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A NEW AIRCRAFT MAINTENANCE APPROACH BASED ON THE MARKOV CHAINS

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Rezumat. *În trecut, călătoria cu avionul era un lux, astăzi este una dintre cele mai dorite opțiuni de transport din lume, fiind în același timp accesibilă și sigură. În industria aviației contemporane, ca o companie aeriană să rămână competitivă, înseamnă să desfășoare cât mai multe activități aeronautice posibil, fără niciun incident. Problemele tehnice joacă un rol semnificativ în stabilirea cauzelor care stau la baza eficienței unei aeronave. Având în vedere complexitatea sistemelor implicate, întreținerea poate fi dificilă fără un sistem de monitorizare a sănătății aeronavelor în timp.Acest studiu își propune să furnizeze o metodologie pentru identificarea timpurie a defecțiunilor unei aeronave, pentru a asigura o întreținere predictivă specifică.Pe parcursul celor 12 luni, au fost monitorizate două sisteme critice aparținând unei aeronave de transport și, cu ajutorul modelului lanțurilor Markov, a fost calculată probabilitatea ca aceste sisteme să cedeze în viitorul previzibil.*

Abstract. *In the past, traveling by plane was a luxury, today it is one of the most desired transport options in the world, being at the same time accessible and safe. In the contemporary aviation industry, for an airline to remain competitive, means to carry out as many aeronautical activities as possible without any incidents. Technical problems play a significant role in establishing the root causes underlying the efficiency of an aircraft. Considering the systems complexity involved, maintenance can be difficult without an aircraft health monitoring system over time. This study aims to provide a methodology for early identification of an aircraft failures, in order to provide specific predictive maintenance. Over the 12 months, two critical systems belonging to a transport aircraft were monitored and with the help of the Markov chains model, the probability of those systems to fail in the foreseeable future was calculated.*

Keywords: Reliability, Markov chains, Aircraft Maintenance, Predictive Maintenance

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1. Introduction

Any company that manages technical equipment that requires regular maintenance aims to operate it at the lowest possible cost and downtime. Sometimes, the goal of being as productive as possible, leads to a neglection of the maintenance activities.

Therefore, maintenance must include the full range of preventive activities necessary to maintain a technical system according to manufacturer's references.

On paper, things seem to be quite simple, but the real challenge comes when you need to take into consideration the profitability of a company which must organize its maintenance at a lowest cost.

In the aviation industry, airlines strive to remain competitive and profitable, because safety must be central point of their actions.

The complexity of aeronautical systems combined with the need for operational safety, involves special measures to monitor the technical condition of an aircraft.

Establishing a maintenance strategy varies depending on the specifics of each company, so the study of maintenance types is a starting point for any company that manages technical equipment within their business.

2. Current context

A study conducted by a US institution suggests that there are significant delays in the airline industry. In 2019 the study reveals that 21% of all flights were delayed by at least 15 minutes and 1.9% of all scheduled flights were cancelled.[1] These delays have directly affected airlines' budgets.

An overall picture captured in 2018 by IATA's Maintenance Cost Technical Group reflects a total aircraft maintenance cost (MRO) of $ 69 billion, considering a global fleet of 27,535 aircrafts. The distribution of maintenance by components can be seen in Figure 1. In addition, studies show that in 2028, total maintenance costs will reach $ 103 billion.

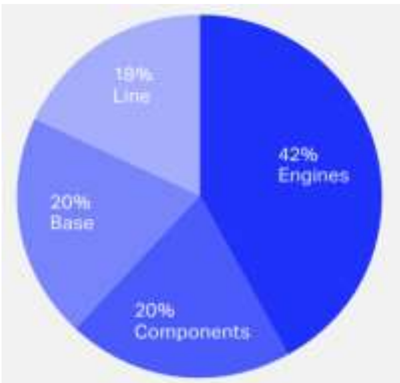

Fig. 1. MRO distribution, spend in 2018 worldwide [2]

Unplanned downtime due to unplanned maintenance is costing airlines between $ 120k and $ 300k per aircraft each year. For an airline operating 500 aircrafts, this cost means between 60M-150M USD per fleet, depending on the type of aircraft, without taking into account the unpleasant experience caused to customers. If a flight is canceled or delayed for more than three hours, the financial compensation paid by the airlines is between $ 200 and $ 700 per passenger.

3. A short insight of an aircraft's maintenance types

Regardless of the technical system approached, maintenance can be divided into three main categories [3]:

3.1. Reactive Maintenance

This approach involves the use of equipment without any maintenance activity until a failure occurs. In the case of new equipment, it can be estimated that in the first part of the operating cycle there will be very few defects which, in the short term, means low costs. In reality, the subsequent costs associated with restoring equipment may be much higher than if certain preventive maintenance activities had been carried out.[4]

In the aviation industry, this type of maintenance is not an option due to the implications, both in terms of passenger safety and in terms of extremely high repairing costs.

3.2. Preventive Maintenance

Preventive maintenance is the most common activity in aircraft maintenance and involves a series of actions performed in advance to extend the lifespan of an equipment by maintaining the level of degradation at an acceptable value.

A preventive maintenance approach involves planning regular cleaning activities, replacement of perishable items, visual inspections, etc. Preventive maintenance, as the word "preventive" suggests, does not appear in response to an inadequate mode of operation of the technical system, but aims to prevent a malfunction.

This type of maintenance increases the lifespan of a technical equipment and significantly reduces the number of failures, which leads to increased productivity and lower repairing costs.

On the other hand, the establishment of preventive maintenance intervals is done on the basis of statistical data, most often recommended by the manufacturer. This shows that sometimes certain maintenance activities are performed without being necessary at that time in the life of the equipment. Therefore, it can be said that the future of maintenance is based on the development of predictability techniques.[5].

3.3. Predictive Maintenance

Predictive maintenance is the most desirable alternative because it involves taking maximum advantages of an aircraft. From an economic point of view, it is the best option if the data collected from an aircraft accurately reflects how and when it will fail. Unfortunately, technology has not reached such a high level that a perfectly accurate prediction can be made.

To prevent a malfunction, predictive maintenance requires thorough monitoring of the degradation process of the technical system and, because of information collected, specific maintenance. The challenge arises in monitoring and evaluating the state of degradation of the technical system, so the way the data is collected and analyzed makes the difference in achieving a predictive maintenance program.

Many manufacturers understood the importance of predictive maintenance and radically changed the design of new products. Specifically, the products have been equipped with a wide range of sensors for a better understanding of how they behave in operation.

4. Predictive maintenance using Markov’s chains

The Markov technique is a statistical model that involves a probabilistic estimation of a future action, given the current state of a variable. Once the probabilities of future actions in each state are defined, a graph of states can be made, which by analogy can be resembled to a tree, due to the branches that form.

The Markov chain, named after the Russian mathematician Andrey Andreevich Markov, describes a process whose future state is not influenced by the past, but only by the current state. It retains the entire past evolution of the process.

Markov analysis is a stochastic process that evolves in a probabilistic way. The method is widely applicable, especially in the business world, where companies use it to forecast customer behavior. It can also be applied in the maintenance activity to estimate the probability of aircraft’s components failures.

Therefore, according to Markov's theory, the probability that an event will occur, given the last "n" previous events, is approximately equal to the probability that that event will occur given the last event:

$$\Pr(ev_t \mid ev_{t-1}, ev_2 \ldots, ev_n) \approx \Pr(ev_t \mid ev_{t-1}) \qquad (1)$$

In the aviation industry, this type of maintenance is not an option due to the implications, both in terms of passenger safety and in terms of extremely high repairing costs.

A Markov matrix, also known as a stochastic matrix, is used to represent the steps in a Markov chain. Each element in the matrix represents the probability that an event will occur. Specific to this type of matrix is the fact that the sum of the probabilities on any row is equal to 1. [6]

$$P = \begin{bmatrix} P_{11} & P_{12} & > & P_{1(n-1)} & P_{1n} \\ P_{21} & P_{22} & & P_{2(n-1)} & P_{2n} \\ \vdots & & \ddots & \vdots & \\ P_{(n-1)1} & P_{(n-1)2} & > & P_{(n-1)(n-1)} & P_{(n-1)n} \\ P_{n1} & P_{n2} & & P_{n(n-1)} & P_{nn} \end{bmatrix} \tag{2}$$

The Markov matrix provides a clear picture of the probabilities of transition from one state to another. That is why it is also called transition matrix.

Therefore, Pij is the transition probability of the analyzed system during the time interval Δt, to move from state "i" to state "j", where:

$$0 \leq Pij \leq 1. \tag{3}$$

A Markov chain is fully defined only after the determination of the initial moment, which is known as the vector of the initial state (V^0).

$$V^0 = (V_1^0, V_2^0, \ldots V_i^0 \ldots V_n^0); \tag{4}$$

V_i^0 – the probability that the system is in the "i" state at the initial moment (t_0).

The probability that the system is in one of the "n" states, after "m" iterations is described by the following syntax:

$$V^0 \cdot P^m = V^0 \cdot \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1(n-1)} & P_{1n} \\ P_{21} & P_{22} & & P_{2(n-1)} & P_{2n} \\ \vdots & & \ddots & \vdots & \\ P_{(n-1)1} & P_{(n-1)2} & \cdots & P_{(n-1)(n-1)} & P_{(n-1)n} \\ P_{n1} & P_{n2} & & P_{n(n-1)} & P_{nn} \end{bmatrix}^m \tag{5}$$

For a better understanding we assume the following situation:

Given a component of a system that can be in two states A and Z:

The probability of transition of the component from state A to state Z derive from the analysis of the system in a determined period and vice versa.[7]

Note:

x – probability of moving from state „A" to state „Z"

y – probability of moving from state „Z" to state „A"

The following graphic representation results:

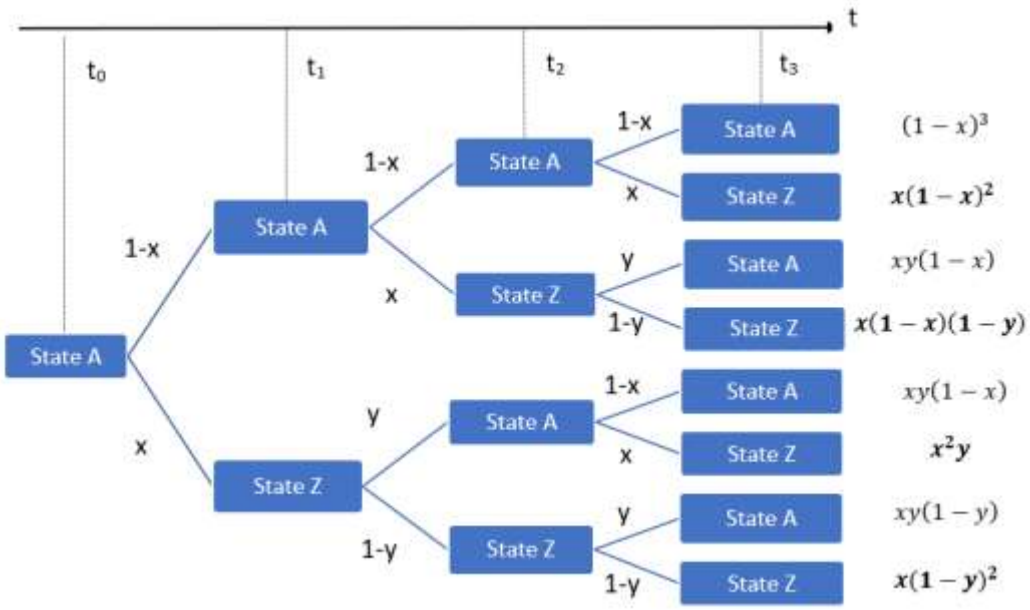

Fig. 2. Graphic representation of Markov chain

The probability of the system to be in the state „A” at the time t_3 is:

$$P_A = (1-x)^3 + 2xy(1-x) + xy(1-y) \tag{6}$$

The probability of the system to be in the state „Z” at the time t_3 is:

$$P_Z = x(1-x)^2 + x(1-y)(1-x) + x^2y + x(1-y)^2 \tag{7}$$

Applying the generalized formula for n states and m iterations results in the same probabilities. So the probability that the system is in one of the "n" (n = 2) states, after "m" (m = 3) iterations according to Markov's theory is:

$$V^0 \cdot P^3 = [1 \quad 0] \begin{bmatrix} 1-x & y \\ x & 1-y \end{bmatrix}^3 = [P_A\, P_Z]; \tag{8}$$

Where:

- $[1 \quad 0]$ - is the vector of the initial state. Being in state A, the first element of the vector is 1 and the second 0.
- $\begin{bmatrix} 1-x & y \\ x & 1-y \end{bmatrix}$ - is the transition matrix for the two states.

That being said, the condition of an aircraft or system can be estimated using the Markov chain technique, as follows:
Further, we assume that an aircraft has "n" systems and "m" states:
According to the role of the components and with the minimum equipment list instructions, some conditions in Table 1 may be accepted for flight while others

may not be accepted. There are situations in which an aircraft may be able to fly with inoperative systems, by applying the principle of delayed maintenance. A state with one or more inoperative systems can be acceptable. Each system can be "functional" or "failed", as it is presented in the following table:

Tabel 1. Aircraft's possible states

State	*System 1*	*System 2*	...	*System n*
1	Functional	Functional	…	Functional
2	Failed	Functional	…	Functional
⋮	⋮	⋮	⋮	⋮
m-1	Functional	Failed	…	Failed
m	Failed	Failed	…	Failed

To simplify the calculation we analyzed only two systems:
A - the hydraulic system of an aircraft
B – the fuel system of the same aircraft

Tabel 2. Aircraft's possible states with two systems

State number	*System A*	*System B*	*Aircraft's possible state*
1	Functional	Functional	Functional
2	Failed	Failed	Failed
3	Functional	Failed	Failed
4	Failed	Functional	Failed

Tabel 3. Aircraft's probability to fail and be repaired

	The probability that the system will fail during one Δt:	*The probability that the system will NOT fail during one Δt:*
A	0,1	0,9
B	0,08	0,92
	The probability that the system will be repaired during the same Δt:	*The probability that the system will NOT be repaired during the same Δt:*
A	0,3	0,7
B	0,35	0,65

The probabilities presented in Table 3 were calculated based on the data resulted from the operation of the fuel and hydraulic systems that served a transport aircraft, for the last **12 months**. They are only used to highlight a calculation methodology.
In a real case scenario, these probabilities are calculated using the basic statistical formulas applied to the data generated by the aircraft in a previous period.
Further, applying Markov's technique, the following expression results:

$$V^0 \cdot \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \\ P_{41} & P_{42} & P_{43} & P_{44} \end{bmatrix}^m \quad (9)$$

P_{ij} is the transition probability of the aircraft during the time interval Δt, to move from state "i" to state "j". It is calculated according to the probabilities in Table 3.

$$\begin{array}{ll} P_{11} = 0{,}9 \cdot 0{,}92 = 0{,}828 & P_{21} = 0{,}3 \cdot 0{,}35 = 0{,}105 \\ P_{12} = 0{,}1 \cdot 0{,}08 = 0{,}008 & P_{22} = 0{,}7 \cdot 0{,}65 = 0{,}455 \\ P_{13} = 0{,}9 \cdot 0{,}08 = 0{,}072 & P_{23} = 0{,}3 \cdot 0{,}65 = 0{,}195 \\ P_{14} = 0{,}1 \cdot 0{,}92 = 0{,}092 & P_{24} = 0{,}7 \cdot 0{,}35 = 0{,}245 \end{array} \quad (10)$$

$$\begin{array}{ll} P_{31} = 0{,}9 \cdot 0{,}35 = 0{,}315 & P_{41} = 0{,}3 \cdot 0{,}92 = 0{,}276 \\ P_{32} = 0{,}1 \cdot 0{,}65 = 0{,}065 & P_{42} = 0{,}7 \cdot 0{,}08 = 0{,}056 \\ P_{33} = 0{,}9 \cdot 0{,}65 = 0{,}585 & P_{43} = 0{,}3 \cdot 0{,}08 = 0{,}024 \\ P_{34} = 0{,}1 \cdot 0{,}3 = 0{,}03 & P_{44} = 0{,}7 \cdot 0{,}92 = 0{,}644 \end{array} \quad (11)$$

The probability that the aircraft to move from state „1" to state „1", during one iteration is:

$$P_{11} = 0{,}828. \quad (12)$$

The probability that the aircraft to move from state „1" to state „2", during one iteration is:

$$P_{12} = 0{,}008. \quad (13)$$

The probability that the aircraft to move from state „4" to state „4", during one iteration is:

$$P_{44} = 0{,}644. \quad (14)$$

The vector of the initial state is [1 0 0 0], given the fact that the aircraft is perfectly functional at the initial moment, which is state 1.

The probability of the aircraft to be in one of the four states, after 3 iterations (3xΔt) according to Markov's theory is:

$$[1 \quad 0 \quad 0 \quad 0] \cdot \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} \\ P_{21} & P_{22} & P_{23} & P_{24} \\ P_{31} & P_{32} & P_{33} & P_{34} \\ P_{41} & P_{42} & P_{43} & P_{44} \end{bmatrix}^3 = \tag{15}$$

$$= [1 \quad 0 \quad 0 \quad 0] \cdot \begin{bmatrix} 0.682 & 0.030 & 0.122 & 0.166 \\ 0.390 & 0.139 & 0.198 & 0.272 \\ 0.530 & 0.066 & 0.270 & 0.124 \\ 0.499 & 0.062 & 0.089 & 0.349 \end{bmatrix} = \tag{16}$$

$$= [0.682 \quad 0.03 \quad 0.122 \quad 0.166] \tag{17}$$

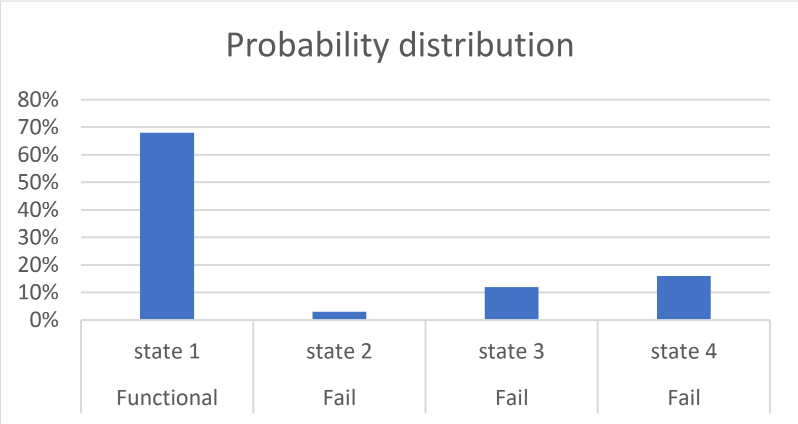

Fig. 3. Aircraft's states probability distribution after three iterations

Conclusions

Identifying the critical components is a first step in developing a maintenance plan in accordance with system's degradation. Following the application of Markov's methodology, a vector of "n" states resulted. Each vector element represents the probability that the aircraft will be in a certain state after a certain time interval. The technical condition of an aircraft and its airworthiness can be estimated using Markov's methodology based on the operating parameters recorded in the past. In the current context, only four possible states of an aircraft were identified because, only two installations were considered. Being two critical installations, a single state was acceptable for flight. Thus, the probability that the aircraft to be effective (state 1) after three iterations is 68%, while the probability of failure (state 2,3,4) during the same interval is 3%,12% or 16%.

This methodology can be extrapolated to all aircraft systems so that airlines can estimate not only the overall condition of the aircraft but also the system that will fail.

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