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OPTIMAL REPLACEMENT POLICY OF JET ENGINE MODULES FROM THE AIRCARRIER'S POINT OF VIEW

ABSTRACT

A mathematical model for optimising preventive maintenance of aircraft jet engine was developed by dynamic programming. Replacement planning for jet engine modules is regarded as a multistage decision process, while optimum module replacement is considered as a problem of equipment replacement. The goal of the optimal replacement policy of jet engine modules is a defined series of decisions resulting in minimum maintenance costs. The model was programmed in C++ programming language and tested by using CFM56 jet engine data. The optimum maintenance strategy costs were compared to costs of simpler experience-based maintenance strategies. The results of the comparison justify further development and usage of the model in order to achieve significant cost reduction for airline carriers.

KEYWORDS

aircraft operation and maintenance, jet engine, dynamic programming, optimal replacement policy

1. INTRODUCTION

According to the data provided by the Association of European Airlines, AEA [1] in 2005 the maintenance costs accounted for 18% of the total direct costs of air carriers. The aircraft maintenance costs account for a whole series of costs that can be classified according to [2] as:

- line maintenance costs(23%),
- engine overhaul costs(34%),
- component costs(21%),
- airframe heavy costs(14%),
- modifications costs(8%).

The presented structure of costs classification shows that the costs of engine overhaul represent the highest share in the maintenance costs.

Besides implying high costs, aircraft engine maintenance is one of the crucial parts in the aircraft maintenance process since it causes delay in aircraft operations and thus influences the operative availability of aircraft. Therefore, special attention is paid to engine maintenance and the engine maintenance scheduling can be regarded in isolation compared to the maintenance of the entire aircraft.

As an example of aircraft engine maintenance, this paper analyses the maintenance of CFM 56 engine which is used in more than 60% of Airbus 320 aircraft family as well as aircraft Boeing 737, McDonnell Douglas DC-8 etc. The reason lies in its simple design with high level of reliability, durability and maintainability in the class of modern generation of jet engines.

CFM56 engine is a two shaft high bypass turbofan engine. For easier maintenance, it is divided into modules, i. e. groups composed of several parts, as shown in Figure 1.

Certain parts of aircraft jet engines operate in extreme conditions, first of all the engine parts behind the combustion chamber (so-called hot engine section) such as the turbine discs, which operate at high temperatures and are loaded by high centrifugal forces. Therefore, during engine development these parts are paid special attention and they are manufactured of special materials and subjected to rigorous control. [3]

During their operation, the proper functioning of these parts can be monitored only indirectly, without the possibility of being checked by any safe method.

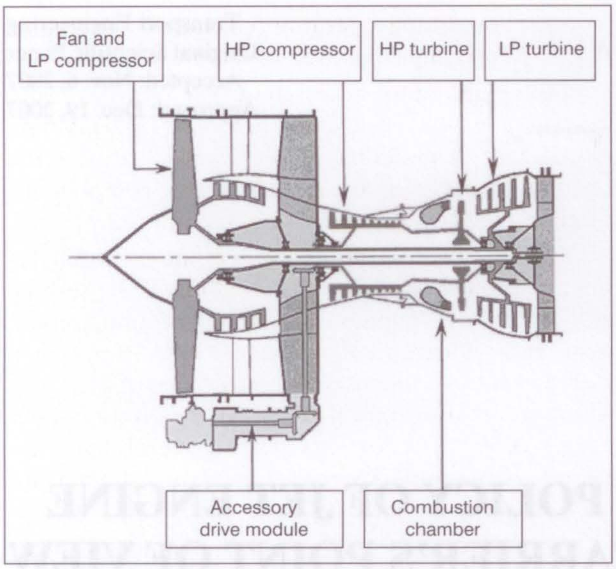

Figure 1 - Schematic view of CFM56 engine

Therefore, limits are set to the service life of these parts and they are replaced either before or at the expiry of the service life and therefore they are called life limited parts (LLP).

When the LLP service life expires, the engine has to be removed from the aircraft and sent to a specialized workshop for overhaul. Shop visit takes approximately three months, and the whole procedure represents a significant cost. Apart from the total maintenance costs, shop visits also affect fleet availability and thus the aircraft operation efficiency.

The CFM 56 engine modules that contain LLPs are:

- module 1: fan and low pressure compressor (3 LLPs),
- module 2: high pressure compressor (5 LLPs),
- module 3: high pressure turbine (4 LLPs),
- module 4: low pressure turbine (6 LLPs).

Accessory drive module and combustion chamber do not contain any LLPs and will not be considered here.

LLPs within one module have approximately the same service life. Service life of modules is limited by the shortest LLP service life in this module. The today's industrial standard for LLP service life, depending on its position in the engine, is between 15,000 and 30,000 cycles (continuous engine running period from startup to shutdown) [4,5].

The moment of LLP service life expiry in one or several modules is followed by the preparation for sending the engine to the workshop and defining the maintenance activities in order to replace the parts or groups of parts whose service life is expiring. It is also possible to consider a simultaneous replacement of another engine part or group of engine parts which – although they could still be used – are nearing the end of their service life. With this approach it is possible to avoid repeated engine removal from the aircraft and a new shop visit shortly after the previous one, which would also mean repeated withdrawal of the aircraft from operation. On the other hand, in this case for the first shop visit of the engine, the number of maintenance activities increases as well as the related workshop costs.

Careful planning of subsequent visits to the workshop because of LLP service life expiry during a certain period of engine operation results eventually in the reduction of total air carrier's operation costs. The question is: how to optimally select the parts that will be replaced during the shop visit, i. e. how to select the optimal strategy (a series of well-made decisions) in order to minimize the total shop visit costs?

The specifics of the problem of optimizing the jet engine module replacement from the air carrier's aspect is reflected in the following:

- service life of each LLP is defined by the maintenance program (according to the manufacturer's recommendation) and being thus legally obligatory for the operator;
- LLP service life is expressed in flight cycles [FCY], as different from flight hours [FH], which are used to express the flight duration.

It should be noted here that the *FH / FCY* ratio represents a very important operational parameter since it is closely connected to the flight duration realized by this carrier. For example, direct flight from Zagreb to Split takes less than 1 flight hour [FH], and represents 1 cycle, i. e. one starting and shutting down of the engine. Direct flight from Zagreb to London takes about 2.5 hours, and also represents 1 cycle [CY] of the engine. This means that air carriers flying on shorter relations will find that the service life of certain engine parts will expire much faster, causing more frequent inspections and visits to repair shops and consequently higher costs.

Consulting the experts from practice and by studying the literature it has been determined that there is no unique model for determining the optimal maintenance strategy of the aircraft powerplant [6]. The maintenance model development relies on the experience of the air carrier acquired during the aircraft operation, based on the analysis of the achieved reliability and the statistical data [7]. The mathematical model presented in this paper has been developed in order to support this practical experience, for better planning and maintenance optimization, by scientifically based approach. Such model may be used as the decision-making tools by experts from practice, in the function of maximal availability and given reliability of aircraft at minimal costs.

2. OPTIMIZING MODELS OF AIRCRAFT JET ENGINES MAINTENANCE

The description of applying scientific models for aircraft jet engine maintenance planning can be found since the 60s in the literature published as part of the research for the needs of the US Air Force [8], which shows in the form of technical commands also the definition of the procedures for determining the failure intensity and life cycle of aircraft engine [9]. These researches bring data on the failure intensity which is presented as the function of jet engine age for all engines that were then used in the US Air Force. Almost all engines show a certain level of fatigue in accordance with the age.

Nowlan [10] showed in 1960 that aircraft engines have characteristics of failure that correspond approximately to Weibull's distribution with parameter of scale $\beta = 3.71 \cdot 10^{-10}$ and parameter of form $\alpha = 3.0$. It also showed that the engine repair costs upon failure (corrective replacement) is approximately 1.5 times higher than the costs of planned (preventive) engine replacement.

The detailed report prepared by Jorgenson, McCall and Radner [11] for RAND Corporation clearly emphasises the basic conditions that have to be fulfilled in order to make preventive equipment replacement with stochastic failure justified:

1. distribution of equipment failure must show increased failure intensity with equipment aging,
2. replacement costs after failure have to be greater than the costs of replacement before failure.

Based on this report a study on the optimal replacement of the basic modules of the F-100 jet engine on aircraft F-15 has been made [12]. This engine differed from those used until then, regarding its modular concept (which, as a good technical solution, has been retained also on other jet engines up to the present). The data on failures were limited, as the engine operation has just started.

Recently, papers that deal with problems of aircraft jet engine maintenance can be found. The author D. Mark Kennet published in 1994 an article [13] in which he presented the aircraft jet engine maintenance model based on the maintenance model of bus engines proposed in 1987 by Rust [14]. The article was written with the intention of determining the structural change in maintaining of jet engines for the types JT8D and JT9D[1] which have gradually resulted in eliminating the limits for the jet engine overhauls at the 1978 Congress. These legal changes have made the airlines fly longer with aircraft engines before they are sent to overhaul. In the model the decision on sending the engine to overhaul was brought by solving the problem of stochastic dynamic programming, with costs of continuing operation (including the engine failure risk) being compared to the overhaul costs.

The results of the research by Yar-Lin Kuo[2] were published in two articles. The first one [15] deals with mathematical modelling of strain which causes the creation of cracks on the aircraft engine components, primarily on the compressor and the turbine.

The second work [16] considers the possibility of joint maintenance of the compressor and the turbine and it therefore belongs to the group of multicomponent joint replacement problems. Literature which studies these problems emphasises that there is no simply optimal structural policy. The quoted work develops three heuristic approaches: hierarchical approach, sequential approach and base interval approach.

As indicated earlier, aircraft maintenance has been regulated by the air carrier maintenance program which is in compliance with the manufacturer's recommendations, legal provisions of state civil aviation authorities and with the aircraft operation conditions depending on the size and profile of the air carrier. However, the air carrier still has a certain freedom in developing the maintenance program. Since the maintenance costs account for approximately 10–15% of operative costs of the air carrier, by selecting a proper maintenance strategy they can achieve certain savings. Therefore, studies are developed daily, based on the scientific models whose aim is the making of commercial computer programs for maintenance optimization, calculation of the required spare parts quantities, etc.

An example of such work is the study [17] which presents and analyzes the mathematical model for forecasting of the expected number of unplanned maintenance actions within one air carrier. For the needs of simulation which calculates the aircraft engine reliability indicators, such as the shop visit rate and engine failures various data have been used: aircraft type, number of engines per aircraft, fleet capacity, weekly number of flights, number of destinations, flying speed and altitude, average duration of one flight, etc.

Another example is the study of a team of experts gathered at the company *Clockwork Solutions* [18] which describes the *SPAR*^{TM} project developed for the European Concern engaged in the construction and production of aircraft and aircraft engines. The objective of this analysis was to find the optimal replacement policy which would result in the minimal engine life-cycle costs retaining the acceptable availability and overhaul time for a certain engine. The study analyses the basic failure mechanisms of jet engine parts, and the maintenance optimization procedure has been solved by Monte Carlo simulation.

3. OPTIMIZING OF JET ENGINE MAINTENANCE BY DYNAMIC PROGRAMMING

This paper presents the optimization of the process of planning the replacement of the jet engine module by dynamic programming method. Planning of jet engine module replacement is considered as a multi-stage process, and optimal replacement of the module belongs to the class of problems which is mentioned in the literature as the problem of optimal equipment replacement [19]. In this context, in literature one usually finds problems that consider the replacement of machines of a certain production plant or operational means, such as e. g. vehicles, aircraft, etc. The problem of optimizing the equipment replacement is reduced to searching for a compromise between the costs of purchasing new equipment and the maintenance costs that result in the use of old equipment. When the problem is modelled as a multi-stage decision-making process, the maximum revenue (or the minimum cost) during n years of equipment operation is taken as the optimizing criterion.

3.1. Jet engine module replacement model

For the jet engine consisting of m modules the operation is planned in the duration of n cycles and at the moment i ($i = 0,1,2,\dots,n$) the cycle age of individual models equals x_{ji} where $j = 1,2,\dots m$. A certain initial condition in jet engine operation can be defined as vector X_i where the vector components represent the single module service life in cycles. In this paper the assumed number of modules is $m = 4$.

$$X_i = \begin{bmatrix} x_{1i} \\ x_{2i} \\ x_{3i} \\ x_{4i} \end{bmatrix} \tag{1}$$

where x_{ji} is the age of module j at moment i expressed in the number of cycles.

At the moment the service life of one of the modules expires, the jet engine is removed from the aircraft and is sent to overhaul in the specialized shop. The decision needs to be made whether – with the module which has to be replaced – any other of the remaining modules whose service lives have not expired need to be kept or replaced, in order to minimize the total costs realized in all the n operation cycles.

The maintenance program defines the module service life, i. e. the maximal number of cycles for reach module ($x_{j\max}$), after which the module has to be replaced. In aircraft engine operation these values represent the current manufacturer's requirements. This has to be defined in the model and can be recorded that the module has to be replaced when $x_{ji} = x_{j_{\max}}$, i. e. $x_{ji} \le x_{j_{\max}}, \forall j, \forall i$.

Here, it is assumed that the old module is always replaced by a new one, which means that the age of the newly built-in module equals 0 cycles.

The module replacement problem can be formulated as a multi-stage decision-making process [19], where the number of cycles i is considered i-th stage, $i=1,2,\dots,n$. The condition on the i-th stage depends on the condition at the moment i-1 and the decision made at the moment i, which can be either "keep" or "replace" for each single module.

Consequently, the decision vector U_i is defined, and it contains all the permissible decisions which affect further trajectory of the process. For the jet engine consisting of four modules ($m=4$) vector U_i has the form:

$$U_i = (u_0\ u_1\ u_2\ u_3\ u_4\ u_{12}\ u_{13}\ u_{14}\ u_{23}\ u_{24}\ u_{34}\ u_{123}\ u_{124}\ u_{134}\ u_{234}\ u_{1234}) \tag{2}$$

where vector components represent the decision as follows:

u_o – replace nothing (keep all the modules);

u_1 – replace only module 1;

$\vdots$

u_{12} – replace modules 1 and 2;

$\vdots$

u_{123} - replace modules 1, 2, 3;

$\vdots$

u_{1234} – replace all modules.

For the jet engine consisting of four modules, the number of decision vector components is 16. Generally, for the jet engine consisting of m modules, one may say that the number of permissible decisions, i. e. the number of decision vector components will be 2^m, since for each module there are only two possible decisions: to keep or to replace.

The law of the transition process from condition X_{i-1} into condition X_i under the influence of decision vector U_i is defined as:

$$X_i = w(X_{i-1}, U_i) \tag{3}$$

where w is the given vector function of the change of condition which for one module has the form:

$$w(x_{j_{i-1}}, u_i) = \begin{cases} 0 & \text{for } u_i = \text{replace} \\ x_{j_{i-1}} + 1 & \text{for } u_i = \text{keep} \end{cases} \quad (4),$$

$$u_i \in U_i, x_{j_{i-1}} \in X_i,\ j = 1,2,3,4$$

The replacement cost generated at moment i depends on the previous engine condition (module) $x_{i\text{-}1}$ and the decision made at moment i which can acquire 16 forms from the set of permissible decisions of decision vector, for engines consisting of 4 modules. Table 1 shows the engine condition after the decision has been made and the inspection costs generated by each decision.

Table 1 - Overview of the conditions and costs after the decision has been made at moment i

Condition at moment $i+1$	$x_{1i}+1$ $x_{2i}+1$ $x_{3i}+1$ $x_{4i}+1$	0 $x_{2i}+1$ $x_{3i}+1$ $x_{4i}+1$	…	0 0 $x_{3i}+1$ $x_{4i}+1$	…	0 0 0 $x_{4i}+1$	…	0 0 0 0
Decision u_i	u_0	u_1		u_{12}	..	u_{123}	…	u_{1234}
Decision-generated cost	C_0	C_1		C_{12}		C_{123}		C_{1234}

3.2 Problem of optimizing the jet engine module replacement

Optimizing in a certain multi-phase decision-making process can be generally defined as finding the minimum or maximum of a real function:

$$f(x_0, x_1, \dots, x_n, u_1, u_2, \dots, u_n) \tag{5}$$

on the set of all the series of permissible decisions u_1, u_2, $\dots u_n$ of this process, where $x_0, x_1, \dots x_n$, is the trajectory that according to (3) corresponds to that series in relation to the initial condition x_0.

The dynamic programming method can be applied only to a special form of the previously described optimization problem in which function (5) is separable, i. e. represents the sum or product of n expressions, where i–th expression depends only on one variable u_i. This form of function of objective very often occurs naturally in actual multi-phase decision-making processes which take into account the direct effects of every selected decision. With such criteria, each phase i is assigned a certain value, e. g. revenue, cost, reliability, which depends on decision u_i and previous condition x_{i-1}. Total value that is optimized is obtained as the sum (e. g. total revenue, total cost), or product (e. g. total reliability) of the direct values in all the phases.

This special class of optimization problems can be more precisely presented as:

maximization or minimization of function

$$\sum_{i=1}^{n} f_i(x_{i-1}, u_i) \quad \text{ili} \quad \prod_{i=1}^{n} f_i(x_{i-1}, u_i) \tag{6}$$

with constraints:

$$x_i = w(x_{i-1}, u_i), \quad i = 1,2,\dots,n$$
$$u_i \in U_i(x_{i-1})$$
x_0 – initial condition,

where $f_i(x,u), i = 1,2,\dots,n$ are the known real functions. A series of decisions $\overset{*}{u}_1, \overset{*}{u}_2, \dots, \overset{*}{u}_n$ for which the function of the problem objective (6) reaches its extreme is called the optimal series of decisions or optimal policy, and the respective trajectory $\overset{*}{x}_1, \overset{*}{x}_2, \dots, \overset{*}{x}_n$ the optimal process trajectory.

When the process of jet engine module replacement is modelled as a multi-phase process (as previously described), to find the optimal policy the recursive relations are formed according to the backward principle (retrogradely).

Minimal cost due to the engine module replacement during operation from moment i to moment n, if at moment i the engine was X_i old can be shown as:

$$F_i(X) = \min_{u_i \dots u_n} \sum_{l=1}^{n} f_l(X_{l-1}, U_l) \tag{7}$$

where $X_{i-1} = X$.

Considering that for the problem of jet engine module replacement there are 16 permissible decisions for 4 jet engine modules and for each of them the function $f_i(x_{i-1}, u_i)$ has a special form, this yields:

– for $i = n$:

$$F_n(X) = \min \begin{cases} (C_0)_n & \text{for } u_0 \\ (C_1)_n & \text{for } u_1 \\ \vdots & \\ (C_{123})_n & \text{for } u_{123} \\ \vdots & \\ (C_{1234})_n & \text{for } u_{1234} \end{cases} \tag{8}$$

– for $i < n$:

$$F_i(X) = \min \begin{cases} C_0 + F_{i+1}(X_i) & \text{for } u_0 \\ C_1 + F_{i+1}(X_i) & \text{for } u_1 \\ \vdots & \\ C_{123} + F_{i+1}(X_i) & \text{for } u_{123} \\ \vdots & \\ C_{1234} + F_{i+1}(X_i) & \text{for } u_{1234} \end{cases} \tag{9}$$

Following the two-phase procedure according to [19] the optimal value of the function of objective is calculated and the optimal series of decisions i. e. optimal trajectory of the process which shows the sequence of decisions that need to be made on certain branches.

3.3 Input data for the model

For finding the solution of the problem regarding optimization of the jet engine module replacement using the dynamic programming method, it is necessary to define the following input data:

1. initial process condition,
2. limited service life of the module,
3. process phase,
4. process observation horizon,

5. decision-making criterion,
6. cost related to every decision.

Initial process condition can be any moment of the means in operation from which the optimization procedure is started. For the procedure of determining the optimal policy, a new engine has been selected as the initial process condition, so that all the modules have 0 cycles.

Limited service life of the module is determined by the engine maintenance program as the maximum number of cycles for each module $x_{j\max}$ after which the replacement of the respective module is obligatory. In aircraft engine operation these values are determined according to the current manufacturer's requirements, and the manufacturer reviews these occasionally based on the empirical knowledge about the actual engine operation. The numbers of cycles for single modules of the CFM 56 engine are given in Table 2.

Table 2 - Limited life cycle of the module

Module	Service life [CY]
M1	30000
M2	20000
M3	15000
M4	25000

Process phase represents the interval between two discrete points in time at which the decision is made. In the considered example of the CFM 56 engine, the phase 5000 CY is taken.

Process observation horizon is the final number of phases, i. e. the planned period of time for which the optimization procedure is to be performed. The selection of the observation horizon shall be harmonized with actual data from the operation:

- flying expressed in flight hours - *FH*;
- flight hours – cycle ratio, *FH* / *FCY*;
- planned duration of engine operation.

Data from practice of one of the regional air carriers flying on short-haul routes have been taken as example to be considered while solving the problem:

- annual flight hours per engine ≅ 2800 FH;
- ratio $FH / FCY = 1.1$;
- planned time of engine usage ≅ 8 – 10 years.

The process observation horizon is taken as 30000 CY, which amounts to 6 phases.

The decision-making criterion, i. e. optimization criterion can be total maximal revenue or total minimal cost for a certain process observation horizon. In this work the decision-making criterion is the minimal cost.

Cost related to each decision: Each decision u_i from the set of permissible decisions U_i is unambiguously related to certain overhaul costs. For instance, the decision u_{12} which represents a shop visit with simultaneous replacement of the first and second module is related to cost C_{12}.

According to the shop visit procedure of an air carrier, the costs of the shop visit can be expressed in dependence on the price of the new modules [20].

$$C_{SV} = 5.5+1.3\cdot(C_{newLLP})_m \quad [\text{CU}] \qquad (10)$$

Further in the calculation, the prices of certain parts are expressed according to the actual data for the engine CFM 56. Because of the confidentiality of this type of data, the cost unit - 1 CU – has been introduced, thus expressing the relations among the costs of replacements and prices of new modules, Figure 2.

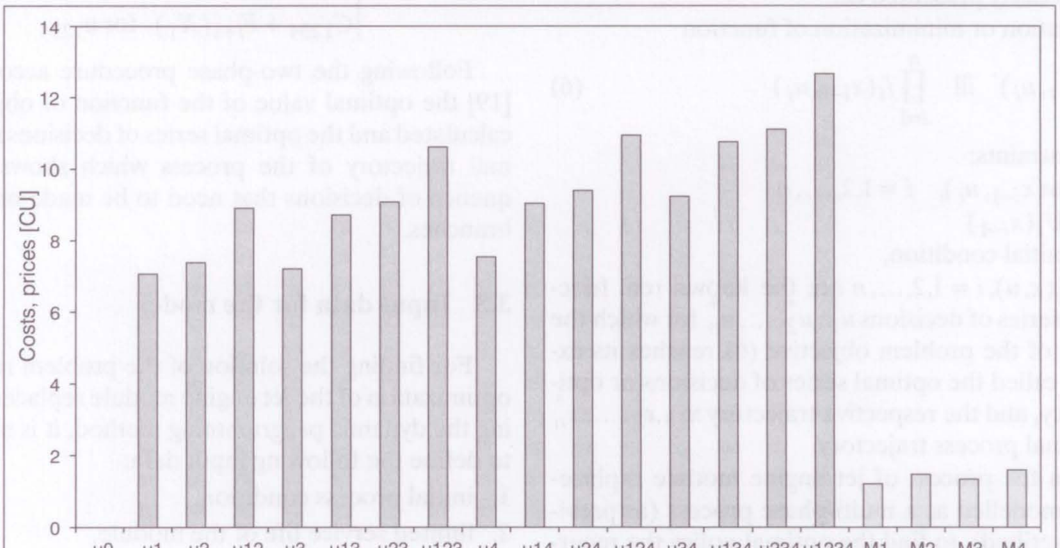

Figure 2 - Replacement costs depending on the decision and prices of new modules

3.4 Optimal policy of jet engine module replacement

Results obtained by model programming in C++ are presented next. The result of modelling is the optimal policy of jet engine module replacement, i. e. a series of well made decisions according to the minimal costs criterion for the final process observation horizon.

The following data have been taken as the initial conditions for determining the optimal policy:

(a) initial engine condition: $X_0 = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$

(b) maximal module service lives: $X_{max} = \begin{bmatrix} 6 \\ 4 \\ 3 \\ 5 \end{bmatrix}$

(c) phase: 5000 CY;

(d) process observation horizon: 6 phases.

The result of modelling is the optimal maintenance policy, presented in Figure 3.

The modules whose service life is expiring (and therefore **must** be replaced) are circled by a solid line, and modules that are replaced as required are circled by a broken line. The moment of decision-making during engine operation is presented by a circle with the entered decision made. The symbols M1 to M4 mark the modules, and numbers in columns mark the module condition per phases of 5000 CY.

It is clear that the optimal module replacement policy consists of 2 shop visits of the engine with decisions u_{13} i u_{234}. Therefore, the total costs of optimal policy for the 6 planned phases, i. e. 30000 CY are:

$$C_{opt} = \sum C_i = C_{13} + C_{234} =$$
$$= (8.75 + 11.14)\mathrm{CU} = 19.89\mathrm{CU}$$

3.5 Comparison of optimal policy and the experiences

Because of the quantification of the realized optimization, the optimal policy was compared to other policies that are based on the simple principles of empirical decision-making according to the found engine condition [20]. The selected comparative policies are:

1. replacement of each (single) module upon service life expiry,
2. joint replacement of two modules,
3. policy of joint replacement of all modules.

Ad 1. This policy forecasts that every individual module is replaced only upon reaching its maximal service life, i. e. no opportunist replacement of the module is planned.

Ad 2. This type of policy is one of the decision-making methods which is implemented in the practice of air carrier maintenance service. When dismounting the engine from the aircraft and sending it to the overhaul workshop because of the service life expiry of one module, opportunistically at least one more module is replaced; the one which has the fewest cycles until the service life expiry.

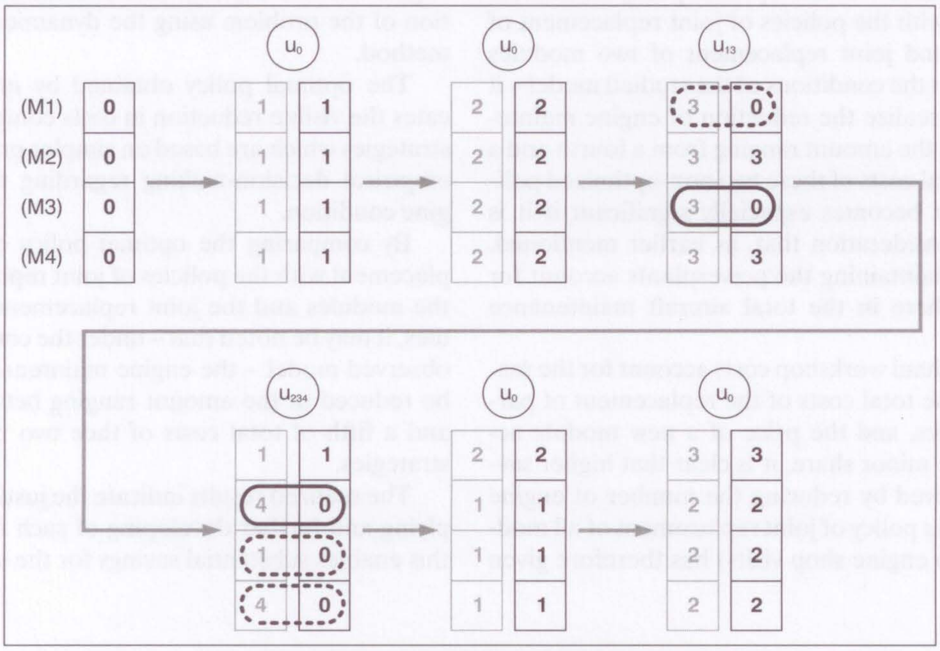

Figure 3 - Optimal engine replacement policy

Ad 3. The replacement policy of all modules during every shop visit of the engine is in principle feasible in practice, but because of the adjustment of the replacement moment to the module with the shortest service life the value of the remaining life cycle of other modules remains unused.

The relations among individual policies is graphically presented in Figure 4.

The optimal policy obtained by modelling indicates visible reduction of costs compared to other policies which are based on the simpler principles of empirical decision-making according to the found engine condition. It should be noted that the comparison with the replacement policy of every module upon service life expiry has been done here only in order to illustrate the maximal non-optimized costs, since this policy, as earlier mentioned, is non-realistic and its implementation in practice cannot be expected.

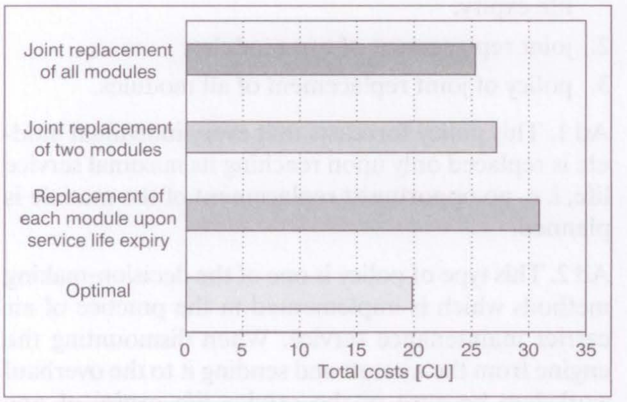

Figure 4 - Comparison of engine repair costs depending on the policy

The comparison of the optimal policy of module replacement with the policies of joint replacement of all modules and joint replacement of two modules shows that – in the conditions of the studied model – it is possible to realize the reduction of engine maintenance costs in the amount ranging from a fourth and a fifth of the total costs of these two non-optimized policies. This fact becomes especially significant if it is taken into consideration that, as earlier mentioned, the costs of maintaining the powerplants account for the highest share in the total aircraft maintenance costs.

Since overhaul workshop costs account for the major share in the total costs of the replacement of particular modules, and the price of a new module accounts for the minor share, it is clear that higher savings are achieved by reducing the number of engine shop visits. The policy of joint replacement of all modules (with two engine shop visits) has therefore given better results than the replacement policy of two modules (which had three shop visits during the considered operation period), regardless of the fact that in case of joint replacement of all the modules a large part of service lives of opportunistically replaced modules has remained unused.

The optimal policy of module replacement also requires two engine shop visits, but features lower total costs than the policy of joint replacement of all modules because in case of optimal policy the engine module service lives are more fully used.

4. CONCLUSION AND PROPOSALS FOR FURTHER RESEARCH

As an economic subject, every air carrier is exposed to the competition of other air carriers and other means of transport. Apart from inevitable safety and quality of service, the competition on the air transport market includes also minimal costs of aircraft maintenance.

There is no universal optimal maintenance program that would be valid for all aircraft of the same type or for all air carriers. Therefore, every air carrier has to analyze in detail various maintenance concepts so as to define the optimal maintenance program for themselves, achieving thus maximal safety at minimal maintenance costs.

Regarding high costs and influence on the operative availability of aircraft, aircraft powerplant maintenance occupies a very significant place in the aircraft maintenance process. This work has described the problem of optimizing the planning process of the jet engine module replacement and the presented solution of the problem using the dynamic programming method.

The optimal policy obtained by modelling indicates the visible reduction in costs compared to other strategies which are based on simpler principles of the empirical decision-making regarding the found engine condition.

By comparing the optimal policy of module replacement with the policies of joint replacement of all the modules and the joint replacement of two modules, it may be noted that – under the conditions of the observed model – the engine maintenance costs may be reduced in the amount ranging between a fourth and a fifth of total costs of thee two non-optimized strategies.

The realized results indicate the justification of applying and further developing of such a model, since this enables substantial savings for the air carrier.

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SAŽETAK

OPTIMALNA STRATEGIJA ZAMJENE MODULA MLAZNOG MOTORA S ASPEKTA ZRAČNOG PRIJEVOZNIKA

Metodologijom dinamičkog programiranja razvijen je matematički model za optimiranje preventivnog održavanja zrakoplovnog mlaznog motora s ciljem dobivanja određenog niza odluka o zamjeni modula motora koji rezultira najmanjim troškovima održavanja. Planiranje zamjene modula mlaznog motora promatra se kao višeetapni proces odlučivanja, a optimalna zamjena modula ubraja se u klasu problema optimalne zamjene opreme. Model je programski formuliran u programskom jeziku C++ i testiran podacima iz eksploatacije mlaznog motora CFM56. Troškovi optimalne strategije održavanja uspoređeni su s troškovima jednostavnijih iskustvenih strategija održavanja. Ostvareni rezultati ukazuju na opravdanost daljnjeg razvoja i primjene ovakvog modela, jer se time mogu postići značajne uštede za zračnog prijevoznika.

KLJUČNE RIJEČI

eksploatacija i održavanje zrakoplova, mlazni motor, dinamičko programiranje, optimalna strategija zamjene

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