

Modeling and reliability analysis of aircraft components and systems: a case study

Rafael Kayque dos Santos^a, Jonatas Ribeiro Mangabeiro^a, Viviane Vasconcellos Ferreira Grubisic^b

^a Faculdade do Gama, Universidade de Brasília – UnB, Brasília, DF, Brasil

^b Faculdade de Tecnologia - FT, Universidade de Brasília - UNB, Brasília, DF, Brasil

e-mails: rafaelkayquepeixoto@gmail.com; jonatas.ribeiro.mangabeiro@gmail.com; vivianegrubisic@unb.br

Abstract: In order to ensure the safety and high performance of an aircraft in flight, it is necessary to attest the operation of its multiple integrated subsystems. In this segment, the aircraft have several redundancies that allow their subsystems to continue operating, even with the failure of some of their components. Therefore, it is of great engineering interest to make sure a high level of reliability associated with the functioning of each of these subsystems. In this article, a reliability study of a complex system was approached, formed by the integration of the sets of engines and controls of a four-engine aircraft. To this end, through the implementation of mathematical and computational algorithms, the steps obtained involved calculating the reliability of an aircraft component, calculating the global the reliability of the global system under consideration, identifying the most critical components, studying the modes and effects of failure using the FMEA, and studying the root causes, carried out through of the FTA.

Keywords: reliability, criticality, failure analysis, complex system, four-engine aircraft.

1. Introduction

The study of reliability is historically the result of the need to compare airplanes concerning the number of accidents that occur per flight hour, as proposed by Knight (1991). Leemis (1995, p. 384) and Dias (2017, p. 1) both propose reliability as the probability of the item to adequately fulfill its specified purpose, for a certain period and under predetermined conditions, according to the product's design specifications. An increase in the reliability of a system is closely linked to a lower probability of failure of the system. Likewise, Fogliatto (2006) proposes that the greater the reliability required for a given item, the higher the level of quality of its manufacture must be. Thus, a company that has a strict policy of quality control of its manufacture, promotes greater acceptance by the market of its products.

An aircraft unit from a given manufacturer, for example, can operate under extreme environmental conditions, making many flights a day, which results in many takeoffs and landings a day. Another unit from the same manufacturer, on the other hand, can operate its flights under milder environmental conditions, traveling longer routes, and making fewer takeoffs and landings per day (Dodson, 2006). This high variability in the aircraft's operating boundary conditions requires that the aircraft have a high-reliability index associated

with its integrated subsystems. In this sense, research on reliability began to develop to become increasingly applicable in engineering systems projects that require high robustness as is the case in the aeronautical industry.

For reliability analysis, this article will address a set of critical subsystems of an aircraft model exposed by Pettit et al. (2001) and Lenz & Rhodin (2011). For this purpose, the numerical calculation will be used considering a computational environment developed in the Python computational language, to assist in obtaining results related to reliability measures, in addition to obtaining graphics to facilitate the interpretation of these results. Nevertheless, the implementation procedure for calculating the reliability estimate of the total system considered will be presented, based on the tie-set method. Birnbaum's Component Importance measure will also be calculated to guide the detection of critical components related to the aircraft subsystems pointed out. The study of the failure modes and effects of the system will be carried out through the analysis of the FMEA (Analysis of Failure Modes and Effects). The root causes will be studied by the FTA (Fault Tree Analysis), from the survey of a combination of events that characterize a possible potential failure of the system.

2. Reliability grounds

The reliability study is performed by implementing mathematical functions that model the behavior of random variables. For that, it is necessary to insert the concept of a random variable. According to Pinheiro et al. (2012), “random variable (v.a.) is a function that associates each element of a sample space with a real number”. Random variables can be discrete or continuous. In this work, the random variable considered is of the continuous type and expresses the aircraft’s operating time. In the reliability study, four functions are used to characterize the behavior of random variables:

- The probability density function, in this work symbolized by $f(t)$;
- The cumulative distribution function, in this work symbolized by $F(t)$;
- The reliability function, in this work symbolized by $R(t)$;
- The hazard function, in this work symbolized by $h(t)$.

From the calculation of one of them, the other variables can be derived by mathematical manipulation (Dodson, 2006).

For study, the measures of $R(t)$ and $F(t)$ will be used in this article. The reliability function or $R(t)$ expresses the unit’s probability of survival, considering a certain operating time “ t ”, which can be described in years, months, hours, cycles, etc. As $R(t)$ is a probability, the domain of the values obtained is comprised in the range between 0 and 1. The higher the item’s operating time value, the lower the associated $R(t)$ value tends to be, so that the values of $R(t)$ decrease from 1 to 0 as t increases. Mathematically, in the continuous domain, $R(t)$ is represented by Equation 1 as being the integral of the probability density function $f(t)$ (Dodson, 2006).

$$R(t) = \int_t^{\infty} f(t) dt \quad (1)$$

The cumulative probability function $F(t)$ is the complement of the reliability function $R(t)$, also known as the non-reliability function. Thus, $F(t)$ represents the probability of failure of the item that is in operation. Therefore, the same mathematical analyzes related to $R(t)$ can also be used for $F(t)$: the lower the t value, the lower the associated $F(t)$ value tends to be, showing values that start from 0 to 1, as t increases. In such a way, Dodson (2006) relates the two reliability measures through the mathematical expression represented by Equation 2 that can be expressed as:

$$F(t) + R(t) = 1 \quad (2)$$

whereas,

$$F(t) = \int_0^t f(t) dt \quad (3)$$

2.1. Components reliability estimation

Component reliability estimation is closely linked to the estimation of parameters of probability density functions. From a failure database (for example, time to failure data also called TTF) it is possible to implement reliability estimation models. The best-known models are (Dodson, 2006):

- Maximum likelihood estimation;
- Probability Plotting;
- Hazard plotting.

This work proposes to use maximum likelihood as a method for estimating reliability for engineering components (see section 4.2), due to its accuracy compared to the others.

2.2. Estimating systems reliability

Structural arrangements for an engineering system can be simple or complex. Fogliatto (2006) exposes methods used to determine the reliability of simple systems (pure series and pure parallel, combinations of series-parallel and k-in-n arrangements). Methods for calculating the reliability of complex systems are also presented by the author, which are: (i) decomposition method; (ii) tie set and cut set methods; (iii) Boolean table method; and (iv) reduction method. For the purpose of the study, this work proposes to use the tie set method to calculate the reliability of the total system considered (R_s).

2.3. Tie set method

The tie set method seeks to determine the total reliability of a complex system, using the following reasoning: it is necessary to identify the minimum operating paths that lead to the functioning of the system. These paths are called minimal tie sets. The reliability of a complex system, whatever it is, is given by the union of all the minimum tie set’s (Fogliatto, 2006).

2.4. Component importance measures

Rausand & Høyland (2003) demonstrates that the importance of a component depends on two factors: the location of the component in the system and the reliability of the component in question. Importance measures can be used as a method of detecting possible weaknesses in the system, making it possible to implement corrections and improvements in the product design or process analyzed. By identifying the critical components of the system, total

reliability may be improved by adding, for example, a highly reliable component, introducing redundant components into the system, improving component maintainability (Elsayed, 1996).

Four measures of importance are presented by Fogliatto (2006), namely: (i) Birnbaum's measure; (ii) Critical importance; (iii) Vesely-Fussell; and (iv) Potential for improvement. For the purpose of study, the present work proposes to use the Birnbaum measure.

2.5. Birnbaum importance measure

According to Birnbaum's Importance measure, the weakest component of a series arrangement is the most important. In this way, the least reliable component is identified as the most important. However, in a parallel system, the most reliable component is considered critical. For a complex system, the criticality analysis is done both in terms of the component's reliability and in terms of the position it occupies in the system (Fogliatto, 2006).

Rausand & Høyland (2003) presents mathematically through Equation 4 Birnbaum's measure of importance, in terms of the partial derivative of the total reliability of the system R_s at a time t , in relation to the partial derivative of component (represented by i) which is considered critical to the system.

$$I^B\left(\frac{i}{t}\right) = \frac{\partial R_s(r(t))}{\partial R_i(t)} \quad (4)$$

2.6. FMEA

The FMEA (Failure Mode and Effects Analysis) deals with a systematic method of failure analysis, carried out by a multidisciplinary team of specialist engineers. This analysis aims to (i) identify and analyze the modes and effects of failures that may arise in a product or process; indicate practical actions that: (ii) eliminate or reduce the chance of these failures occurring; (iii) that increase the chance of detecting failure modes; (iv) that reduce the severity of the failure effects; (v) in addition to allowing the registration of the study carried out, creating a technical reference that collaborates in future updates and creations of the product project (Fogliatto, 2006).

The present work presents the construction of the FMEA for the aircraft system considered in the section 4.5.

2.7. Failure Tree Analysis (FTA)

Smith (2001) proposes a definition for the Fault Tree or FTA as a graphical method that describes the combination of events in order to characterize the failure of a given system. The failure in the system is called the top event and its ramifications are the possible causes of its failure, where logical operators are employed to determine the propagation of the failure.

Such logical operators used are "AND" and "OR", where for the case of the "AND" operator all inputs need to occur for the output to occur, and for the "OR" operator, any input causes the exit occurs. Thus, Fogliatto (2006) states that the logical operator "AND" represents a system in parallel that is characterized by having a safer operating condition compared to a system arranged in a series configuration. According to the author, the logical operator "OR" represents the operating situation of a system in series, which corresponds to a less secure operation, since for the total system does not present failure each of its items needs to be successful in its operation. Birolini (2007) adds that the Failure Tree Analysis can be applied together with the FMEA in order to enhance the study, since the FTA helps to identify the logical relationships between the causes and their consequences.

3. Aircraft fundamentals

In this section, the aircraft system (object of the case study) will be presented, considering its engine and control subsystems, which make up the total system considered for calculating the reliability estimate.

3.1. Engine system

For analysis, the present work proposes a division of the aircraft engine system into four subsystems, which have their respective components. The subsystems considered are (i) engine; (ii) heating; and cooling, (iii) fuel system, and (iv) propeller. The divisions proposed by the present work of the aircraft engine and control systems in subsystems and components are in accordance with the aircraft model presented by Pettit et al. (2001).

For Pettit et al. (2001), the engine subsystem involves all components of the engine safe as well as the exhaust system. Also, according to the authors, the fuel subsystem of the aircraft includes the components that work intending to supply the adequate amount of fuel to the engines, in any operating regime and flight altitude. The fuel injection pump, despite being driven by the engine, is part of the fuel subsystem. However, the tank and fuel lines are also included in the latter. The aircraft heating and cooling subsystem encompasses all components responsible for the task of controlling the temperature and air flows in the cockpits and the passenger cabin. Finally, the propeller subsystem, likewise, includes components involved in converting the engine torque into thrust for the aircraft.

Through Birnbaum's Importance analysis, the fuel injection subsystem was detected as occupying the first place in the ranking of the aircraft's most critical components. The second most critical component of the aircraft's engine system is the heating and cooling subsystem (see subsection 4.4).

3.2. Control system

Likewise, Pettit et al. (2001), divide the control system into nine subsystems, which together are tasked with ensuring total control of the aircraft in the three axes (x, y, and z) of rotation during the flight. Specifically, directional control, longitudinal control, side control, flaps, stabilizers (also called compensators), hydraulic components (hydraulic circuit), landing gear, rudder, and, finally, the two wings of the aircraft are displayed. The working mechanisms of such components are not addressed in this text but are available in Pettit et al. (2001).

Through Birnbaum Importance analysis (see section 4.4), the stabilizers were detected occupying the first place in the ranking of the most critical components of the aircraft, considering the aircraft's control system. They have the role of facilitating the piloting of the aircraft and, in most planes, they help to maintain the direction of the aircraft in the three axes of rotation. The second most critical component of the aircraft's control system in question is the flaps.

3.3. Global function

In Figure 1, it is possible to observe the global function of the system and how each subsystem is related to each other. Analyzing from left to right, it is noted the presence of a complex system composed of four sets of engines (since it is a four-engine plane), followed by a series system responsible for the control of the aircraft.

In the complex system, the motor assemblies are connected by a cross link that creates redundancy in the system. This redundancy makes the entire system more

reliable due to the fact that no engine will fail due to the failure of another engine.

4. Results and discussion

In this section, a failure data randomization procedure for the Weibull probability distribution will be discussed. Right after this stage, the method of estimating reliability will be presented using the maximum likelihood model. The reliability data provided through a bibliographic survey will be used to calculate the reliability of the total system considered (R_s). This section will also present the calculation of Birnbaum's importance measure for the system components, as well as a failure analysis through the elaboration of the FMEA and FTA.

4.1. Failure data acquisition

In order to estimate the reliability of engineering components, data acquisition fails is necessary. This data can come from tests carried out on a bench or from field tests, or even from customer guarantee programs. However, the acquisition of these data may take time, as it depends on the degradation of the performance characteristics of the engineering components (Fogliatto, 2006). To solve this delay in obtaining failure information for engineering products, accelerated tests are widely used to demonstrate reliability. For the immersion in the theme of accelerated tests, the study of Nelson (2009) is recommended.

For didactic purposes, to demonstrate the procedure for estimating the reliability of engineering components, a

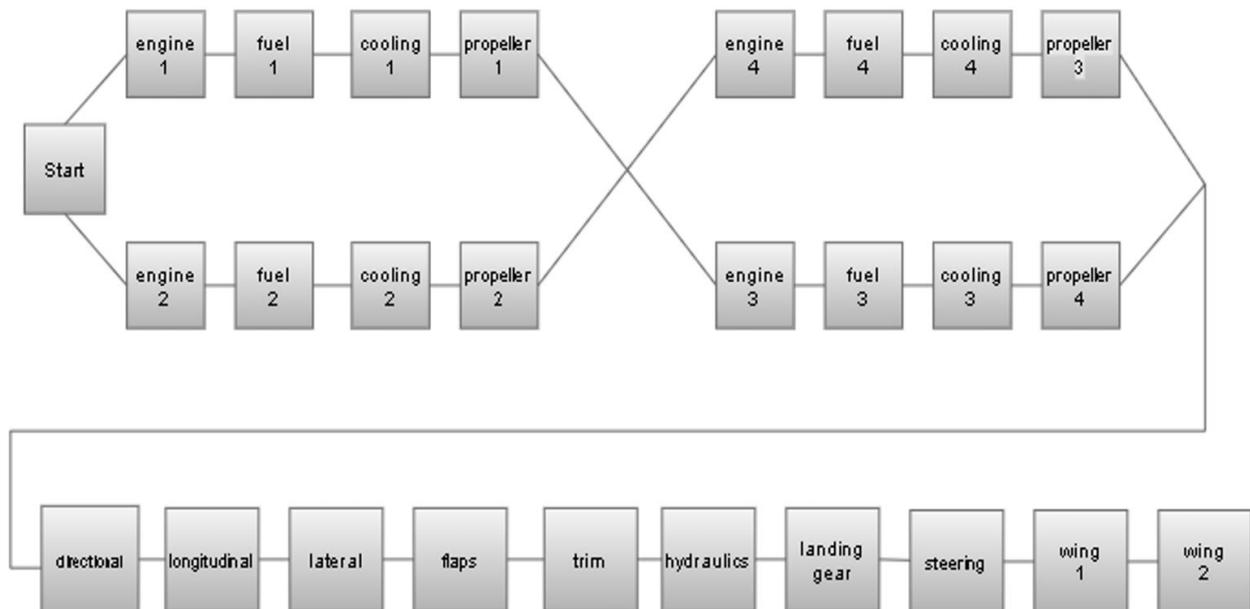


Figure 1. Global aircraft system function.

technique of randomization of time to failure (TTF) data is very promising.

4.1.1. Failure data randomization

Dodson (2006) explores a technique for randomizing failure data (also called Time to Fail - TTF) related to the Weibull probability distribution. This technique is connected with the method of estimating reliability with maximum likelihood. This distribution is also used to obtain the reliability values of the aircraft system (Table 1) proposed by Pettit et al. (2001) and also by Lenz & Rhodin (2011). The Weibull distribution scale and shape parameters are represented in Equation 5 by theta (θ) and beta (β), respectively. Weibull's distribution is widely recognized for its flexibility, as it can adapt to different types of probability distribution as the β changes. The alternation of the θ is responsible for changing the variance of the distribution format.

In this work, the method of randomization of time-to-failure data was computationally implemented using the python language to create a numerical solution algorithm for the mathematical Equation 5. The term ρ in this equation refers to random values in the interval between zero and one originating from the Python *math* library, using the command *random.random()*.

$$TTF's = \theta [-\ln(1 - \rho)]^{1/\beta} \quad (5)$$

It is possible to note in the equation that the randomized TTF values are closely related to specific values of β and θ . It means to say that at the end of the implementation of the maximum likelihood reliability estimation model (section 4.2), these same theta and beta values (which are values that identify the Weibull distribution behavior) need to be obtained, as a method of validating the calculation. Lenz & Rhodin (2011) in their work display values for β and θ (Table 1) inherent to each component of the aircraft system, the object of the case study of the present work.

These values will be used as a parameter to verify the convergence of the numerical solution proposed in this work for Equation 6 and Equation 7.

Dodson (2006) draws attention to the fact that alternating the sample size is closely linked to alternating the error of the result. To examine the convergence of the result to the beta and theta values proposed by Lenz & Rhodin (2011) as the sample size changes, the present study randomized the failure data to three different planes (A, B and C) that will be used in the method of maximum likelihood in order to estimate the reliability of a specific component, each plan with its respective sample size. Therefore, by means of a random choice, the aircraft flaps were chosen as a component to have their reliability estimated. TTF values for plans A, B and C express flight hours and can be seen in Tables 2, 3 and 4.

4.2. Reliability estimation using the maximum likelihood method

The maximum likelihood method is known to be the most accurate mathematical model for estimating reliability (Dodson, 2006). Iteration techniques are necessary to solve the expressions of the maximum likelihood model. This study proposes a numerical solution using the bisection mathematical model for iterations. An error of 10^{-4} was also established as a stopping method for these iterations, as well as a 95% confidence in the estimate result. The interval [0.0001, 10] was defined as the scope of analysis so that the root of Equation 6 could be found. The maximum likelihood equations for the Weibull distribution for two parameters β and θ are shown below:

$$\frac{1}{r} \sum_{i=1}^r \ln(t_i) = \left[\sum_{i=1}^n t_i^\beta \ln(t_i) \right] \left[\sum_{i=1}^n t_i^\beta \right]^{-1} - \frac{1}{\beta} \quad (6)$$

$$\theta = \left[\frac{1}{r} \sum_{i=1}^n t_i^\beta \right]^{1/\beta} \quad (7)$$

Table 1. Weibull probability density function parameters proposed by Lenz & Rhodin (2011).

Component	β	θ	$R(\theta)$
motor	1.58	4830	0.99997436
fuel	1.44	5130	0.99994005
cooling	1.60	4190	0.99997182
propeller	1.63	3740	0.99997219
directional	1.85	4729.02	0.9999956
longitudinal	1.57	4718.22	0.9999716
lateral	2.25	5843.58	0.9999998
flaps	0.95	3956	0.9979040
trim	0.73	2672.1	0.9884144
hydraulics	1.14	3977.39	0.9993927
landing gear	0.92	2895.62	0.9966088
steering	1.65	3994.78	0.9999780
wing	1.79	4250	0.9999208

Table 2. Randomization of flap failure data, for n = 15.

Plan A		
303	304	1891
1404	8819	645
524	277	2366
22372	314	4172
1593	16511	1552

Table 3. Randomization of flap failure data, for n = 25.

Plan B				
5566	5663	5389	5347	4519
1271	84	665	2032	2965
166	6698	9386	3899	1642
109	2155	2037	627	1614
1057	14	12921	2755	1956

Table 4. Randomization of flap failure data, for n = 40.

Plan C				
1561	662	875	2288	6229
2834	55	192	3804	20734
2456	4971	15764	1672	3179
410	4723	4842	5721	3961
1011	2133	11177	447	3455
4227	990	35	3860	5060
8701	3492	3382	3876	8481
483	615	4612	1549	6411

Table 5. Results of β and θ estimation using the maximum likelihood method.

Plan	n	β	θ
A	15	0.70	3178
B	25	0.90	3088
C	40	0.97	3974

The indices r and n express the uncensored amount and the total amount of failure data, respectively. Fogliatto's (2006) study is recommended for greater immersion in the subject of data censorship. The index t refers to the time of operation of the aircraft in the case study, with t being a continuous random variable. The result of the β and θ estimate can be seen in Table 5.

4.3. Calculation of the reliability of the system (R_s)

Based on the reliability data of the aircraft components shown by Pettit et al. (2001) and also by Lenz & Rhodin (2011), it is possible to calculate the total reliability of the system (R_s). For calculation purposes, the complex system formed by the integration of the engine and control systems of the presented aircraft was considered. The data used for the calculation of R_s are shown in Table 1, where t represents a mission time equivalent to six (6) hours of flight.

Parameters of the Weibull probability density function associated with failure data for the components of the aircraft engine and control assemblies were provided by Lenz

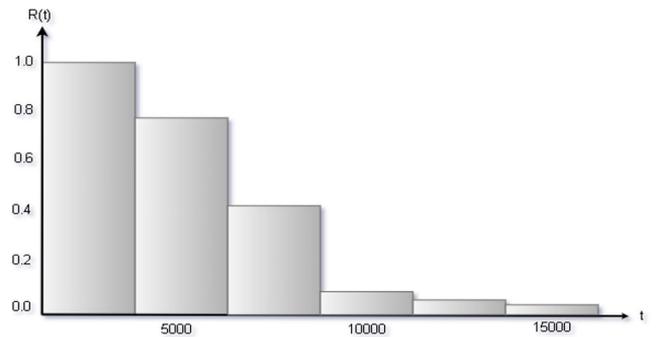


Figure 2. Bar graph of $R(t)$ of the aircraft trim.

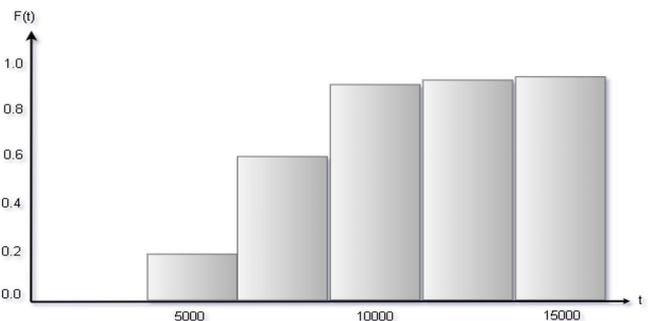


Figure 3. Bar graph of $F(t)$ of the aircraft trim.

& Rhodin (2011), where θ and β represent, respectively, the scale and shape parameters of this function (Table 1). These data were used as input in the *Proconf* software to obtain the graphics associated with the reliability measures, shown by Figure 2 and Figure 3. For simplification, only the stabilizer component, proper to the aircraft's control system, was considered for the graphical demonstration of the measures of $F(t)$ and $R(t)$.

A simplification of the total aircraft system was proposed, in view of Figure 1. to facilitate the calculation demonstration for R_s . This simplification shows the association of components related to the aircraft engine system, as shown by Equation 8, with m being subsystems A, B, C, and D, whose numerical identification n is 1, 2, 3, and 4 respectively.

$$R_m = (R_{motor\ n}) \times (R_{fuel\ n}) \times (R_{A\&R\ n}) \times (R_{propeller\ n}) \quad (8)$$

Therefore, by making the products, the following results are obtained:

$$R_A = R_B = R_C = R_D = R = 0.9998584$$

Also, in order to facilitate the calculation of R_s , the set of components of the aircraft's control system was related to a single subsystem E, shown by Equation 9.

$$R_E = (R_{directional}) \times (R_{longitudinal}) \times (R_{lateral}) \times (R_{flaps}) \times (R_{trim}) \times (R_{hydraulic}) \times (R_{landing\ Gear}) \times (R_{steering}) \times (R_{wing\ 1}) \times (R_{wing\ 2}) \quad (9)$$

In this way,

$$R_E = 0.9821912$$

As specified in section 2.3, for the calculation of the estimate of Rs, the tie set method will be used. For that, the minimum tie set's obtained are:

$$T1 = path[ABE]$$

$$T2 = path[ADE]$$

$$T3 = path[CDE]$$

$$T4 = path[CBE]$$

Performing the due calculation for the union of the four events associated with the minimum tie sets's the mathematical expression displayed by Equation 10 is obtained. By replacing the reliability values corresponding to each of the subsystems A, B, C, D and E, the reliability of the total system (Rs) can be obtained.

$$R_s = 4(R^2 R_E) - 4(R^3 R_E) + (R^4 R_E) \quad (10)$$

Soon,

$$R_s = 0.9821912$$

4.4. Calculation of the Birnbaum Importance measure

As specified in section 2.5, in order to detect the critical components of the system, the Birnbaum Importance measure was adopted.

When applying Equation 4, assuming $i = A$, it is obtained:

$$I^B(A/t) = 2(RR_E) - 3(R^2 R_E) + (R^3 R_E) \quad (11)$$

Since $R_A = R_B = R_C = R_D$,

Soon,

$$I^B(A/t) = I^B(B/t) = I^B(C/t) = I^B(D/t) = 1,390627649 \times 10^{-4}$$

Likewise, when applying Equation 4, assuming $i = E$, it is possible to state that:

$$I^B(E/t) = 4R^2 - 4R^3 + R^4 \quad (12)$$

From Equation 12 the following result is obtained:

$$I^B(E/t) = 0.999999959$$

In this way,

$$I^B(A,B,C,D/t) < I^B(E/t)$$

Analyzing the results obtained from Equation 11 and Equation 12, it is possible to verify that the importance of components A, B, C and D is the same (considering only their reliability values, since these values are equal). In this

context, only the position of the components in the system defines their importance (Fogliatto, 2006). Therefore, components C and D, for which there is no alternative path, are the most important (see Figure 1). The components that offer an alternative path for the others in case A and B (as they serve as a connecting bridge for C, D, and E) follow the ranking of importance, as shown in Table 6.

When considering the aircraft's control system, structured in pure series (simplified reduced to component E), it is known that the weakest (least reliable) component of a series arrangement is the most important (Fogliatto, 2006). In this sense, the Trim is considered the critical component of the aircraft's control system, since its reliability value is the lowest compared to the others. By attributing the same reasoning to the pure series fragment of the engine system (considering A, B, C and D), involving the engine, fuel, ventilation and heating components and, finally, the propeller, it is possible to verify that the item less reliable analyzed is the fuel (in its entirety it represents the system responsible for the fuel injection), being considered, therefore, the most critical component of the aircraft engine system.

4.5. FMEA

Through brainstorming, the FMEA analysis was performed as shown in Figure 4. As an explanation of the FMEA, the most important line is the one with the highest Risk Priority Number (NPR). This means that the stabilizing component is the most critical among those analyzed, whose NPR is equal to 72. For analysis purposes, the criteria used to calculate the NPR are: (i) probability of failure occurring; (ii) possibility of detecting the failure mode and (iii) degree of severity of the failure effect (Fogliatto, 2006).

For the calculation of the failure occurrence index, the probability of failure of each analyzed aircraft component was taken into account. In this sense, Fogliatto (2006) presents a suggestion of a quantitative evaluation criterion based on the failure rate of the analyzed item, in order to determine the classification in which it fits. The author also presents a suggestion of a qualitative criterion for the failure detection level and for the severity of the failure, which was also adopted in this present work.

4.6. FTA

According to the criticality results obtained from the Birnbaum Importance measure and FMEA study (see

Table 6. Birnbaum Importance Ranking.

Component	Birnbaum ranking
C	1°
D	1°
A	2°
B	2°

Function	Failure mode	Effect	Severity	Cause	Occurrence	Design controls	Detection controls	Detection	RPN	Recommended actions
trim - decrease physical strength in the airplane control and assist the balancing of airplane	Loss of direction control	Destabilization	9	Leakage of hydraulic fluid	8	Electronic pressure monitoring	Visual inspection of the cab instrumentation	1	72	Preventive maintenance of the system according to the manufacturer's manual
			10	Low pressure in the hydraulic circuit	7	Pressure ducts analysis	Electronic monitoring of the forward and backward flaps	1	70	Preventive maintenance of the system according to the manufacturer's manual
flaps - increase wing lift and drag by changing its shape	Loss of lift and drag	Airplane crash due to stall	10	Failure in the electric actuators	7	Monitoring the voltage level of the actuators		1	70	Preventive maintenance of the system according to the manufacturer's manual
			9	Contaminated fuel	7	Use of certified fuel	Laboratory analysis	1	63	Fuel analysis or certification
Fuel injection system - injection of fuel inside the combustion chamber.	Loss of efficiency in the fuel injection process	High fuel consumption	9	Contaminated fuel	7			1	63	Fuel analysis or certification
			9	Power loss	7			1	63	Fuel analysis or certification
cooling - change the temperature inside the airplane	Air-conditioning doesn't change the temperature	Discomfort for passengers Leakage of refrigerant gas from the pipe	5	Compressor failure	7	Maintenance inspection	Meter at the compressor ducts	1	35	Preventive maintenance of the system according to the manufacturer's manual
			9	Wear of pipe seals	7	Pressure monitoring		1	63	Keep the system running

Figure 4. FMEA analysis of critical aircraft components.

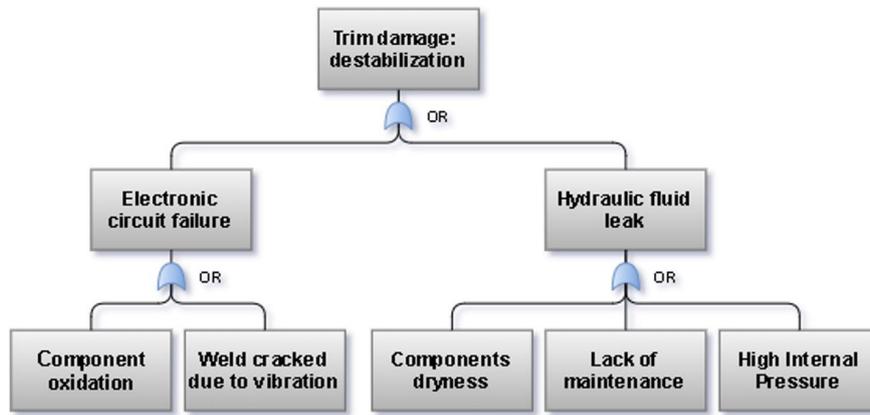


Figure 5. FTA for aircraft trim.

sections 4.4 and 4.5), to simplifying the demonstration, the FTA study was implemented only for the aircraft trim component, as shown in Figure 5.

Starting from the top event ‘Trim damage: destabilization’, two intermediate failures were raised as critical: (i) electronic circuit failure or (ii) hydraulic fluid leak. The first failure is subject to two possible independent root causes, in which the occurrence of only one of these causes the failure of the intermediate event and consequently the failure of the top event. The second intermediate failure, on the other hand, is characterized by three other independent root failures that follow the same reasoning exposed above.

5. Conclusion

The paper sought to present a model for the reliability of a complex system formed by the integration of the control and engine systems of an aircraft model proposed by Pettit et al. (2001). Weibull’s probability density function was chosen to be implemented in the mathematical algorithm presented due to its flexibility in adapting to other probability distributions as its shape and scale parameters are changed. This allows extending this reliability modeling to several other failure modes of different components and systems. The maximum likelihood method is more accurate in obtaining the estimate of Weibull distribution parameters when compared to other models available in the literature, being chosen for this reason. This work also presented a model of failure data randomization as an important method of verifying the computational modeling of the reliability that had been built.

The reliability values for the aircraft components used in the modeling, as well as the representation of the complex system, are the results of a bibliographic survey. From the knowledge of the reliability and the position occupied by each component in the system, the criticality of the analyzed items (illustrated by A, B, C, and D) could be measured. This monitoring of the components considered critical may favor the efficient execution of a maintenance program,

as well as an improvement project for the system. To this end, Birnbaum’s measure of importance was explored allowing the numerical mapping of the criticality level of each subsystem considered. Once the sets of components most relevant to the system were weighed, this diagnosis could be even more representative when it was implemented separately for each component through a systemic analysis of the failures presented. At this stage, it is possible to characterize each failure through the analysis of the FMEA, and its logical propagation can be determined through the analysis of the FTA, where it becomes plausible to recommend actions to control and detect the failure under study, as well as to know which it is its root cause, thus promoting the practice of continuous improvement on the studied system.

For failure analysis from the FMEA, the most relevant components of the system were considered, they are stabilizer, flaps, fuel injection system, and heating and cooling system. The failure analyzed in each specified component was divided into three instances: mode, cause, and effect. The measurement of the priority level of each failure was calculated using the RPN (Risk Priority Number) through a qualitative analysis proposed by Fogliatto (2006), where it was inferred that the trim presented itself as the primary item to receive intervention from preventive maintenance.

For FTA analysis, the trim component was used to demonstrate that the propagation of the failure may be a result of several other failures that have occurred previously, and that can logically connect. Through an in-depth analysis of the FTA it becomes possible to know the root cause of the observed effect, which allows for a timely and effective correction, reducing the possibility of recurrence of the problem. The root cause found for the effect of destabilization may assume one of the following possibilities: (i) oxidation of components; (ii) breakage of the weld due to excessive vibrations; (iii) dryness of

material, high internal pressure in the system; (iv) and failure in periodic maintenance.

6. References

- Birolini, A. (2007). *Reliability engineering: theory and practice* (5th ed., pp. 72). Berlin: Springer.
- Dias, A. (2017). Design for reliability: an application to natural gas pipelines. *Product: Management & Development*, 1(2), 39-50.
- Dodson, H. S. B. (2006). *Accelerated testing: a practitioner's guide to accelerated and reliability testing* (pp. 19). Warrendale: SAE Internacional.
- Elsayed, E. A. (1996). *Reliability engineering*. New York: Prentice-Hall.
- Fogliatto, J. R. F. (2006). *Confiabilidade e manutenção industrial* (pp. 87-96). Rio de Janeiro: Elsevier.
- Knight, C. R. (1991). Four decades of reliability progress. In *Proceedings of the Annual Reliability and Maintainability Symposium* (pp. 156-159). Piscataway: IEEE Reliability Society.
- Leemis, L. (1995). *Reliability: probabilistic models and statistical methods* (pp. 384). New York: Prentice-Hall.
- Lenz, M., & Rhodin, J. (2011). *Reliability calculations for complex systems* (pp. 44). Semantic Scholar.
- Nelson, W. B. (2009). *Accelerated testing: statistical models, test plans, and data analysis*. New York: John Wiley & Sons.
- Pettit, D., and A. Turnbull. General Aviation Aircraft Reliability Study (pp. 24-27). Inc., Hampton, Virginia (2001).
- Pinheiro, J. I. D., Ramírez Carvajal, S. S., Cunha, S. B., & Gomes, G. C. (2012). *Probabilidade e estatística: quantificando a incerteza* (pp. 150). Rio de Janeiro: Elsevier.
- Rausand, M., & Høyland, A. (2003). *System reliability theory: models, statistical methods, and applications* (2nd ed., pp. 183-193). New York: John Wiley.
- Smith, D. J. (2001). *Reliability, maintainability, and risk: practical methods for engineers* (6th ed., pp. 118). Boston: Butterworth-Heinemann.