft components is not only influenced by corrosive medium but also accelerated by static and/or cyclic load [12].

According to the results in tables 2.4, 2.5 and 2.6 the majority of malfunctions were discovered during preliminary or post-flight checks. This fact stands for high efficiency preventive maintenance works and accurate monitoring system, as reflected in the calculated percentage. It encompasses huge data-base creation and management in order to reduce malfunctions occurrence.

The methods of detection involve high capability, but the preemption probability is characterized by high values. It is recommended to identify devices which pose significant risk and to replace them with higher reliability ones, adapted to platform working conditions (temperature, vibrations, corrosion, etc.). This fact requires supplementary maintenance costs, but also leads to superior availability and safety of aircraft.

As a conclusion for Airframe and Engine technical systems it can be stated that:

– most malfunctions are identified during post-flight and preliminary checks, as a result of parts getting older for time in service and vibration fatigue;
– RPN may be modified in a rather high percentage;
– RPN may change by subtraction of probability to occur;
– the main cause for malfunctions is wear and tear.

2.2.Electrical and automation (IESA) technical systems

The results from tables 2.4, 2.5 and 2.6 lead to the idea that the majority of malfunctions were recorded during scheduled maintenance checks, a fairly regular behavior having in view the specific of the equipment (rarely subject to efficient visual control procedures). The identification of such malfunctions, unlike those on the airframe and engines, are mainly discovered during mandatory maintenance, and less during regular maintenance. Therefore, their identification is more difficult, thus requiring higher levels of training for maintenance personnel.

It is possible to change RPN to lower percentage by comparison with the airframe and engine components case, but discrepancies are identified approximately half by detection and half by occurrence. Occurrence may be influenced both by identification of parts subject to wear and tear, fatigue, corrosion and also by replacing such parts with more reliable ones, bought directly from the aircraft manufacturer. Another method is to improve detection through personnel expertise and proficiency in the field, in order to identify lower reliability components and modernize them, if accepted by airworthiness authority. This process requires higher costs. In case of IESA technical systems, the discrepancy causes are presented in table 2.5, fatigue being the main factor, followed by wear and tear.

Conclusions for Electrical and Automation (IESA) technical systems:

– the identification for most malfunctions occurs when performing scheduled maintenance, fact that shows difficult detection during aircraft checks performance;
– RPN is modified on higher percentage (66.67%);
– the main cause for malfunctions is material wear and tear (64.00%).

2.3. Radio technical systems

The results as shown in table 2.4 demonstrate that the majority of malfunctions were observed during preliminary or post-flight check-ups. RPN could be changed in accordance with table 2.5, obtained values indicating the influence of radio technical systems on the indicator.

A great number of radio devices are subject to delayed maintenance, not always leading to non-mission-capable aircraft, unlike airframe and engine or IESA technical systems. In the case of radio technical systems, the causes are presented in table 2.6, wear and tear being the main factor with the highest value so far. Radio systems are sensitive to high amplitude vibrations, caused by many years of service.

Conclusions are:

– preliminary and post-flight checks are a source to identify most of the malfunctions. Radio devices fail and require fixing during aircraft on ground for a prolonged time but also during post-flight check after a 5-7 hour flight;
– RPN may be altered on high percentage (71.08%);
– it may change mostly by lowering occurrence (92.22%);
– the main cause for malfunctions is parts' wear and tear (79.52%).

2.4. Navigation technical systems

The results shown in table 2.4 prove that the majority of malfunctions were observed during preliminary or post-flight check-ups. One can notice the percentage RPN and occurrence has the main part by influencing RPN both by identifying devices subject to fatigue, wear and tear etc.

Occurrence may be influenced both by identification of parts subjected to wear and tear, fatigue, corrosion and by their replacement with more reliable ones, bought directly from the aircraft manufacturer.

A great part of navigation systems are subject to delayed maintenance, not always leading to non-mission-capable aircraft, but it directly affects mission accomplishment. Wear and tear is again the main causing factor, but all causes are presented in table 2.6.

Conclusions are:

– preliminary and post-flight checks identify most of the malfunctions. that is navigation devices fail and require fixing during aircraft on ground for a prolonged time but also during post-flight check (the main cause is vibration);

– RPN may be altered on high percentage (65.74%);

– it may change mostly by lowering occurrence (74.71%);

– the main cause for all system malfunctions is wear and tear (65.74%).

3. Conclusions

This paper has investigated through a method named Simplified Failure Mode and Effects Analysis the causes which conducted into an aeronautical organization to lack of availability of helicopters and to a significant number of not available spare parts.

The main cause for components' malfunction is prolonged wear and tear, especially in the case of engines (the failure severities are not very high and, because of these immediately corrective actions are not needed). To decrease Risk Priority Number decrease of occurrence probability and increase of the detection are chosen as solutions.

Vibrations have negative influence especially on radio and navigation systems. One may say the existing methods suffice to detect malfunctions before they occur, and, if they happen, they are due to poor liability of the component parts. Reliability may be increased, leading to lower occurrence, but implies high costs.

The simplified analysis is useful to rapidly identify causes of malfunction which lead to helicopters' lower availability. Still, these causes are not completely studied that is why the analysis needs to be extended by cause-effect analysis, on ground and in flight failures analysis, labor hours analysis for intermediately and complex level maintenance, the analysis of malfunctions for spare parts to be fixed only by the producer (depot level maintenance) and so on.

REFERENCES

[1] *B. P. Heinz*, Practical Machinery Management for Process Plants. Improving Machinery Reliability, **Vol.I**, Third Edition, Elsevier Science, USA, 1998
[2] *N. Eliaz, R. M. Latanision*, Preventive Maintenance and Failure Analysis of Aircraft Component, in Corrosion Reviews, **Vol. 25**, Issue 1-2, 2007, pp.107-144
[3] *** Statistical Summary – Aviation Occurrences, Transportation Safety Board of Canada, 2009
[4] *S. J. Findlay, N. D. Harrison*, Why Aircraft Fail, Materials Today, **Volume 5**, Number 11, Elsevier, November 2002 , pp. 18-25
[5] *** Air Force System Safety Handbook, Air Force Safety Agency, 2000
[6] *** Guide to method and tools for Airline Flight Safety Analysis, 2003
[7] *K. Riplová*, Tool Of Risk Management: Failure Mode And Effects Analysis and Failure Modes, Effects and Criticality Analysis, Journal of Information, Control and Management Systems, **Vol. 5**, 2007, pp.111-120
[8] *F. J. G. Carazas, G F. Martha de Souza*, Availability Analysis of Gas Turbines Used in Power Plants, Int. J. of Thermodynamics, **Vol. 12**, No. 1, March 2009, pp. 28-37
[9] *http://www.reliasoft.com/newsletter/2q2003/rpns.htm*
[10] *http://wiki.ece.cmu.edu/ddl/index.php/FMEA*
[11] *** Failure Mode and Effect and Criticality Analysis (FMCA), Reliability Analysis Center, 1993
[12] *** Military Aviation Engineering, Ministry of Defence, 2012
[13] *L. T. Ostrom, C. A. Wilhelmsen*, Developing Risk Models for Aviation Inspection and Maintenance task, Aeronautics and Astronautics, September 2011 pp.487-498
[14] *B. B. John*, Failure Modes and Effects Analysis From: ASM Handbook **Vol. 11**, Failure Analysis and Prevention (ASM International), 2002, pp. 50-59
[15] *R. K. Mobley, L. R. Hihhins, D. J. Wikoff*, Maintenance Engineering Handbook, The McGraw-Hill Companies, Inc., USA, 2008
[16] *M. Niraj, P. Kumar, Dr. A.Mishra*, FMECA Analysis (A Heuristic Approach) For Frequency of Maintenance and Type of Maintenance, International Journal of Scientific & Engineering Research, **Vol. 3**, Issue 1, January-2012, pp. 322-326
[17] *N. Sellappan., K. Palanikumar.*, Modified Prioritization Methodology for Risk Priority Number in Failure Mode and Effects Analysis, International Journal of Applied Science and Technology, **Vol. 3**, No. 4, April 2013, pp.27-36
[18] *L. S. Lipol, J. Haq*, Risk analysis method: FMEA/FMECA in the organizations, International Journal of Basic & Applied Sciences IJBAS-IJENS, **Vol: 11**, No:05, October 2011, pp.74-82.