IJRRS
International Journal of Reliability, Risk and Safety: Theory and Application

Online ISSN: 2676-3346

OPEN ACCESS

Vol. 6/ Issue 2/ 2023/ pp. 65-75
DOI: 10.22034/IJRRS.2023.6.2.8
Received: 19 October 2023, Revised: 23 December 2023, Accepted: 24 December2023
Available online at: https://www.ijrrs.com

Original Research Article

Reliability Evaluation of Systems Related to PC-7 Aircrew Using FMEA Method

Mostafa Livani[1*], Mahmud Ketabi[2] and Mahammad Davarzani[2]

1- Department of Aerospace Engineering, Shahid Sattari Aeronautical University of Science and Technology, Tehran, Iran
2- Faculty of Graduate Studies, Shahid Sattari Aeronautical University of Science and Technology, Tehran, Iran

*** m.livani@ssau.ac.ir**

Abstract

In this article, the reliability of the equipment related to the PC-7 aircrew is evaluated using the FMEA method. For this purpose, a complete review of the equipment and systems related to the PC-7 aircrew was done. Then, the potential failure modes were determined for each of the subsystems. In the following, the parameters of the RPN formula were determined by the questionnaire method and obtaining the opinions of technical experts and pilots of the PC-7 aircraft about the severity of the failure, the probability of their occurrence, and the difficulty of detecting them. Also, the risk diagram was drawn based on two main parameters, including the severity of the effect and the probability of failure. Finally, the highest RPN coefficient determined that the three electronic, engine, and airplane fuel systems have the highest RPN values and risk probability.

Keyword: PC-7; FMEA; RPN; Reliability; Risk Diagram.

Nomenclature

Symbol	Description
ARC	Automatic Recirculation Valve
ATT	Attitude
C	Celsius
D	Detection
FM	Failure mode
FMEA	Failure Mode and Effects Analysis
FBD	Foreign Body Damage
ft	Foot
HIS	Horizontal Situation Indicators
hp	Horse Power
imp gal	Imperial Gallon
in	Inch
ITT	Inter Turbine Temperature
kg	Kilogram
km/h	Kilometer per Hour
kn	Nautical Mile per Hour
kW	Kilo Watt
lb	Pound
m	Meter
mi	Mile
mph	Miles per Hour
Nmi	Nautical Mile
O	Occurrence
OAT	Outside Air Temperature
RMI	Radio Magnetic Indicator
RPM	Revolutions per Minute
S	Severity
shp	Shaft Horse Power
sq	Square
US gal	United States Gallon
VVI	Vertical Velocity Indicator
°	Degree

1. Introduction

With the development of electronic technology, aircraft systems' performance tends to improve. To ensure their working order and enhance their performance, the operational reliability of the aircraft systems should be guaranteed: Low failure probability and long-time running [1].

Failure mode and effects analysis (FMEA) reviews as many components, assemblies, and subsystems as possible to identify potential failure modes in a system and their causes and effects. Each component's failure modes and their effects on the rest of the system are recorded in a specific FMEA worksheet. There are numerous variations of such worksheets. An FMEA can be a qualitative analysis [2] but may be put on a quantitative basis when mathematical failure rate models [3] are combined with a statistical failure mode ratio database. It was one of the first highly structured, systematic techniques for failure analysis. Reliability engineers developed it in the late 1950s to study problems that might arise from malfunctions in military systems. An FMEA is often the first step of a system reliability study.

Lališ et al. [4] performed FMEA and reliability ontology of an aircraft engine lubrication system. Their results show that the ontology method has significant potential for improving aviation reliability's consistency

How to cite this article:
M. Livani, M. Ketabi and M. Davarzani, “Reliability Evaluation of Systems Related to PC-7 Aircrew Using FMEA Method,” *International Journal of Reliability, Risk and Safety: Theory and Application*, vol. 6, no. 2, pp. 65-75, 2023.

and overall quality. Song et al. [5] performed fatigue reliability-based design optimization of aircraft turbine disks. They used a hierarchical fuzzy-neuro surrogate method and multi-level collaboration optimization model. Using the FMEA method, Khanlo and Mahmodi Kohan [6] calculated the risk priority number of the Ilyushin-76 aircraft hydraulic system, and its critical parts were identified. Alamri and Mo [7], using the identified failure mode and effects analysis, present an integrated preventive maintenance scheduling methodology for complex systems. The genetic algorithm determines optimal replacement intervals and spare part quantities. Moghimi Esfandabadi and Djavareshkian [8] performed the risk analysis in flight safety, the performance evaluation index of safety, security, and flight to save from plane crashes. Liu et al. [9] investigated the FMEA framework for integrated drive generator risk identification and classification considering expert reliability in an unbalanced, hesitant fuzzy linguistic term sets environment. The operational reliability evaluation model was established based on the data envelopment analysis method by Jia-Qi et al. [10]. They proposed an intelligent extremum machine learning model by integrating the extremum response surface method, artificial neural network, improved particle swarm optimization algorithm, and Bayesian regularization algorithm. Zhou et al. [11] evaluated the service life and reliability of the aviation systems. They optimized the long-term planning of the most significant shop visit overhauls by maximizing the fleet time-on-wing availability. Jiang et al. [12] proposed a new improved modified Weibull distribution. They studied order statistics, moment estimates, and maximum likelihood estimates of the new distribution. Vališ et al. [13] performability and capability modeling examined the reliability of lithium-ion batteries that are the source of energy of an electric. The obtained results showed that the stored batteries did not have a higher quality or reliability degradation rate. Peng et al. [14] proposed a dynamic landing and arrest cable model using a specific carrier-based aircraft. They investigated the effects of sinking velocity, pitch angle, and horizontal velocity on the collision rebound performance of the arresting hook. Also, the arresting hook system's reliability was studied using the Support Vector Machine and Monte Carlo methods.

According to the conducted studies and the importance of preventing airplane failure, this article evaluates the risk of PC-7 aircrew using the FMEA method. For this purpose, a complete survey of the equipment and systems related to the aircrew is done. Then, the potential failure modes are determined for each of the systems. In the following, the possible effects of each failure mode will be determined, and then their causes will be determined. Listing the current controls to identify each of these failures and calculating the priorities and importance of each risk are the next steps of this article.

2. Pilatus PC-7

The Pilatus PC-7 Turbo Trainer is a low-wing tandem-seat training aircraft designed and manufactured in Switzerland by Pilatus Aircraft. The aircraft can perform all basic training functions, including aerobatics, instrument, tactical, and night flying. The PC-7 was developed from the preceding piston-powered Pilatus P-3 [15], mainly differing by adopting a turboprop engine, a bubble canopy, and a new one-piece wing. Introduced during the 1970s, it has since developed a sizable presence in the global trainer market [16]. Over twenty air forces have adopted the type as their ab initio trainer and multiple civilian operators. Over one million hours have reportedly been flown by PC-7s worldwide.

Figure 1 shows a PC-7 in flight, three view drawings, and the cabin.

Figure 1. Pilatus PC-7

3. Accidents and Incidents of PC-7

The South African Air Force (SAAF) grounded their PC-7 Mk-II M aircraft fleet after a crash on 15 January 2008. The aircraft went down shortly after take-off from Overberg Air Force Base in the Western Cape Province. SAAF Lieutenant-Colonel Chris Meiring, 58, died shortly after the crash. The aircraft was flying to Langebaanweg Air Force Base for maintenance, but it rolled and flew into the ground shortly after take off. The cause is believed to have been a structural problem.

In March 2010, a pilot was killed when his Royal Malaysian Air Force aircraft exploded and caught fire in midair during a solo airshow [17].

In June 2010, two Mexican pilots were killed when their Mexican Air Force PC-7 crashed after taking off from Pie de la Cuesta, a district in the resort city of Acapulco, Mexico. The PC-7 crashed into the sea near Acapulco [18,19].

On 20 October 2011, two PC-7s of the Botswana Defence Force were involved in a mid-air collision over Letlhakeng 100 kilometers (62 miles) west of Gaborone. Two of the four aircrew involved were killed in the accident [20].

On 12 September 2017, a pilot was killed when his Swiss Air Force PC-7 crashed at the Schreckhorn in Canton Bern on its way from Base aérienne Payerne to Base aérienne Locarno [21].

4. Specifications of PC-7

The general characteristics of Pilatus PC-7 are:

Crew: two, pilot instructor and student pilot.

Capacity: two.

Length: 9.78 m (32 ft 1 in).

Wingspan: 10.40 m (34 ft 1 in).

Height: 3.21 m (10 ft 6 in).

Wing area: 16.60 m^2 (178.7 sq ft).

Aspect ratio: 6.5:1.

Airfoil: NACA 64_2A-415 at root, 64_1A-612 at tip.

Empty weight: 1,330 kg (2,932 lb).

Max takeoff weight: 2,700 kg (5,952 lb).

Fuel capacity: 474 L (104 imp gal; 125 US gal) usable internal fuel,2×240 L (53 imp gal; 63 US gal) external fuel drop tanks.

Max landing weight: 2565 kg.

Powerplant: 1× Pratt & Whitney Canada PT6A-25A turboprop, 410 kW (550 hp)(derated from 485 kW (650 shp)).

Propellers: 3-bladed Hartzell HC-B3TN-2/ T10173C-8 constant-speed propeller, 2.36 m (7 ft 9 in) diameter.

Maximum speed: 412 km/h (256 mph, 222 kn) (max cruise at 6,095 m (19,997 ft)).

Cruise speed: 316 km/h (196 mph, 171 kn) (econ. cruise at 6,095 m (19,997 ft)).

Stall speed: 119 km/h (74 mph, 64 kn) (flaps and gear down, power off).

Never exceed speed: 500 km/h (310 mph, 270 kn) EAS.

Range: 1,200 km (750 mi, 650 nmi) standard range without external drop tanks, ferry range with external drop tanks (cruise power, at 5,000 m (16,000 ft) - 20 min reserves).

Ferry range: 2,630 km (1,630 mi, 1,420 nmi).

Endurance: 4 hr 22 min.

Service ceiling: 10,060 m (33,010 ft).

g limits: -3 / +6.

Rate of climb: 10.9 m/s (2,150 ft/min) climb to 5,000 m in 9 min 0-sec take-off run 780 m at max take-off weight, landing run 505 m at max landing weight.

Hardpoints: 6 × underwing hardpoints for bombs and rockets with a capacity of 1,040 kg (2,294 lb) [22].

5. Failure Mode and Effects Analysis

The failure mode and effects analysis (FMEA) reviews as many components, assemblies, and subsystems as possible to identify potential failure modes in a system and their causes and effects [2].

Failure mode (FM) refers to how something might break down. It includes potential errors, especially errors that could affect the customer. Effective analysis (EA) involves deciphering the consequences of those breakdowns. It does this by ensuring all failures can be detected, determining how frequently they might occur, and identifying which potential failures should be prioritized [23].

A business analyst might perform an FMEA when a product or service is being designed or fixed or when an existing product or service is being used in a new way. FMEA can also be used before developing control plans for a new process or following a quality function deployment. Lean production methodology uses FMEA periodically throughout the lifecycle of a product or service. FMEA can also be used to identify and mitigate potential hardware risks [23].

FMEA is generally used when improvement goals are implemented or when designs, changes, new features, regulations, or feedback is given, as this is where potential failure and detection can occur [23].

FMEA offers organizations the following benefits [23]:

1. Gives them an early way to identify and mitigate potential modes of failure;

2. Minimizes the need to make late changes to a project due to potential issues;

3. Reduces the risk of a problem happening more than once;

4. Provides prompts for employees to follow when facing a potential failure mode;

5. Promotes more collaboration among teams that handle areas such as design, manufacturing, quality, testing and sales;

6. reduces the cost involved by avoiding fixing issues in development.

FMEA procedures may differ depending on the organization, but these are eight general steps to follow while implementing FMEA [23]:

1. Create a team of employees with collective knowledge or experience with the system, design or process, and customer needs. This includes employees with experience in customer service, design, maintenance, manufacturing, quality, reliability, testing, and sales.
2. Identify the scope of the system, design, process, product or service. Define the purpose of the system process, service, and design.
3. Break down a system, design, or process into different components.
4. Go through system, design, or process elements to determine each possible issue or single point of failure.
5. Analyze the potential causes of those failures as well as the effects the failures would have.
6. Rank each potential failure effect based on decided criteria such as severity, likelihood of occurrence, and probability of being detected. Organizations can use a risk priority number (RPN) to score a system, design, or process for risk potential.
7. Determine how to detect, minimize, mitigate, and solve the most critical failures. This helps keep failure effect risks low by creating a list of potential failures and corrective actions to take.
8. Revise risk levels as needed.

6. Risk Priority Number

Risk Priority Number is a numerical assessment of the risk priority level of a failure mode/failure cause in an FMEA analysis. It helps the responsible team/individual prioritize risks and decide corrective actions [24].

FMEA RPN is calculated by multiplying Severity (S), Occurrence (O), and Detection (D) indexes. Severity, Occurrence, and Detection indexes are derived from the failure mode and effects analysis [24]:

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D} \quad (1)$$

Severity: The severity of the failure mode is rated on a scale from 1 to 10 based on Table 1. A high severity rating indicates severe risk.

Occurrence (or Probability): The potential of failure occurrence is rated on a scale from 1 to 10 based on Table 1. A high occurrence rating reflects high failure occurrence potential.

Detection: The failure detection capability is rated on a scale from 1 to 10 based on Table 1. A high detection rating reflects low detection capability [24].

RPN may not be essential in choosing action against failure modes, but it will help indicate the threshold values for determining the areas of greatest concentration. In other words, the analysis and corrective action should prioritize a failure mode with a high RPN number [26].

The relationship between RPN, risk level, and required actions is shown in Table 2.

7. Risk Diagram

To estimate the criticality of the risk level, it is more common to use only the severity of the effect and the probability of occurrence of the risk for each failure mode. Figure 2 identifies the risk diagram, catastrophic, high-risk, low-risk, and safe areas for a detection level 10. According to the coordinates of the severity and the probability of occurrence, the coordinates of the area resulting from these two points can be easily determined in the risk diagram, and basic measures can be taken for the points located in the high-risk area.

Table 1. Severity, occurrence, and detection rating scales [25]

Severity (S)	Occurrence (O)	Detection (D)	Rating
Hazardous without warning	Very high failure is almost inevitable	Absolute uncertainty	10
Hazardous with warning	Very high failure is almost inevitable	Very remote	9
Very high	High repeated failures	Remote	8
High	High repeated failures	Very low	7
Moderate	Moderate occasional failures	Low	6
Low	Moderate occasional failures	Moderate	5
Very low	Moderate occasional failures	Moderately high	4
Minor	Low relatively few failures	High	3
Very minor	Low relatively few failures	Very high	2
None	Remote failure is unlikely	Almost certain	1

Table 2. RPN score range, risk level description, and required actions [27]

RPN	Risk level	Required action
499<RPN≤1000	Red: Catastrophic	Must be mitigated with a detailed action plan
250<RPN≤499	Orange: High	Must be mitigated with a detailed action plan
100<RPN≤249	Yellow: Moderate	Require specific monitoring or response procedures
RPN≤100	Green: Low	Acceptable, can be managed with routine procedures

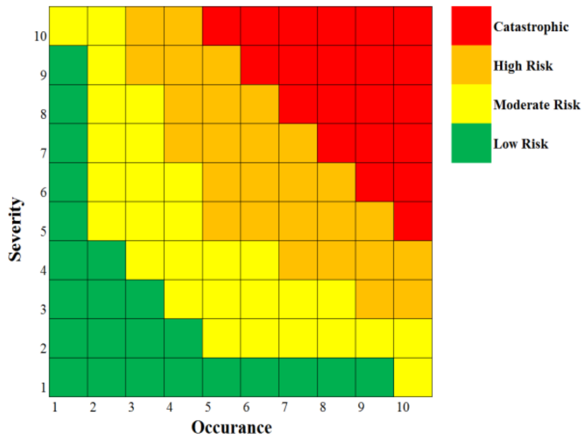

Figure 2. Risk diagram for detection level of 10 [27]

8. Implementation of the FMEA method on Equipment related to PC-7 Aircrew

In this section, the systems of the PC-7 aircraft that are involved in flight safety are selected, and the failures that may occur to them are specified.

9. PC-7 Engine System Failure Modes

The failure modes of the engine system are as follows:

- Engine fire on the ground.
- Engine fire in flight.
- Engine failure during take off.
- Engine fire in flight.

The causes of engine system failure are as follows:

1. Usually, the airflow moves uniformly in the jet engine. When the shape of this flow is disturbed at the engine inlet, the possibility of compressor stall increases.
2. The common reasons for the disturbance of the input engine airflow are foreign body damage (FOD) (such as a bird) into the engine, old and broken parts of the engine, in-flight icing, operating outside the manufacturer's design instructions, and not the proper way to use of the engine.
3. The separation of airflow and stall inside the engine compartment is created at the critical limit angle of the blade, just like what happens on the wing of an airplane. This phenomenon leads to the entry of turbulent airflow into the engine.
4. Seeing a flame in the door does not necessarily mean the engine is on fire. When the airflow is interrupted, the amount of fuel increases relative to the air required. The flame seen is the excess fuel that is being burned.

10. PC-7 Fuel System Failure Modes

The failure modes of the fuel system are as follows:

- Low Fuel Pressure
- Booster pump failure
- Fuel system leak
- Fuel Asymmetry

The causes of fuel system failure are as follows:

1. Aging of parts.
2. Corrosion of pipes and tanks.
3. A technical defect in the fuel pump.
4. Clogging of fuel lines.

11. PC-7 Oil System Failure Modes

Oil system failure modes are as follows:

- Low oil pressure in the range (not less than 40 psi).
- Low oil pressure and temperature out of range (less than 40 psi and temperature above 99°C).

The causes of oil system failure are as follows:

1. An oil leak in the oil pressure channels.
2. The oil pump has failed or isn't working correctly.
3. Clogging in the oil pressure channels.
4. Clogging in the oil filter.
5. Failure of the oil cooling system.

12. PC-7 Electronic System Failure Modes

The failure modes of the electronic system are as follows:

- Generator failure
- Battery overheat
- Inverter failure
- Runaway trim
- Electrical LDG control inoperative

The reasons for failure of the electronic system are as follows:

1. Aging of parts.
2. Lack of enough experience in using electronic systems.
3. Poor maintenance of electronic equipment.

13. PC-7 Flight Control System Failure Modes

Flight control system failure modes include the following:

- Jammed aileron
- Jammed elevator
- Jammed rudder

The failure of the flight control system mentioned above includes the following reasons:

1. The left and right flaps of the plane should be placed at different angles to each other.

2. When the flaps control handle is not calibrated correctly, and we choose one of the flap positions, it is possible that the flaps are not in their correct position.
3. Aging of flight control rods, levers, and cables.

14. Failure Modes of PC-7 Indicators

The failure modes of indicators are failures of:

- Aircraft altitude indicator.
- Aircraft attitude (ATT) indicator.
- Aircraft fuel indicator.
- Aircraft Radio Magnetic Indicator (RMI). Horizontal Situation Indicators (HIS) and homing indicators.
- Inter Turbine Temperature (ITT), Outside Air Temperature (OAT), and RPM indicators.
- Torque and propeller indicator.
- Airspeed indicator and Vertical Velocity Indicator (VVI).
- Oil Pressure and Temperature Indicator.
- Flaps indicator.

Reasons for the failure of aircraft indicators are:

1. Major defects and do not work indicator.
2. Stuck the indicator on a specific number.
3. Showing the wrong number.
4. Bad weather conditions.

15. Results

This article evaluates the severity, occurrence, and detection of systems failure modes related to PC-7 aircrew by expert opinions based on Table 3. This questionnaire was prepared based on the pilot's checklist, which lists the most dangerous possible events that can happen to the aircrew. For this purpose, the opinions of 10 technical experts and 15 PC-7 pilots were considered. They should fill in each system's severity, occurrence, and detection according to the leveling presented in Table 1. Then, the values of severity, occurrence, and detection are calculated as follows:

$$\mathrm{S} = \left(\sum_{i=1}^{25} S_i\right)/25 \tag{2}$$
$$\mathrm{O} = \left(\sum_{i=1}^{25} O_i\right)/25 \tag{3}$$
$$\mathrm{D} = \left(\sum_{i=1}^{25} D_i\right)/25 \tag{4}$$

where S_i, O_i, and D_i are the values of severity, occurrence, and detection according to the opinion of each technical expert and pilot. For example, the value of occurrence for engine fire on ground failure mode is calculated as follows:

$$\begin{gathered}\mathrm{O} = \left(\sum_{i=1}^{25} O_i\right)/25 = 1+2+1.5+2+2+2+ \\ 3+3+2+2.6+2+2+1+3+2+2+ \\ 2.5+2+1.5+1+2+3+2+2+2 = 2.003\end{gathered} \tag{5}$$

Table 3 shows the average severity, occurrence, and detection of systems failure modes related to PC-7 aircrew.

16. RPN for the PC-7 Engine System

The severity of the engine system failures varies according to different flight modes. For example, the failure of the engine system during taxiing, the approach, and landing of the aircraft do not pose a high hazard. However, during the flight path, the engine's vital role in providing the plane's thrust force causes the aircraft to stall catastrophically. According to the mentioned contents, the severity of engine system failure in flight operations is very high, and according to the opinion of technical experts and pilots, the severity rate of engine system failures is 7.046.

Table 3. The severity, occurrence, and detection of the systems failures related to PC-7 aircrew

Row	Systems	Failure Modes	Severity 1 to 10	Occurrence 1 to 10	Detection 1 to 10
1	Engine	Engine Fire on Ground	6.235	2.003	3.282
		Engine Fire in Flight	8.581	3.004	2.498
		Engine Failure during Takeoff	3.029	2.012	7.682
		Engine Failure in Flight	5.916	4.150	4.379
2	Fuel	Low Fuel Pressure	4.463	4.052	3.681
		Boost Pump Failure	4.974	3.807	4.055
		Fuel System Leaks	4.751	4.550	4.451
		Fuel Asymmetry	3.120	2.966	2.124
3	Oil	Low Oil Pressure	5.608	5.339	1.969
		Oil Pressure Blow Green ARC (Not Less Than 40 psi)	4.551	4.371	3.400
		Oil Pressure / Temperature Outside Limit (Below 40 psi or Above 99°C)	6.015	5.826	1.815
4	Electronic	Generator Failure	6.802	5.229	2.793
		Battery Overheat	5.817	2.997	3.638
		Inverter Failure	4.421	1.781	4.721
		Runaway Trim	7.236	4.644	3.925
		Electrical LDG Control Inoperative	6.216	3.012	4.254
5	Flight Control	Jammed Aileron	8.214	2.804	2.504
		Jammed Elevator	8.196	3.125	2.248
		Jammed Rudder	7.410	2.572	2.711
6	Indicators	ALT Indicator	4.661	4.936	3.093
		ATT Indicator	7.110	4.557	2.671
		Fuel Indicator	3.755	4.041	3.026
		RMI & HIS & Homing Indicator	4.820	2.968	1.837
		ITT & OAT & RPM Indicator	7.219	3.476	3.275
		Torque & Prop Indicator	2.972	4.075	3.525
		Airspeed & VVI Indicator	2.101	2.209	3.507
		Oil Press/Temp Indicator	4.411	3.961	2.902
		Flap Indicator	2.069	3.493	5.487

Since the engine system of the PC-7 aircraft is safe, the occurrence of engine system failure is moderate, and based on the opinion of technical experts and pilots, the occurrence rate of engine system failures is 3.488.

Due to the importance of the engine system, the pilot and the co-pilot continuously check its condition through the ITT, OAT, and RPM indicators. If a failure is detected, they take action according to the emergency checklist. Based on the opinion of technical experts and pilots, the detection of engine system failure is 3.320 out of 10.

Then, the amount of RPN of the engine system failures is calculated according to Eq. (1):

$$\text{RPN} = 7.046 \times 3.488 \times 3.320 = 81.594 \quad (6)$$

According to Table 2, the amount of RPN equal to 81.594 is at a low-risk level, so the risk of engine system failures is acceptable and can be managed with routine procedures.

Figure 3 shows the risk diagram for engine system failures at a detection level of 3.32. As can be seen, engine system failures are located in low-risk areas.

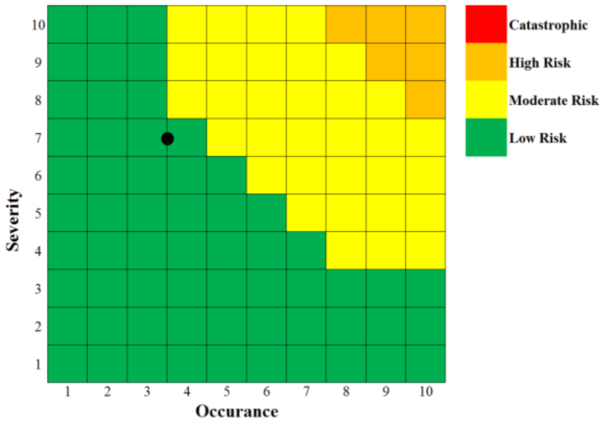

Figure 3. Risk diagram of the engine system failures for detection level 3.32.

17. RPN for the PC-7 Fuel System

The severity of the fuel system failure varies according to the phases of aircraft flight. Burning fuel provides engine power, and the plane will crash if unavailable. However, according to the plane's indicators, the PC-7 plane can glide a regular flight routine if the pilot takes timely action and can land safely. According to the mentioned contents, the severity of fuel system failure in flight operations is moderate, and according to the opinion of technical experts and pilots, the number 4.75 out of 10 is

The occurrence of the fuel system failure is moderate, and based on the opinion of technical experts and pilots, the occurrence rate of the fuel system failures is 4.74 out of 10.

The pilot and the co-pilot continuously check their status through the fuel indicator, and in case of failure, they take timely measures according to the checklist of emergencies. Based on the opinion of technical experts and pilots, 3.007 out of 10 have been recorded to detect fuel system failure.

Then, the amount of RPN of the fuel system failures is calculated according to Eq. (1):

$$\text{RPN} = 4.75 \times 4.74 \times 3.007 = 67.703 \quad (7)$$

According to Table 2, the amount of RPN equal to 67.703 is at a low-risk level, so the risk of fuel system failures is acceptable and can be managed with routine procedures.

Figure 4 shows the risk diagram for the fuel system failures for a detection level 3.007. As can be seen, the fuel system failures are located in the low-risk area.

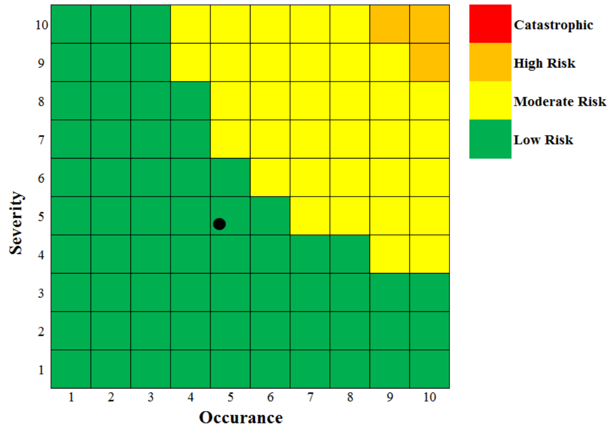

Figure 4. Risk diagram of the fuel system failures for detection level 3.007.

18. RPN for the PC-7 Oil System

The severity of oil system failure is not high risk considering that cables and levers control the PC-7 flight control system, and the landing gear system is also electric. According to technical experts and pilots, the severity of oil system failure on flight operations is 4.489 out of 10.

The occurrence of oil system failures is very rare because high-reliability parts are used in this system. However, increasing the life of the PC-7 aircraft increases the occurrence of component failure of the oil system. Based on the opinions of technical experts and pilots, the occurrence of oil system failures is 3.56 out of 10.

The oil system failure detection is usually easy due to pressure sensors in the oil path and temperature sensors inside the oil tanks. Of course, in cases where these sensors are damaged or lose their ability to identify and warn. In such cases, it is impossible to identify the failures quickly, but they can be determined according to the performance of the systems and the pilot's experience. Based on the opinion of technical experts and pilots, 3.255 out of 10 have been recorded for the degree of difficulty in detecting a failure in the oil system.

Then, the amount of RPN of the oil system failures is calculated according to Eq. (1):

$$RPN = 4.489 \times 3.56 \times 3.255 = 52.018 \quad (8)$$

According to Table 2, the amount of RPN equal to 52.018 is at a low-risk level, so the risk of oil system failures is acceptable and can be managed with routine procedures.

Figure 5 shows the risk diagram for the oil system failures for a detection level 3.255. As can be seen, the oil system failures are located in the low-risk area.

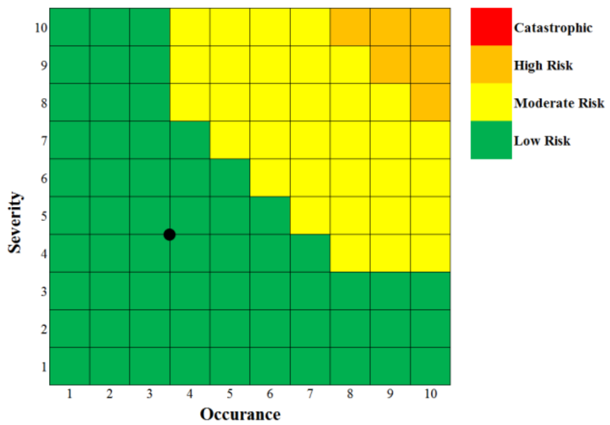

Figure 5. Risk diagram of the oil system failures for detection level 3.255.

19. RPN for the PC-7 Electronic System

The severity of each of the electronic system failure is different according to the tasks they have. According to the opinion of technical experts and pilots, the severity of electronic system failures is 6.617 out of 10, which is almost high.

According to the opinion of experts and pilots, the occurrence of electronic system failures is 3.738 out of 10. Then, the occurrence of those is almost moderate, with occasional failures.

The pilot and co-pilot continuously check the status of the electronic systems through the indicators. In case of failure, they take timely actions according to the checklist of emergencies.

Based on the opinion of technical experts and pilots about the difficulty of detecting failure in the electronic system, the number 3.39 out of 10 has been recorded.

Then, the amount of RPN of the electronic system failures is calculated according to Eq. (1):

$$RPN = 6.617 \times 3.738 \times 3.39 = 83.850 \quad (9)$$

According to Table 2, the amount of RPN equal to 83.850 is in the low-risk level, so the risk of electronic system failures is acceptable and can be managed with routine procedures.

Figure 6 shows the risk diagram for the electronic system failures for a detection level 3.39. As can be seen, the electronic system failures are located in the low-risk area.

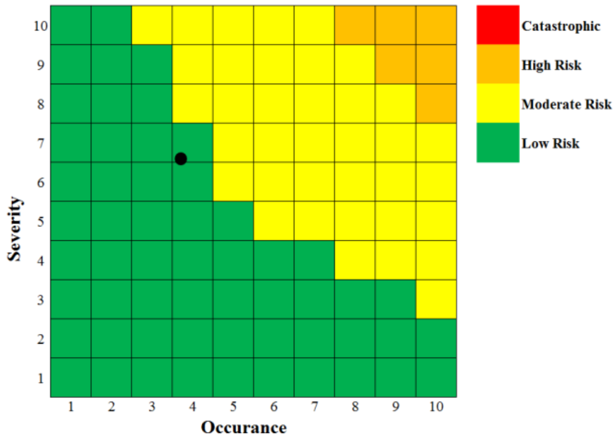

Figure 6. Risk diagram of the electronic system failures for detection level 3.39.

20. RPN for the PC-7 Flight Control System

The severity of flight control system failures differs according to different flight modes. In the take-off and landing mode of the plane, since the aircraft's speed is very low and the presence of wheels creates additional drag on the aircraft, the severity of the damage effect increases, and if the damage happens suddenly, it will cause catastrophic accidents. In these two flight modes, the plane is highly dependent on the flaps, and the smallest failure in the provision of lift by the flaps, due to the low height of the aircraft, causes loss of control of the plane. At a high altitude of the aircraft, the failure of the flight control system is more easily controllable.

Based on the opinion of technical experts and pilots, the severity of the flight control system failures is 8.928 out of 10, which implies hazardous with warning.

Failures in the flight control system of the PC-7 plane rarely happen because it has high reliability due to the use of metal levers and cables instead of hydraulic systems. However, it can be dangerous due to wear and tear of the main parts. The occurrence of flight control system failure based on the opinion of technical experts and pilots is 2.990 out of 10, which shows relatively few failures.

Since the flaps are part of the main flight surfaces of the aircraft, the detection of failure in them is very fast because it affects the steering and controllability of the aircraft. Failure detection is not easily done only in cases where the flaps are not in their correct position. Therefore, when using the flaps, their position is always checked by the technical experts and reported to the pilot. For ease and accuracy in recognizing the position of the flaps during flight and from inside the airplane cabin, the surface on it is graded according to the angle of placement concerning the wing, and these numbers are easily visible from inside the cabin and during flight. The detection of flight control system failures is very high, and a number 2.34 is considered for it by technical experts and pilots.

Then, the amount of RPN of the flight control system failures is calculated according to Eq. (1):

$$RPN = 8.928 \times 2.990 \times 2.34 = 62.466 \qquad (8)$$

According to Table 2, the amount of RPN equal to 62.466 is at a low-risk level, so the risk of flight control system failures is acceptable and can be managed with routine procedures.

Figure 7 shows the risk diagram for the flight control system failures for detection level 2.34. As can be seen, the flight control system failures are located in the low-risk area.

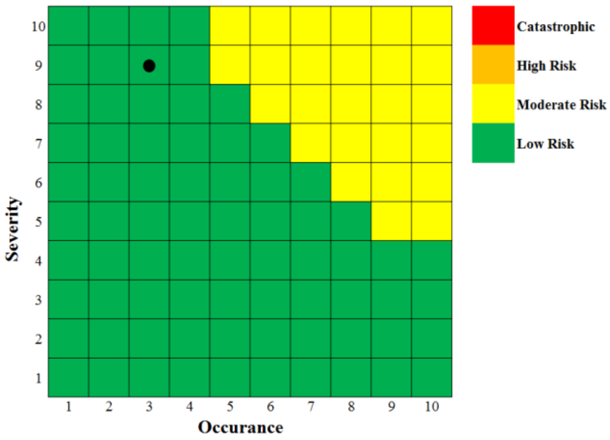

Figure 7. Risk diagram of the flight control system failures for detection level 2.34.

21. RPN for the PC-7 Cockpit Indicators

The severity of the failure effect of each of the indicators is different according to those tasks. According to the opinion of technical experts and pilots, the severity of the indicator failures is an average of 5.84 out of 10, which means the severity of indicator failures is at a medium level.

The occurrence of indicator failures based on the opinion of technical experts and pilots is 3.57 out of 10.

The pilot and co-pilot can detect indicator failures based on experience, information from ground systems, visual parameters, and the use of equipment. Based on the opinion of technical experts and pilots, the difficulty of detecting a failure in the indicators, a number 2.838 out of 10, has been recorded.

Then, the amount of RPN of the indicator failures is calculated according to Eq. (1):

$$RPN = 5.84 \times 3.57 \times 2.838 = 59.169 \qquad (9)$$

According to Table 2, the amount of RPN equal to 59.169 is in the low-risk level, so the risk of indicator failures is acceptable and can be managed with routine procedures.

Figure 8 shows the risk diagram for the indicator failures for a detection level 2.838. As can be seen, the indicator failures are located in the low-risk area.

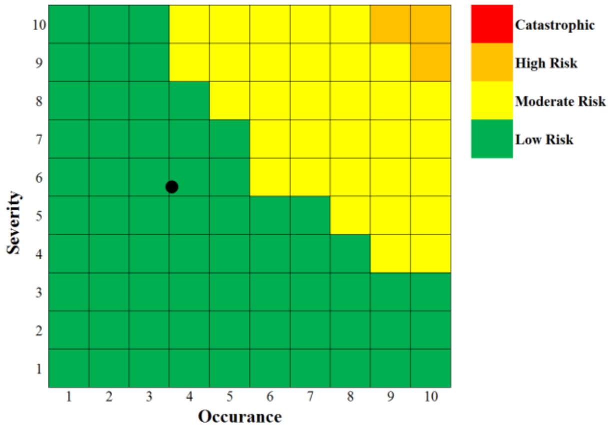

Figure 8. Risk diagram of the indicator failures for a detection level 2.838.

22. Highest RPN of the PC-7 Aircrew

According to the RPN numbers obtained for the PC-7 aircraft systems, the risk priority classification is sorted in Table 4. As shown in Table 4, the electronic, engine, and fuel systems have the highest RPN values and risk probability among all systems.

Table 4. Comparison of the RPN for PC-7 aircraft systems failures

Row	System of PC-7	RPN
1	Electronic	83.850
2	Engine	81.594
3	Fuel	67.703
4	Flight Control	62.466
5	Indicators	59.169
6	Oil	52.018

According to the opinions of the technical experts and pilots in the questionnaire, the RPN of each of the PC-7 aircraft systems is sorted in Table 5.

Table 5 shows that electronic system failures have the highest RPN among the PC-7 aircraft systems. A wide range of practical problems could arise following onboard electrical failure(s). Depending on the type of failure(s), whether it includes loss of all generators (alternators) and battery power only available (power supply reduced to emergency level), some possible effects on the crew are:

- Increased workload: Crew determining the nature and the severity of the problem.
- Turning off non-critical electrical items (such as second radio, passenger cabin lighting, recirculation fans, and other nonessential

electrical systems) to isolate and identify the problem's source and reduce the electrical load.

- A decision to land at the nearest/most suitable airport.

The worst case related scenario is an on-board fire in flight caused by an electrical fault that cannot be contained readily by the crew.

To mitigate such trim-related risks, the following actions are suggested:

- To provide aircrews with tools to detect and immediately recognize dangerous out-of-trim conditions and trim degraded mode operation or failures.
- To enhance pilot proficiency and skills to deal with full or partial out-of-trim conditions.
- To enhance knowledge and awareness of this accident by systematically including and analyzing trim data as part of the occurrence reporting process.

According to Table 5, engine system failures have the second highest RPN among the PC-7 aircraft systems. Engine failures can be caused by mechanical problems in the engine itself, such as damage to portions of the engine or oil leaks, as well as damage outside the engine, such as fuel pump problems or fuel contamination. External factors, such as volcanic ash, bird strikes, or weather conditions like precipitation or icing, can also cause engine failure. Weather risks such as these can sometimes be countered through supplementary ignition or anti-icing systems.

Preventing engine failures can be divided into two broad areas: maintenance and operation. What stands out in so many accident investigations resulting from engine failure is that pilots and maintenance personnel fail to follow established procedures. These can include conducting a thorough engine run-up after maintenance and checking for leaks. Nevertheless, one of the most valuable and easiest ways to help prevent an engine failure is to closely monitor the engine parameters reported by the aircraft's instrumentation. While aircraft engines are now more reliable than ever, failures do occur. Often, there are signs of impending trouble, which, if addressed early on, could prevent malfunctions or complete failure.

Table 5. Comparison of the RPN for PC-7 aircraft systems failures

Row	System	First Failure Priority	Second Failure Priority
1	Electronic	Trim Failure	Generator Failure
2	Engine	Engine Fire in Flight	Engine Failure During Take-off
3	Fuel	Fuel System Leaks	Boost Pump Failure
4	Flight Control	Jammed Aileron	Jammed Elevator
5	Indicators	ALT Indicator	ATT Indicator
6	Oil	Oil Pressure / Temperature Outside Limit	Low Oil Pressure

The results of comparing the severity of the systems failures of PC-7 aircraft are sorted in Table 6. Based on the results presented in Table 6, the most severity of PC-7 aircraft systems are the flight control, engine, and electronic systems, respectively.

Table 6. Comparison of the RPN for PC-7 aircraft systems failures

Row	System	Severity
1	Flight Control	8.93
2	Engine	7.046
3	Electronic	6.617
4	Indicators	5.84
5	Fuel	4.75
6	Oil	4.489

23. Conclusion

In this article, the reliability evaluation of the equipment related to the PC-7 aircrew was evaluated using the FMEA method. The potential failure modes were determined for each of the subsystems. In the following, the parameters of the RPN formula were determined by the questionnaire method and obtaining the opinions of technical experts and pilots of the PC-7 aircraft about the severity of the failure, the probability of their occurrence, and the difficulty of detecting them.

According to the present research results, the electronic, engine, and fuel systems have the highest RPN values and risk probability among all systems, and the most severe of PC-7 aircraft systems are the flight control, engine, and electronic systems, respectively.

Also, the current results show that the equipment related to the PC-7 aircrew has an acceptable risk level and can be managed with routine procedures.

24. References

[1] L. Lu-ning, "Reliability analysis of electric element in ground tester," *Aircraft Design*, no. 2, pp. 50-53, 1998.

[2] R. Marvin, and H. Arnljo, *System Reliability Theory: Models, Statistical Methods, and Applications*, 2nd edition, Wiley, p. 88, 2004, doi: https://doi.org/10.1002/9781119373940.fmatter

[3] K.M. Tay, and C.P. Lim, "On the use of fuzzy inference techniques in assessment models: part II: industrial applications," *Fuzzy Optimization and Decision Making*, vol. 7, no. 3, pp. 283–302, 2008, doi: https://doi.org/10.1007/s10700-008-9037-y

[4] A. Lališ, S. Bolčeková, and O. Štumbauer, "Ontology-based reliability analysis of aircraft engine lubrication system," *Transportation Research Procedia*, vol. 51, pp. 37-45, 2020, doi: https://doi.org/10.1016/j.trpro.2020.11.006

[5] L.K. Song, G.C. Bai, X.Q. Li, and J. Wen, "A unified fatigue reliability-based design optimization framework for aircraft turbine disk," *International Journal of Fatigue*,

vol. 152, 2021, doi: https://doi.org/10.1016/j.ijfatigue.2021.106422

[6] H. Mohamad Khanlo, and A.M. Mahmodi Kohan, "Failure mode and effects analysis on the hydraulic system of aircraft ilyushin-76," *International Journal of Reliability, Risk and Safety: Theory and Application*, vol. 5, no. 1, pp. 49-58, 2022, doi: https://doi.org/10.30699/IJRRS.5.1.7

[7] T. Alamri, and J. Mo, "Optimising system continuity in preventive maintenance schedules based on integrated failure mode and spare part inventory modelling," *International Journal of Reliability, Risk and Safety: Theory and Application*, vol. 5, no. 2, pp. 19-31, 2022, doi: https://doi.org/10.30699/IJRRS.5.2.3

[8] M.H. MoghimiEsfandabadi, M. Djavareshkian, and S. Abedi, "The significance of aviation safety, its evaluation, and ways to strengthen security," *International Journal of Reliability, Risk and Safety: Theory and Application*, vol. 6, no. 2, pp. 37-45, 2023, doi: https://doi.org/10.22034/IJRRS.2023.6.2.5

[9] Z. Liu, Y. Zhao, and P. Liu, "An integrated FMEA framework considering expert reliability for classification and its application in aircraft power supply system," *Engineering Applications of Artificial Intelligence*, vol. 123, Part B, p. 106319, 2023, doi: https://doi.org/10.1016/j.engappai.2023.106319

[10]L. Jia-Qi, F. Yun-Wen, T. Da, C. Jun-Yu, and L. Cheng, "Operational reliability evaluation and analysis framework of civil aircraft complex system based on intelligent extremum machine learning model," *Reliability Engineering & System Safety*, vol. 235, p. 109218, 2023, doi: https://doi.org/10.1016/j.ress.2023.109218

[11]H. Zhou, M. Farsi, A. Harrison, A. Kumar Parlikad, and A. Brintrup, "Civil aircraft engine operation life resilient monitoring via usage trajectory mapping on the reliability contour," *Reliability Engineering & System Safety*, vol. 230, 2023, doi: https://doi.org/10.1016/j.ress.2022.108878

[12]D. Jiang, Y. Han, W. Cui, F. Wan, T. Yu, and B. Song, "An improved modified Weibull distribution applied to predict the reliability evolution of an aircraft lock mechanism," *Probabilistic Engineering Mechanics*, vol. 72, 2023, doi: https://doi.org/10.1016/j.probengmech.2023.103449

[13]D. Vališ, J. Hlinka, J. Koláček, P. Procházka, O. Pokora, R. Cipín, and R. Koštial, "Comprehensive study on reliability, deterioration, and aging of lithium-ion batteries in electric-powered aircraft assessed after a storage period using functional data analysis and non-parametric backup," *Engineering Failure Analysis*, vol. 154, 2023, doi: https://doi.org/10.1016/j.engfailanal.2023.107661

[14]Y. Peng, Y. YIN, P. XIE, X. WEI, and H. NIE, "Reliability analysis of arresting hook engaging arresting cable for carrier-based aircraft influenced by multifactors," *Chinese Journal of Aeronautics*, vol. 36, no. 1, pp. 311-323, 2023, doi: https://doi.org/10.1016/j.cja.2022.01.001

[15]*Pilatus PC-7*, MilitaryAviation.eu., Military Aviation, 2008, Available: http://MilitaryAviation.eu/trainer/Pilatus/PC-7.htm

[16]*Training - Bridging the gap*, Flightglobal.com., Flight International, 2001, Available: https://www.flightglobal.com/training-bridging-the-gap-/38896.article

[17]*Nasional Karnival konvokesyen UUM bertukar tragedy*, Bharian.com.my. Bharian. March, 2010, Available: http://www.bharian.com.my/bharian/articles/KarnivalkonvokesyenUUMbertukartragedi/Article

[18]*Cae avión militar en Acapulco*, debate.com.mx, El Debate, 2013, Available: http://www.laht.com/article.asp?ArticleId=370468&CategoryId=14091

[19]*Two die in military plane crash in Mexico*, LAHT.com., Latin American Herald Tribune, 2016, Available: http://www.laht.com/article.asp?ArticleId=370468&CategoryId=14091

[20]*Two BDF planes collide*, killing two pilots, Mmegi.bw. Mmegi online, 2018, Available: https://www.mmegi.bw/news/two-bdf-planes-collide-killing-one-pilot/news

[21]*PC-7 crash on Schreckhorn*, 20min.ch., 2017, Available: https://www.20min.ch/story/leiche-des-pc-7-piloten-gefunden-484479452509

[22]*Air International Magazine*, p. 113, 1979, Available: https://www.magazineexchange.co.uk/cw/air-international-magazine-september-1979-issue.html

[23]A.S. Gillis, *FMEA (Failure Mode and Effects Analysis)*, Technical Writer and EditorWendy Schuchart, TechTarget, Available: https://www.techtarget.com/searchcio/definition/FMEA-failure-mode-and-effective-analysis

[24]J. Hartwell, *FMEA RPN – Risk Priority Number. How to Calculate and Evaluate*? 2022, Available: https://www.iqasystem.com/news/risk-priority-number/

[25]*Standard SAE, Potential Failure Mode and Effects Analysis in Design (Design FMEA) and Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (Process FMEA) and Effects Analysis for Machinery (Machinery FMEA)*, Warrendale, PA: SAE; 2002, Available: https://www.sae.org/standards/content/j1739_202101/

[26]D.R. Kiran, "Failure Modes and Effects Analysis," *in Total Quality Management*, 2017, doi: http://dx.doi.org/10.1016/B978-0-12-811035-5.00026-X

[27]M. Marquez, D. Terhaer, K. Scheinemann, P. Mirnajafizadeh, A. Carty, C.P. Stewart, and A. Rodney, "Quality by Design for industry translation: Three-dimensional risk assessment failure mode, effects, and criticality analysis for additively manufactured patient-specific implants, *Engineering Reports*, vol. 2, no. 1, 2020, doi: https://doi.org/10.1002/eng2.12113