SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage: https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Application of Reliability Centred Maintenance in Improving Aircraft Availability with Preventive Maintenance Intervention

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ARTICLE INFO

Article history:
Received 17 July 2023
Received in revised form 12 December 2023
Accepted 20 February 2024
Available online 26 March 2024

Keywords:
AHP; Availability; FMECA; Preventive Maintenance; RCM

ABSTRACT

Aircraft are intricate flying machines equipped with advanced technologies and state-of-the-art information and communication systems. Maintaining these aircraft to ensure maximum availability and minimal downtime is a critical and challenging task. Therefore, aircraft maintenance, repair, and servicing are of utmost importance. This research work aims to develop a methodology for the application of reliability centred maintenance (RCM) to enhance aircraft availability. An RCM approach with the Multi attribute decision making (MADM) technique for assigning criticality of systems was implemented to improve aircraft availability. Failure mode effect and criticality analysis (FMECA) was utilized for the failure investigation in the aircraft systems. However, instead of the Risk priority number (RPN) due to its inherent flaws, the Analytical hierarchy process (AHP) was utilized to evaluate the criticality of systems. The remedial measures to minimize the failure frequency and downtime were proposed. The improvement in availability, post implementation of proposed preventive maintenance was validated with positive results. An improvement of approximately 6.62% in availability and a reduction of about 15.71% in the total downtime was observed on the implementation of proposed preventive measures. The availability analysis was carried out for aircraft systems; however, the model could also be used for other repairable systems following a similar maintenance philosophy.

1. Introduction

Aircraft being the most important resource for mission accomplishment, maximum availability of aircraft for missions must be ensured. Broadly mission can be, a threat to the country or any natural disaster where the readiness of aircraft at any moment of time is very important to accomplish the task. The latest aircraft are equipped with advanced technologies blended with state-of-the-art information and communication systems. Maintenance of these aircraft is a critical and challenging task in terms of maintenance planning, performance, cost, components availability, and other support responsiveness. Maintenance, repair, and servicing of aircraft thus assume greater importance.

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https://doi.org/10.37934/araset.42.1.115129

Extensive research on the use of Reliability centred maintenance (RCM) in improving plant availability in many industrial applications like Oil and gas, nuclear, power, automobile, aviation, and other industries was found in the existing literature. However, limited work focused specifically on improving aircraft availability utilizing Failure modes, effects, and criticality analysis (FMECA) and Analytical hierarchy process (AHP) with preventive maintenance (PM) intervention was available. The presented work is an effort to fill this research gap. The research work effectively applied RCM, AHP, and FMECA to improve availability and reduce downtime of aircraft. The main objectives of this paper are:

i. To identify the critical systems responsible for maximum downtime of aircraft.
ii. To suggest preventive maintenance measures to reduce downtime, and
iii. To improve the availability of aircraft.

2. Literature Review

Availability is the probability that a system is ready to perform its functions when called for at any point in time randomly. Aircraft Availability is dependent on effective repair and maintenance of complex aircraft systems [1]. The aging of aircraft is a major factor for enhanced maintenance requirements resulting in downtime. Aging poses different challenges in terms of frequent failures affecting the reliability and availability of aircraft [2]. Aircraft systems are inherently complex and safety critical. Maintenance is an inescapable requirement to ensure safe flying and maintenance operations. Maintenance planners have to schedule the maintenance checks for each aircraft and the associated tasks to improve the availability of aircraft in a fleet and to reduce maintenance downtime [3]. Aircraft Availability can be increased by optimal scheduling of the component replacement periodicity, during the operational cycle of the aircraft [4]. The effectiveness of a maintenance management system in terms of resources employed is an important issue for any organization.

Regular maintenance is necessary to keep the equipment satisfactory and reliable through its lifecycle [5,6]. The availability depends on maintainability and reliability. Therefore, effective maintenance is essential to minimize downtime and improve availability and reliability [7]. investigated various causes resulting in production loss and suggested preventive measures. A Root cause analysis was also carried out to identify causes of breakdowns and suitable measures were suggested to minimize the downtime. Ab-Samat *et al.,* [8] analysed the various reasons for maintenance deficiencies and suggested suitable measures to improve the efficiency and effectiveness of preventive maintenance. Investigation of the reasons for failures by separating the machines into critical and non-critical categories was considered effective. Kiran *et al.,* [9] suggested an approach to identify critical components in a cement plant. Reduction in downtime and improvement in the availability of the plant was achieved in the demonstrated case study by formulating and implementing an optimized servicing schedule. Mostafa *et al.,* [10] studied the processes of maintenance and associated activities from the perspective of lean management in the maintenance of equipment. The paper suggested strategies to apply lean principles to improve the efficiency and effectiveness of the maintenance process.

Gabbar *et al.,* [11] proposed an RCM approach with an improvised autonomous process with embedded CMS. Wessels, [12] presented a computer assisted maintenance environment resulting in an economic maintenance procedure. Eisinger *et al.,* [13] modelled a probability-based approach to map reliability certainty in maintenance processes. Hipkin *et al.,* [14] proposed a novel integration of TPM, TQM, and BPR management techniques to improve reliability in maintenance. However, it was

Rausand, who presented and discussed in detail all stages of RCM comprehensively. RCM analyses the failure pattern and suggests preventive actions to reduce downtime of equipment [15]. Failure mode effects and criticality analysis (FMECA) are also used as effective decision-making tools for the assessment of risk in preventive maintenance [16]. Eti *et al.,* [17] carried out fault tree and root cause analysis and used FMECA to develop PM. The PM resulted in improved availability, reduction in downtime, and economic maintenance operations. Sahno Jevgeni *et al.,* [18] introduced a new framework that allows continuous improvement for the reliability of production process and output. Chopra *et al.,* [19]. Analysed the effects of RCM implementation on the productivity process chain, and significant enhancement in production was achieved through maintenance optimization.

Even though RPN evaluation with FMECA is the most common technique for reliability and failure mode analysis [20,21], there are some considerable problems associated with FMECA, which have been addressed in existing literature [22]. The most important problems discussed were regarding the assumption that the scales of three Severity (*S*), Occurrence (*O*), and Detection (*D*) indexes have the same metric and the three indexes are equally important and identify situations with the same priority number. The major weakness recognised by maintenance managers is due to the fact that this technique takes into account only some kinds of failure attributes that is, chance of failure, non-detection, and severity, whereas many other important factors are not considered.

To overcome the deficiencies of FMECA with conventional RPN evaluation, Multi-attribute Decision Making (MADM) approaches are proposed in the literature. Almeida *et al.,* [23] discussed the application of decision-making theory to maintenance with particular attention to multiattribute utility theory. Triantaphyllou *et al.,* [24] suggested the use of AHP considering four maintenance criteria: cost, reparability, reliability, and availability. Bevilacqua *et al.,* [25] presented an application of the AHP technique for maintenance strategy selection in an Italian oil refinery processing plant, combining many features that are important in the selection of the maintenance policy: economic factors, applicability and costs, safety, etc. Bertolini *et al.,* [26] proposed a combined AHP and goal programming-based model for maintenance strategy selection taking into account the budget and labour constraints along with classical FMECA criteria.

Further efforts are needed to make criticality evaluation more realistic by considering factors that are related to quality, performance, capacity, and society, and their impact can be far from severe and vast. There is a need to evolve a decision system based on these factors which can help identify systems/components that are significant from the point of view of maintenance so as to enable the maintenance managers to decide upon relevant maintenance strategies. This paper presents a multi attribute decision making (MADM) approach for the evaluation of the maintenance criticality of components of the system based on the AHP technique.

The paper is organized into eight sections. The literature review is given in Section 2. RCM process is elaborated in Section 3. Section 4 contains the data source and selection of experts, Pareto charts, and Failure data analysis using FMECA and AHP. Preventive measures are suggested in section 5. Section 6 presents the results. Section 7 presents the conclusion and limitations and the future scope is given in Section 8.

3. RCM Procedure

RCM guides maintenance actions such that a system remains operational for its intended purpose in the present operating context. RCM assumes that the main purpose of doing any kind of maintenance is not to prevent failures in general but to reduce or avoid the negative consequences of failure. Therefore, RCM focuses on maintaining function rather than paying attention to the hardware itself, Moubray. RCM achieves high plant availability and reliability, greater safety, better product quality, longer equipment life, and cost effectiveness.

The RCM concept was initially presented by Nowlan and Heap [27] after the economic concerns were raised on the scheduled overhaul procedure on Boeing 747. The case study of Boeing overhaul revealed that only a small fraction (11%) of the components had a failure pattern that could be prevented by regular maintenance, while the majority failed randomly, regardless of scheduled check-ups or replacements. Therefore, RCM was suggested as a methodical way to design a maintenance plan that would keep the essential system functions intact. A key part of the RCM philosophy is to rank the components and systems according to how critical their failure consequences are. Based on the priority levels, maintenance policies are chosen for the main causes of preventable failures. Thawkar *et al.*, [28] RCM is widely used for planning maintenance in civil aviation. Boeing developed maintenance manuals MSG-1, MSG-2, and MSG-3, and applied them to the design of Boeing 747, 757, and 767. These manuals became models of RCM for the creation of commercial aircraft and other industrial systems. SAE International (1999) issued the standards for civil aviation and the RCM process encompasses the following stages:

i. Identify the functions of each system
ii. Investigate critical failures
iii. Analyse the causes of critical failures
iv. Describe the impact of the failures on the system
v. Propose remedial measures to arrest failures.

Although there is a great deal of variation in the application of RCM, However, the process begins with the identification and selection of the critical system. Further, the functions of each system and subsystem are studied. Thereafter, the identification of various failure modes is undertaken. Causes and effects of failure are deliberated and then the criticality of failure is usually defined in terms of risk priority number or RPN. Subsequently, maintenance tasks to address the failures are suggested to reduce downtime and improve the availability of a machine or a system.

Siddiqui *et al.*, [29] demonstrated the RCM methodology in detail with different aspects of implementation through case studies. All the steps were covered in sufficient detail from the selection of the critical system to FMECA analysis and implementation of recommendations to achieve desired results. The reliability-centred approach was initially oriented toward aircraft maintenance. However, realizing the importance, subsequently, it had been effectively utilized across industries in Oil and gas, nuclear power, cement, railways, automobile, etc. The various steps involved in the RCM process are shown in Figure 1.

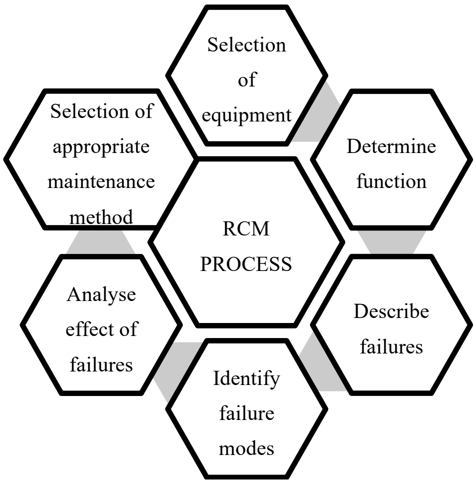

Fig. 1. Steps in RCM

4. Case Study

The proposed methodology of improving the availability of aircraft by reducing downtime and utilizing FMECA analysis with AHP was validated with a case study on an aircraft fleet.

4.1 Data Source and Selection of Experts

Failure data of aircraft was collected from a computer maintenance management system (CMMS) maintained by the aircraft maintenance control centre (AMCC) of an aircraft maintenance setup. Aircraft logbooks, OEM publications, and maintenance manuals were also referred to for relevant details. Three experts, qualified aircraft maintenance engineers (AMEs) were consulted, to evaluate human factors in aircraft maintenance. These experts were current on the system and had equal weightage in the calculation, as they had similar qualifications and experience. The comparative judgments given by the three experts were consistent as verified using the consistency ratio (CR< 0.1) [30]. Relevant information about each expert is presented in Table 1.

Table 1
Information of experts

Expert	Role in the organization	Professional Qualification (AME)	Experience (Years)	Currency on system
Expert 1	Senior Maintenance Engineer	Qualified	16	Current
Expert 2	Senior Quality Control Manager	Qualified	12	Current
Expert 3	Maintenance Engineer	Qualified	10	Current

4.2 Availability of Aircraft

In this section, the existing availability of aircraft, reasons for the unavailability of aircraft, and identification of critical systems are presented. The availability is calculated as:

$$AVAILABILITY = \frac{UPTIME}{UPTIME+DOWNTIME} \text{ x } 100 \quad (1)$$

The availability and downtime of aircraft for a year were calculated from the failure data using Eq. (1). The average annual availability of aircraft was 57.87%. The month-wise availability of the aircraft is presented in Figure 2.

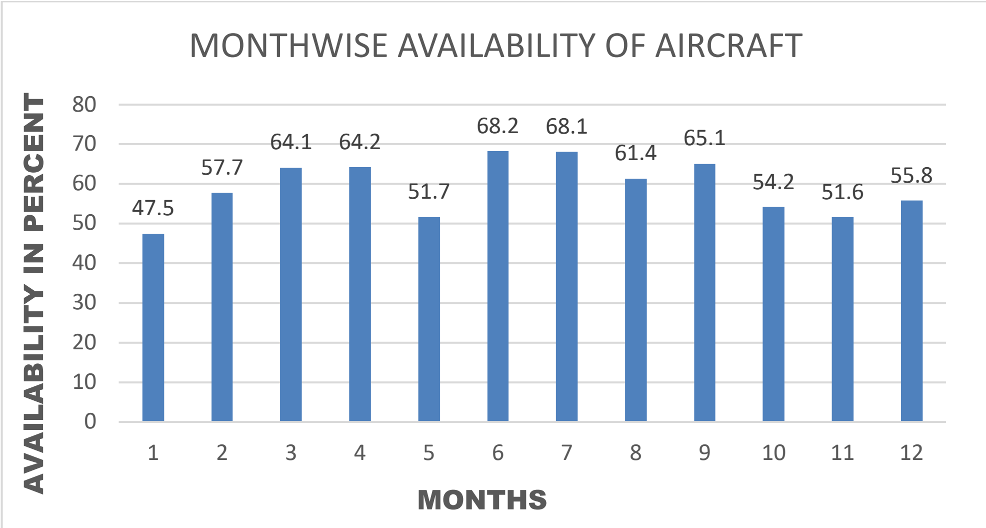

Fig. 2. Month-wise aircraft availability

4.3 Possible Causes of Aircraft Downtime

In this section, the factors responsible for the downtime of aircraft are analysed. The case study considered a sample size of aircraft for the calculation of availability and downtime. If all 18 ac are available all the time in flying-worthy condition availability would be 100% (*Ideal situation*). Assuming each aircraft to undertake flying of 20 hours per month approximately then, 18 aircraft with 100% availability would have generated 4320 hours in a year. However, due to downtime of 1820 hours in a particular year under consideration, an annual flying task of 2500 hours was achieved with *57.87%* availability of aircraft. Various reasons for the non-availability of aircraft could be the deficiency of spares, field repair and modifications, major repair and overhaul, and defects or snags as shown in Figure 3.

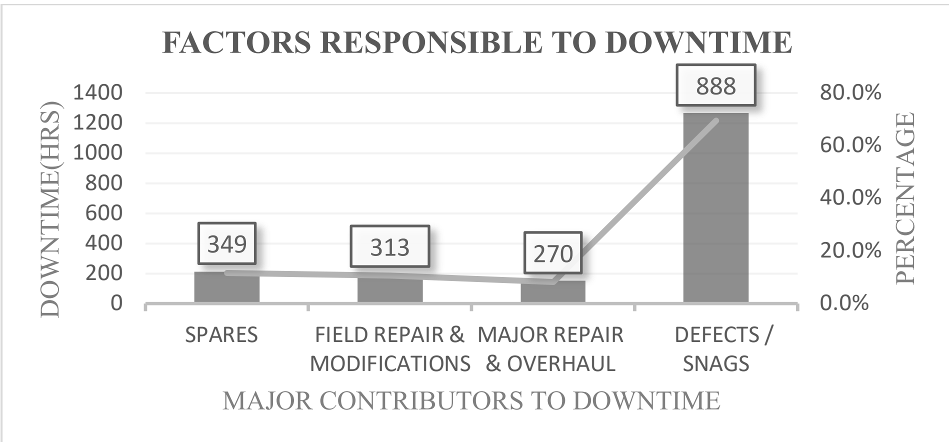

Fig. 3. Factors responsible for downtime of aircraft

As evident from Figure 3, defects/snags of systems and components were major contributors to the downtime of aircraft amounting to 888 hours out of 1820 hours or 48.79% of total downtime.

4.4 Failure Analysis

To identify and prioritize critical systems responsible for failures were analysed in this section. The frequency and downtime data of all systems/components (represented as S1, S2, S3... etc.) responsible for the downtime of aircraft was investigated. Table 2 gives the systems with the frequency of failures and downtime of aircraft.

Table 2
Systems / Component failures responsible for downtime

Systems / Components	Frequency	Downtime (Hours)
S1	115	138
S2	58	75
S3	19	65
S4	92	124
S5	105	155
S6	35	60
S7	83	45
S8	75	80
S9	15	88
S10	10	58
S11	20	80
S12	8	40
S13	4	36
S14	7	30
S15	3	18
S16	2	20
S17	8	4
S18	3	12
S19	5	10
S20	4	8
S21	2	10
S22	3	6
S23	3	3
S24	2	2
S25	5	10
S26	1	5
S27	4	4
S28	6	12
S29	5	10
S30	3	9
S31	6	6
S32	7	14
S33	5	10
S34	4	8
S35	4	8
S36	6	6
S37	3	6
S38	2	8
S39	1	2
S40	2	8

Failure data analysis was done using Pareto charts of frequency and downtime of systems/components to prioritize critical components responsible for major downtime of aircraft. These critical components were further subjected to FMECA analysis to assess failure modes effects and criticality on the aircraft systems and systems/components and suggest preventive measures to reduce downtime. The graphical representation of Pareto charts of frequency and downtime is given in Figure 4 and Figure 5 respectively. From the Pareto results, it can be seen that there were 10 critical components/system failures that were responsible for 888 hours out of 1820 hours of downtime of the aircraft due to snags or defects.

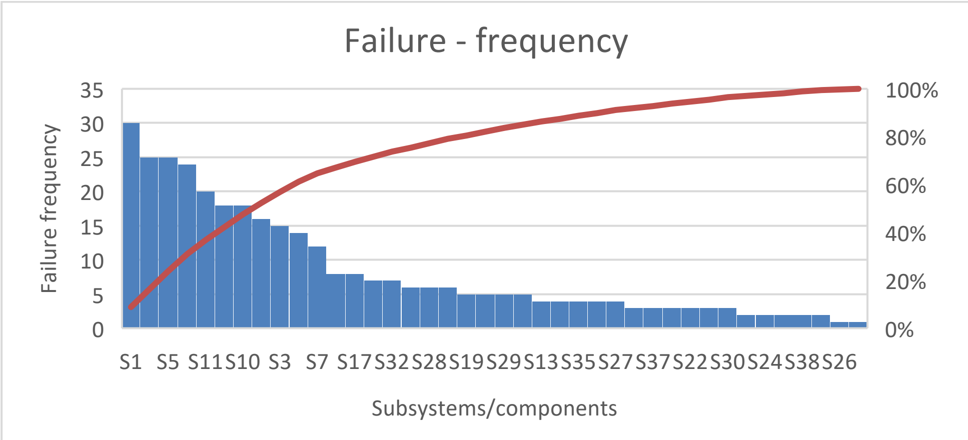

Fig. 4. Pareto analysis of failure frequency

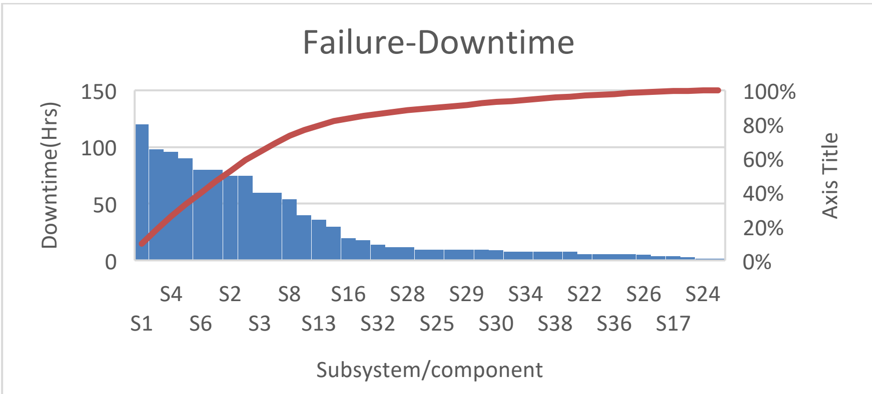

Fig. 5. Pareto analysis downtime

Critical systems /components (represented as C1, C2, C3… etc.) with downtime (DT), total failures (TF), failure rate (FR), MTBF, MTTR, reliability, and availability are shown in Table 3.

Table 3
Critical systems/ components

System/ Component	System	DT	TF	FR	MTBF	MTTR	Reli-ability	Avail-ability
C1	Aeroengine	138	115	0.028	35.17	28.40	0.972	0.55
C2	Air conditioning system	75	58	0.014	71.90	38.07	0.986	0.65
C3	Electrical system	65	19	0.005	220.53	30.42	0.995	0.88
C4	Radar system	124	92	0.023	44.26	29.98	0.978	0.60
C5	Fuel system	155	105	0.026	38.19	22.76	0.974	0.63
C6	Landing Gear system	60	35	0.008	120.00	28.06	0.992	0.81
C7	Computer system	45	83	0.020	50.96	20.07	0.981	0.72
C8	Electronic system	80	75	0.018	55.47	38.81	0.982	0.59
C9	Instruments system	88	15	0.004	276.27	57.60	0.996	0.83
C10	Autopilot system	58	10	0.002	420.40	48.20	0.998	0.90

4.5 FMECA Analysis

FMECA analysis of the critical systems/components was undertaken to identify possible failure modes with their effects on the operation of the system. criticality of component failure was assigned using AHP instead of RPN evaluation as discussed in section 2. Remedial measures to reduce failures were formulated and implemented based on FMECA results. MILSTD-1629A [31] were used for analysis. Table 4 shows the critical systems and components of aircraft and their functions.

Table 4
Critical component functions, failure modes, causes and effects of failures

Comp	Function	Failure modes	Causes of failure	Effect on function
C6	Landing gear	Not switched on	Power supply, component failure	Landing gear not coming down
		Intermittent operation	Power supply, component failure, overheating	Intermittent operation
C3	Electrical system	Fail to regulate power supply	regulating mechanism malfunction	Less or excessive rating of voltage, current, and frequency
C8	Electronic system	Fail to communicate	Erased data, component failure	Not able to identify Communication
C4	Radar system	Not switching on	No power supply, component failure, or fault in the sensor	No or erratic indication
		Erratic reading	Overheating, loose connection	
C7	Computer system	Computer interface to other subsystems Not switched on	Power supply, component failure	Results in malfunction of other electronic subsystems
		Intermittent operation	Power supply fluctuation, component failure, overheating	
C10	Autopilot	Not cutting in	Power supply, component failure, sensor failure, loom discontinuity	Aircraft not able to hold altitude, bank, or attitude
		Malfunction		Erratic auto-pilot functions
C9	Instruments system	No indication of the angle of attack, altitude, attitude and speed	No power supply, component failure, fault in the sensor	No or erratic indication
		Erratic reading	Sensor faulty, component failure, loose connection	
C2	Air conditioning system	Not functioning	Faulty regulator, blower, or mixture	Not able to maintain a controlled environment
		Inconsistent function	Fault in thermostat sensor or regulator	

C1	Aeroengine	No supply of air/fuel to the aeroengine	Faulty NRV, fault in regulation	No or inconsistent supply of air/fuel to the engine as per altitude and airspeed
		Inconsistent supply of air/fuel	Faulty barometric sensor, faulty regulator	
C5	Fuel supply	No fuel supply	Pump, governor, engine computer, NRV, failure, filter blocked, fuel supply line discontinuity	No or inadequate supply of fuel to aero engine
		Inadequate fuel pressure	Orifice blocked, pressurization failure	No or erratic supply of fuel to the aero engine
		Erratic fuel supply		

4.6 Analytical Hierarchy Process (AHP)

FMECA utilizes the Risk priority number for the failure investigation and assigning criticality. However, instead of the RPN due to its inherent flaws as discussed in section 2, the Analytical hierarchy process (AHP) was utilized to evaluate the criticality of aircraft systems. A brief introduction to the AHP technique is presented in this section. The steps performed in this method are as follows:

i. *Step 1*: Each element of the decision problem is compared to the others by using the Saaty scale as shown in Table 5 [30]. The values obtained will be collected and organized on a comparison matrix. The judgment is made according to the importance of those elements, and the matrix will have a size equal to the number of elements.

ii. *Step 2*: After obtaining the value comparison values matrix, the next step is to calculate the priority vector using Eq. (2). The a_{jk} value is the comparison value obtained by using Table 5.

$$W_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}, \tag{2}$$

$Where\ i, j = 1,2 \ldots\ldots n.$
For instance, the calculation for the first priority vector in Table 6, using Eq. (2), is as follows
(1/3.42) + (2/6.33)+(2/6)+(2/7.17)+(3/10.33)+(3/13.33)+(4/19)
= 0.29+0.316+0.333+0.279+0.290+0.225+0.211 = 1.944, and finally, divide this sum by the number of elements (n = 7) hence, 1.944/7 = 0.278. Priority vectors calculated for considered criteria is presented in Table 6.

iii. *Step 3*: By using the calculated weights and normalized values, it is possible to find the score of an alternative as

$$P_o = \sum_{i=1}^{n} w_j\ n_{ij}\ , \tag{3}$$

Here w_j =the weigh oe n_{ij} = normalized value of alternative, and P_0 is the overall priority vector. The calculation for the first overall priority vector in Table 7, using Eq. (3), is as follows:
(5/57*0.28)+(5/73*0.15)+(6/73*0.17)+(4/58*0.15)+(4/59*0.11)+(3/57*0.09)+(3/48*0.05) =0.074. The overall priority vectors of considered alternatives are given in Table 7. The highest value of *Po* is considered the best alternative.

Table 5
The Saaty scale [30]

Numerical values	Verbal pairwise comparisons
1	Equal importance of two elements
3	Moderate importance of one element over another
5	Strong importance of one element over another
7	Very strong importance of one element over another
9	Extreme importance of one element over another
2, 4, 6, 8	Intermediate values

Safety, reliability, repair time, and downtime are also important factors in addition to severity, occurrence, and detection in aircraft maintenance. Hence these criteria were considered in criticality analysis. Instead of conventional RPN evaluation, prioritization was carried out using AHP. Evaluation of Safety (SA), Reliability (RE), Severity (SE), Occurrence (OC), Detection (DT), Repair time (RT), and Repair cost (RC) for each failure mode of components were obtained from the experts. The effect of failure was considered for severity evaluation. Failure frequency was counted for occurrence ranking. Ease of detection and detection time for failure were considered for ranking of detection of aircraft system failures. The experts' evaluation of the criteria and priority vectors calculated using Eq. (2) is presented in Table 6.

Table 6
The experts' evaluation of the criteria

CRITERIA	SA	RE	SE	OC	DT	RT	RC	*Priority*
SA	1	2	2	2	3	3	4	*0.28*
RE	0.5	1	1	1.5	1.5	2	2	*0.15*
SE	0.5	1	1	1.5	2	2	3	*0.17*
OC	0.5	0.66	0.66	1	2	3	3	*0.15*
DT	0.33	0.66	0.5	0.5	1	2	3	*0.11*
RT	0.33	0.5	0.5	0.33	0.5	1	3	*0.09*
RC	0.25	0.5	0.33	0.33	0.33	0.33	1	*0.05*
Σ	3.42	6.33	6	7.17	10.33	13.33	19	*0.28*

The overall priority score of alternatives calculated from Eq. (3) is given in Table 7. Aeroengine, landing gear, and autopilot systems were prioritized as critical systems, whereas electrical, instrument, and electronic systems were comparatively less critical in the ranking.

Table 7
The rank of the critical components

Component	Safety (SA)	Reliability (RE)	Severity (SE)	Occurrence (OC)	Detection (DT)	Repair time (RT)	Repair cost (RC)	Overall priority vector
Weightage	***0.28***	***0.15***	***0.17***	***0.15***	***0.11***	***0.09***	***0.05***	----
C8	5	5	6	4	4	3	3	0.074
C9	6	5	8	5	7	4	3	0.093
C3	7	7	8	6	8	6	3	0.094
C2	5	8	7	5	6	7	3	0.095
C7	8	9	9	7	7	6	6	0.097
C4	4	9	8	6	5	7	6	0.098
C5	6	6	5	6	6	7	6	0.102
C10	6	7	5	6	5	5	6	0.110
C6	6	8	8	7	6	6	6	0.112
C1	4	9	9	6	5	6	6	0.125
Σ	57	73	73	58	59	57	48	

A graphical representation of the ranking of critical components is given in Figure 6.

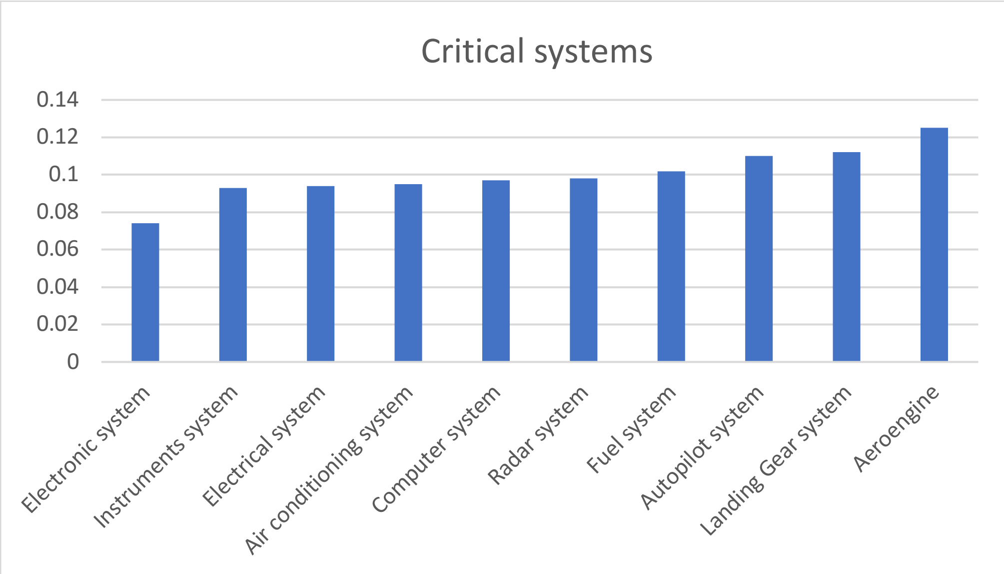

Fig. 6. Critical systems ranking

5. Proposed Preventive Maintenance (PM) Measures

After criticality prioritization of the component failures based on AHP ranking, preventive maintenance (PM) measures were formulated to reduce failures of critical components. The proposed PM measures are presented in Table 8.

Table 8
Proposed PM Measures

Component	Proposed PM measures
C6	Check the flow rate of the regulator on the ground simulating various altitude conditions. Adjustment on diaphragm assembly to be carried out with master test set on the test bench.
C3	Carry out COM TEST and check V1 fail caption red on the instrument cluster. Check for suspected fault during ground test. Carry out complete functional test with the master test bench.
C8	Check for erasing of data of valid codes from EEPROM IC of processor card resulting in the display of error codes. Reset valid codes in all modes through the master computer and carry out self-test. Check software validation.
C4	Check saw tooth logic card (STLC) for failure caption. Replace C10 & C11 capacitors. The spurious warning could be due to leakage between the Transmitter and Receiver path in the RF module.
C7	Check the availability of supply voltage to DVTR by powering the MEU and ensuring availability of 28 V between Pin no 33 and 35 of the J4 connector.
C10	The faulty module is to be replaced with an OEM-modified module. Check the continuity between the connector and the module during testing in the lab.
C9	The existing flash disk is to be replaced with an upgraded flash disk
C2	Replacement for failing relays to be done with OEM-modified relays to improve reliability
C1	Check for any intermittent malfunction of NRV, and barometric sensors during ground running of engine check. If a leak is detected replace pad valve part. Check continuous output on the test stand and carry out functional tests.
C5	Rubberised particles in the pressure filter housing and metal particles in the circulation filter housing are to be checked. ROH technology provided by OEM to be implemented. Software upgrade to be undertaken after due validation.

Parameters of critical components after implementation of PM measures are presented in Table 9. It can be seen that the Implementation of PM measures resulted in a reduction in downtime and frequency of failure. Significant improvement in availability and reliability due to improved MTBF is evident from Table 9.

Table 9
Parameters after implementation of PM measures

System/ component	After PM intervention						
	DT	TF	FR	MTBF	MTTR	Reliability	Availability
C1	98	105	0.026	38.90	28.4	0.975	0.58
C2	43	50	0.012	84.04	38.1	0.988	0.69
C3	36	14	0.003	301.36	30.4	0.997	0.91
C4	69	80	0.019	51.59	30.0	0.981	0.63
C5	65	93	0.023	44.09	22.8	0.978	0.66
C6	61	30	0.007	139.97	28.1	0.993	0.83
C7	55	76	0.018	55.53	20.1	0.982	0.73
C8	50	68	0.016	61.62	38.8	0.984	0.61
C9	45	11	0.003	380.64	57.6	0.997	0.87
C10	80	7	0.002	597.43	48.2	0.998	0.93

6. Results and Discussion

i. Availability of aircraft before and after implementation of proposed remedial action is calculated from Eq. (1).
ii. After the implementation of the RCM approach and incorporating maintenance recommendations, the reduction in downtime comes out to be 286 hours and the availability of aircraft was increased by 6.62% as given in Table 10.
iii. Downtime of aircraft after implementation of PM measures reduced by 15.71%.
iv. The significant improvement demonstrated in the case study validates the robustness and effectiveness of the proposed methodology of improvement in aircraft availability.

Table 10
Availability of aircraft before and after implementation of PM measures

Remedial measures	Total time aircraft was available (hours/year)	Downtime of aircraft (hours/year)	Uptime of aircraft (hours/year)	Availability (%)
Before Implementation	4320	1820	2500	*57.87*
After Implementation	4320	1534	2786	*64.49*

6.1 Caveat

i. Although 10 critical components contributing to only 888 hours of downtime out of a total of 1820 hours have been considered during the analysis. However, downtime of 1820 hours has been taken for availability calculations assuming other downtime contributors remain constant.
ii. Existing preventive maintenance and recommended maintenance activities post RCM analysis were scheduled hence not considered in the availability calculation.

7. Conclusion

Aircraft Availability is considered an important parameter of mission readiness. Thus, availability of aircraft for undertaking flying tasks remains a focus area of maintenance engineers and managers. Frequent breakdown due to failures results in the unavailability of aircraft. The research work implemented the RCM approach and failures analysis using FMECA and AHP. Based on the recommended PM actions, downtime of the aircraft was reduced by 15.71% and the availability improved by 6.62% on implementation of the PM measures.

8. Limitations and Future Scope

The study was carried out with limited data on failures of aircraft systems of a particular fleet. The research work investigated preventive maintenance for improvement of availability using FMECA with AHP. The limitations of the MADM technique should not be disregarded. Reliability and availability analysis of repairable systems, lack of spares, resource constraints, and optimization of maintenance and resources may also be explored as future work.

Acknowledgment
This research was not funded by any grant. The authors express their gratitude to the anonymous reviewers for their valuable suggestions on improving the paper.

References
[1] Ziółkowski, Jarosław, Jerzy Małachowski, Mateusz Oszczypała, Joanna Szkutnik-Rogoż, and Aleksandra Łęgas. "Modelling of the Military Helicopter Operation Process in Terms of Readiness." *Defence Science Journal* 71, no. 5 (2021). https://doi.org/10.14429/dsj.71.16422

[2] Freitas, F., Francisco JG Silva, R. D. S. G. Campilho, C. Pimentel, and R. Godina. "Development of a suitable project management approach for projects with parallel planning and execution." *Procedia Manufacturing* 51 (2020): 1544-1550. https://doi.org/10.1016/j.promfg.2020.10.215

[3] Deng, Qichen, Bruno F. Santos, and Wim JC Verhagen. "A novel decision support system for optimizing aircraft maintenance check schedule and task allocation." *Decision Support Systems* 146 (2021): 113545.

[4] Moubray, John. *Reliability-centered maintenance*. Industrial Press Inc., 2001. https://doi.org/10.1016/j.dss.2021.113545

[5] Kobbacy, Khairy AH, DN Prabhakar Murthy, Marvin Rausand, and Jørn Vatn. "Reliability centred maintenance." *Complex system maintenance handbook* (2008): 79-108.

[6] Asjad, Mohammad, Makarand S. Kulkarni, and O. P. Gandhi. "An insight to availability for O&M support of mechanical systems." *International Journal of Productivity and Quality Management* 16, no. 4 (2015): 462-472. https://doi.org/10.1504/IJPQM.2015.072418

[7] Kiran, M., Cijo Mathew, and Jacob Kuriakose. "Root cause analysis for reducing breakdowns in a manufacturing industry." *International Journal of Emerging Technology and Advanced Engineering* 3, no. 1 (2013): 211-216.

[8] Ab-Samat, Hasnida, Livendran Nair Jeikumar, Ernnie Illyani Basri, Nurul Aida Harun, and Shahrul Kamaruddin. "Effective preventive maintenance scheduling: a case study." In *Proceedings of the 2012 International Conference on Industrial Engineering and Operations Management*, pp. 3-6. 2012.

[9] Kiran, S., KP Prajeeth Kumar, B. Sreejith, and M. J. P. T. Muralidharan. "Reliability evaluation and Risk based maintenance in a process plant." *Procedia Technology* 24 (2016): 576-583. https://doi.org/10.1016/j.protcy.2016.05.117

[10] Mostafa, Sherif, Jantanee Dumrak, and Hassan Soltan. "Lean maintenance roadmap." *Procedia Manufacturing* 2 (2015): 434-444. https://doi.org/10.1016/j.promfg.2015.07.076

[11] Gabbar, Hossam A., Hiroyuki Yamashita, Kazuhiko Suzuki, and Yukiyasu Shimada. "Computer-aided RCM-based plant maintenance management system." *Robotics and Computer-Integrated Manufacturing* 19, no. 5 (2003): 449-458. https://doi.org/10.1016/S0736-5845(03)00031-0

[12] Wessels, William R. "Cost-optimized scheduled maintenance interval for reliability-centered maintenance." In *Annual Reliability and Maintainability Symposium, 2003.*, pp. 412-416. IEEE, 2003.

[13] Eisinger, Siegfried, and Uwe Kay Rakowsky. "Modeling of uncertainties in reliability centered maintenance—a probabilistic approach." *Reliability Engineering & System Safety* 71, no. 2 (2001): 159-164. https://doi.org/10.1016/S0951-8320(00)00088-0
[14] Hipkin, Ian B., and Christian De Cock. "TQM and BPR: lessons for maintenance management." *Omega* 28, no. 3 (2000): 277-292. https://doi.org/10.1016/S0305-0483(99)00043-2
[15] Kiyak, E. "The effects of aircraft preventive maintenance on reliability." *International journal of applied mathematics and informatics* 6, no. 1 (2012): 9-16.
[16] Carlson, Carl S. "Understanding and applying the fundamentals of FMEAs." In *Annual Reliability and Maintainability Symposium*, vol. 10, pp. 1-35. 2014.
[17] Eti, Mark C., S. O. T. Ogaji, and S. D. Probert. "Development and implementation of preventive-maintenance practices in Nigerian industries." *Applied energy* 83, no. 10 (2006): 1163-1179. https://doi.org/10.1016/j.apenergy.2006.01.001
[18] Jevgeni, Sahno, Shevtshenko Eduard, and Zahharov Roman. "Framework for continuous improvement of production processes and product throughput." *Procedia Engineering* 100 (2015): 511-519. https://doi.org/10.1016/j.proeng.2015.01.398
[19] Chopra, Amit, Anish Sachdeva, and Arvind Bhardwaj. "Productivity enhancement using reliability centred maintenance in process industry." *International Journal of Industrial and Systems Engineering* 23, no. 2 (2016): 155-165. https://doi.org/10.1504/IJISE.2016.076397
[20] Jun, Li, and Xu Huibin. "Reliability analysis of aircraft equipment based on FMECA method." *Physics Procedia* 25 (2012): 1816-1822. https://doi.org/10.1016/j.phpro.2012.03.316
[21] Chen, Yuan, Li Du, Yan-Feng Li, Hong-Zhong Huang, and Xiaopeng Li. "FMECA for aircraft electric system." In *2011 International Conference on Quality, Reliability, Risk, Maintenance, and Safety Engineering*, pp. 122-125. IEEE, 2011. https://doi.org/10.1109/ICQR2MSE.2011.5976581
[22] Sankar, Nune Ravi, and Bantwal S. Prabhu. "Modified approach for prioritization of failures in a system failure mode and effects analysis." *International Journal of Quality & Reliability Management* 18, no. 3 (2001): 324-336. https://doi.org/10.1108/02656710110383737
[23] De Almeida, A. T., and G. A. Bohoris. "Decision theory in maintenance decision making." *Journal of Quality in Maintenance Engineering* 1, no. 1 (1995): 39-45. https://doi.org/10.1108/13552519510083138
[24] Triantaphyllou, Evangelos, Boris Kovalerchuk, Lawrence Mann, and Gerald M. Knapp. "Determining the most important criteria in maintenance decision making." *Journal of Quality in Maintenance Engineering* 3, no. 1 (1997): 16-28. https://doi.org/10.1108/13552519710161517
[25] Bevilacqua, Maurizio, and Marcello Braglia. "The analytic hierarchy process applied to maintenance strategy selection." *Reliability Engineering & System Safety* 70, no. 1 (2000): 71-83. https://doi.org/10.1016/S0951-8320(00)00047-8
[26] Bertolini, Massimo, and Maurizio Bevilacqua. "A combined goal programming—AHP approach to maintenance selection problem." *Reliability Engineering & System Safety* 91, no. 7 (2006): 839-848. https://doi.org/10.1016/j.ress.2005.08.006
[27] Nowlan, F. Stanley, and Howard F. Heap. "Reliability-centered maintenance." (1978). https://doi.org/10.21236/ADA066579
[28] Thawkar, Aniket, Pravin Tambe, and Vishwas Deshpande. "A reliability centred maintenance approach for assessing the impact of maintenance for availability improvement of carding machine." *International Journal of Process Management and Benchmarking* 8, no. 3 (2018): 318-339. https://doi.org/10.1504/IJPMB.2018.10012845
[29] Siddiqui, Atiq Waliullah, and Mohamed Ben-Daya. "Reliability centered maintenance." In *Handbook of maintenance management and engineering*, pp. 397-415. London: Springer London, 2009. https://doi.org/10.1007/978-1-84882-472-0_16
[30] Saaty, Thomas L. "The analytic hierarchy process: planning, priority setting, resource allocation." (1980). https://doi.org/10.21236/ADA214804
[31] United States Department of Defense. "MIL-STD-1629A – Military Standard Procedures for Performing a Failure Mode, Effects and Criticality Analysis." *System Reliability Center, DoD, Washington, DC*. (1980).