Maintenance Interval Adjustment Based on the Experience, Case Study of Marine Air Compressor System

Podešavanje intervala održavanja temeljem iskustva, studija slučaja sustava brodskih kompresora

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Summary

The paper presents the initial case of a research of analysing maintenance interval adjustment in the shipping industry. This case is an example of the adjustment of the maintenance interval carried out by ship's crew on starting air compressor system. The example is found and followed through the records in the computerized Planned Maintenance System. Maintenance interval adjustment proposal and actual adjustment were carried out based on user's experience, after rechecking maintenance data and actual machinery condition, without theoretical approach or analysis. That process created new maintenance plan which is in use on the system for past ten years. Missing actions in the process, i.e. theoretical analysis of the initial and modified maintenance, are performed using the MA-CAD method with a modified reliability testing and are described in the paper. Results obtained by the theoretical analysis are compared with the requested and performed modification of the Maintenance Plan and a conclusion about performed action has been derived.

KEY WORDS

Air compressor
Planned Maintenance
reliability
maintenance interval adjustment

Sažetak

U radu je predstavljen inicijalni slučaj istraživanja analize podešavanja intervala održavanja u brodskoj industriji. Ovaj slučaj je primjer podešavanja intervala održavanja koji obavlja brodska posada pri pokretanju sustava kompresora. Primjer smo pronašli i pratili kroz evidenciju u računalnom sustavu planiranog održavanja. Prijedlog podešavanja intervala održavanja i stvarno podešavanje provedeni su na temelju iskustva korisnika nakon ponovne provjere podataka o održavanju i stvarnog stanja stroja bez teorijskog pristupa ili analize. Taj je postupak rezultirao novim planom održavanja koji se u sustavu koristi posljednjih deset godina. Radnje koje nedostaju u tom postupku, tj. teorijska analiza inicijalnog i modificiranog održavanja, provedene su primjenom MA-CAD metode s modificiranim ispitivanjem pouzdanosti i opisane su u ovom radu. Rezultati dobiveni teorijskom analizom uspoređuju se s traženom i izvedenom modifikacijom Plana održavanja i donesen je zaključak o izvršenim radnjama.

KLJUČNE RIJEČI

kompresor
planirano održavanje
pouzdanost
podešavanje intervala održavanja

1. INTRODUCTION /UVOD

Ships planned maintenance is a complete system that is carried out mainly by using a computer program specifically designed for this purpose. Computerized PMS (Planned maintenance systems) are in use for more than thirty years [18], during which time they have become an important and irreplaceable factor in the maintenance of ship and ships systems.

Computerized PMS and its operations are determined by the ISM code, Chapter 10 [15] and IACS recommendations (Planned Maintenance Scheme for. Machinery Z-20) [10]. The core of each computerized PMS is a good database, composed of reliable and high-quality data. Initial DB (database) in the system will develop over time and will be enriched with the data on the use of various ships equipment. These new data are feedback that should enable maintenance and especially management personnel (ship inspectors) to plan, organize and execute changes in the maintenance process [9], [11]. Changes in the maintenance process are, as a rule, the fruit of exhaustive analysis and reflection, aimed at improving the process itself, increasing reliability, and reducing maintenance costs.

The paper analyses the maintenance of the air compressor system (Figure 2) and the changes that have been made in that system over the time using data read in the computerized PMS. Adjustment of the maintenance interval for a device or system is a procedure that should be executed after systematic analysis of the system, performed maintenance and failures which will serve to determine the optimal way to maintain it. In this case, changes in the maintenance process were carried out by using exclusively user experience, without the theoretical analysis and calculation that was supposed to precede the changes. Checking the results of the maintenance interval adjustment was also absent, no one was systematically monitoring what happens after the maintenance interval has changed.

Using the MA-CAD (**MA**intenance **C**oncept **A**djustment and **D**esign) method [4], [20], the analysis of the maintenance was performed on the initial maintenance plan, before the change was made. The analysis yielded results that were compared with the actual change in the maintenance plan. In addition, maintenance data and failures after the change of intervals were analysed to determine the actual effect of the performed change and its justification. Adjustment of the maintenance approach based on the real operational data [1], [6] is more reliable than the design of the initial maintenance concept for a new ship.

1.1. Confidentiality note / *Napomena o povjerljivosti*

This research was conducted on real shipping company databases, where authors were given certain confidential data. The data was given under no disclosure conditions, therefore all details leading to the identification of the shipping company or the vessel have been withheld.

2. AIR COMPRESSOR SYSTEM AND INITIAL MAINTENANCE PLAN / *Sustav kompresora i inicijalni plan održavanja*

Reliable and safe performance of main engine propulsion depends on several essential sub-systems including air compressors system with its own individual components. Therefore, the reliability of the main engine is interdependent with the reliability of several subsystems [2]. The starting air compressor system analysed in this paper consists of three compressors powered by electric motors. (Figure 1).

Compressors in day-to-day operation work in a cold parallel system, one compressor is in operation, while two are in reserve (stand-by). Due to the need for a larger amount of air, the only time when all three compressors are in operation is occasionally during manoeuvring, i.e. when the main engine is started several times in a shorter period.

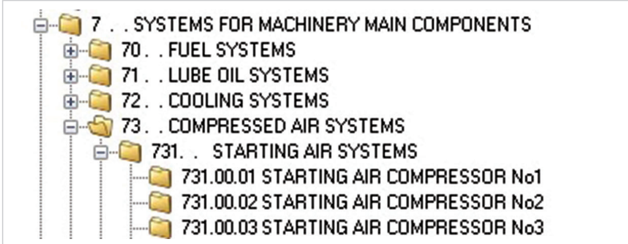

Figure 1 Air compressors in computerized PMS
Slika 1. Kompresori u kompjuteriziranom PMS sustavu

In the database there are operations recommended by the manufacturer [16] together with the operations required by the Classification Society [12] and operations required by the shipping company's rules. All of them create an initial air compressor Maintenance Plan (Figure 2).

The ship's handover and the beginning of maintenance of the air compressor system according to the initial maintenance plan took place in March 1998, and in February 2007 the maintenance interval change was requested. It was introduced to the system in October 2007. Until the change of the Maintenance Interval, i.e. the emergence of a new Maintenance Plan, the air compressors were working:

- Air Compressor No.1: 9600 running hours,
- Air Compressor No.2: 11400 running hours,
- Air Compressor No.3: 9300 running hours.

Table 1 presents operations performed during maintenance according to the Initial Maintenance Plan.

Failure means presence of conditions causing the engine or component out of order according to the regulatory parameters [13]. Failures during maintenance according to the initial plan are:

- Compressor No.1, failure of electric motor bearing, occurred on June 21st, 2002, at 4242 running hours of compressor, 128 hours after engine overhaul and installation of new bearing.
- Compressor No.2, 3rd stage valve failure, occurred on November 3rd, 2004 at 7233 running hours of compressor, 1092 hours after the valve change.

The downtime (outage duration) and MTTR (mean time to

ACC025	AIR COMPRESSOR REGULAR CHECK	3 Month(s)	Engineer
ACC026	AIR COMPRESSOR CHECK 1000 h	12 Month(s), 1000 Hours	Engineer
ACO007	AIR COMPRESSOR VALVES 2000 h	2000 Hours	Engineer
ACO008	AIR COMPRESSOR OVERHAUL 4000 h	60 Month(s), 4000 Hours	1st Engineer
ACT 002	AIR COMPRESSOR ALARMS TEST	6 Month(s)	Electrician
CSM 001	CONTINUOUS SURVEY MACHINERY (CSM)	60 Month(s)	Ch. Engineer
EMO 001	ELECTRIC MOTOR OVERHAUL	60 Month(s), 8000 Hours	Electrician
MEG 001	MEGGER TEST MEASUREMENT	6 Month(s)	Electrician

Figure 2 Initial maintenance plan in PMS
Slika 2. Inicijalni plan održavanja u PMS-u

Table 1 Operations performed according to the Initial Maintenance Plan
Tablica 1. Izvršene radnje prema Inicijalnom planu održavanja

	ACC 025	ACC 026	ACO 007	ACO 008	ACT 002	CSM 001	EMO 001	MEG 001
Air Comp. No.1	50	9	4	2	20	2	3-1	21-1
Air Comp. No.2	50	10	6-1	2	20	2	2	20
Air Comp. No.3	50	9	5	2	20	2	2	20

Notes: The number of unexpected operations (failures) is given after "-". The total number of operations includes unexpected operations.
Grey fields are overhaul operations or replacements. The other fields are only checks.
Compressor No. 1, both unexpected works are one event that is entered separately!

repair) is based on the review of the maintenance records in the database, data in the generic database [17], as well as on the author's experience. The downtime due to the change of the electric motor bearings was obtained by analysing the time required to complete the EMO001 work which varies from 6-36 hours, depending on the scope of the work performed and the person doing the operation [17]. As this replacement of the electric motor bearings was caused by the failure of the bearing, there should be no insulation (varnishing) of the windings. Therefore, the delay time for bearing replacement will be, in the worst case, less than six hours. The downtime due to the change of the third stage valve was determined by an analysis of the time required to carry out the ACO007 work, up to 2 hours. As this operation includes first and second valve check, the downtime only for the third stage valve change should be less than one hour.

Although this is a very small sample, which cannot be considered as reliable [19], the estimated MTTR of 3.5 hours will be used for calculation.

3. MAINTENANCE PLAN MODIFICATION AND NEW MAINTENANCE PLAN / *Modifikacija plana održavanja i novi plan održavanja*

In February 2007, the Chief Engineer suggested modification of the air compressor system maintenance intervals. The Improvement Suggestion Proposal was created by the Chief Engineer and required an increase in maintenance intervals by 50%. By inspecting the communication within the PMS system, it can be established that the criterion used in the proposal of the maintenance interval modification was exclusively experiential, with a view of the records of the previous maintenance and insight into the condition of the device at that moment. No traces of the analysis or calculations were found in the communication prior to submitting the proposal for modification of the maintenance interval. The modification in the maintenance plan (Figure 3) or the increase of the maintenance period was carried out in the computerized PMS in October 2007. The maintenance period was increased by 25% by the decision of the ship's inspector, without explanation of the decision or any other comment. The communication did not indicate that any calculation was used during the consideration of the problem, thus missing an ideal opportunity to analyse (determine) the maintenance, faults and condition of the equipment. ''*The most reliable way of determining the maintenance model of the equipment in operation is the recording of faults, their reasons and the situation when the breakdown occurred*'' [5].

Since the Maintenance modification air compressors run:

- Air Compressor No.1: 10058 running hours, (total 19658 running hours),
- Air Compressor No.2: 11095 running hours, (total 22495 running hours),
- Air Compressor No.3: 14662 running hours, (total 23662 running hours).

In the mentioned period, a considerable number of operations was performed (Table 3), among those are three corrective works, i.e. malfunctions.

4. MA-CAD METHOD MAINTENANCE ANALYSIS / *MA-CAD metoda za analizu održavanja*

Initial maintenance was analysed using the MA-CAD method [4], [20]. It is a method for adjustment and designing a maintenance concept by analysing failures and maintenance modes of the machinery. The method reduces the LCC (Life Cycle Costs), while meeting the safety limits [4]. The MA-CAD method analyses and adjusts the maintenance concept, which is transformed into the maintenance plan within PMS. Therefore, in this paper, these two terms are considered identical. During the MA-CAD analysis the following parameters were checked:

- Initial maintenance plan,
- The running hours during the maintenance period according initial plan,
- Collecting data on failure,
- Failure analysis to define the type of failure and parts where failure has occurred,
- Downtime during the maintenance period according

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ACC026	AIR COMPRESSOR CHECK 1000 h	12 Month(s), 1250 Hours	Engineer
ACO007	AIR COMPRESSOR VALVES 2000 h	2500 Hours	Engineer
ACO008	AIR COMPRESSOR OVERHAUL 4000 h	60 Month(s), 5000 Hours	1st Engineer
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CSM 001	CONTINUOUS SURVEY MACHINERY (CSM)	60 Month(s)	Ch. Engineer
EMO 001	ELECTRIC MOTOR OVERHAUL	60 Month(s), 5000 Hours	Electrician
MEG 001	MEGGER TEST MEASUREMENT	6 Month(s)	Electrician

Figure 3 Modified Maintenance plan
Slika 3. Modificirani plan održavanja

Table 2 Operations performed according Modified Maintenance Plan
Tablica 2. Izvršene radnje prema Modificiranom planu održavanja

	ACC 025	ACC 026	ACO 007	ACO 008	ACT 002	CSM 001	EMO 001	MEG 001
Air Comp. No.1	55	9	5-1	2	20	2	2	20
Air Comp. No.2	55	9	4	3-1	20	2	2	20
Air Comp. No.3	55	12	7-1	4-1	20	2	2	20

Notes: The number of unexpected operations (failures) is given after ''-''. The total number of operations includes unexpected operations.
Grey fields are overhaul operations or replacements. The other fields are only checks.
Compressor No. 1, both unexpected works are one event that is entered separately!

initial plan,
- Failure mode analysis,
- Analysis of spare parts storage and inventory planning
- Risk analysis (Significance Analysis, Expected Life Failure Frequency, Risk Analysis), to determine suitable maintenance policy,
- Reliability analysis (exponential and Γ-exponential),
- Maintenance concept adjustment, i.e. modelling of the maintenance period (maintenance plan).

Failure mode analysis (FMA) shows a causal sequence of events between the cause of failure and the effects of the failure. Failure mode analysis was made for Air Compressor No.1 (Table 3) and Compressor No.2 (Table 4).)

Table 3 Air compressor No.1 Failure mode analysis
Tablica 3. Kompresor br.1 Analiza kvara

Failure mode analysis for	Electric motor bearing
Failure mode	Bearing failure
Failure mechanism	Vibration and excessive heating of electric motor
Cause of failure	Usage, faulty part, fault during installation
Cause location	Internal or external
Basic failure effects	Excessive heating of bearing, vibration, increase in operation sound
Failure effects	Difficulties in operation of electric motor, leading to termination of operation

Table 4 Air compressor No.2 Failure mode analysis
Tablica 4. Kompresor br. 2 Analiza kvara

Failure mode analysis for	Third stage valve
Failure mode	Termination of operation of the valve, locking in the open position
Failure mechanism	Dirt accumulation
Cause of failure	Usage, Air humidity, dirty oil
Cause location	Internal
Basic failure effects	No valve closure
Failure effects	Termination of air supply

Analysis of spare parts storage and inventory planning determined that starting air compressors have a related detailed list of spare parts (Figure 4). Each item (spare part) has all the necessary details for ordering and storing.

Numerous and frequent spare parts transactions show the regular use of this part of the computerized PMS. The quantity of individual items in the store is duly recorded, together with the location where the spare part is located.

Significance analysis is analysed through Significance index (SI), which shows the seriousness of the event and the magnitude of the expected loss associated with an unexpected (unwanted) event [20]. Significance index is divided into two smaller parts, safety and operational, value ranges from 0 to 1. (Table 5.) Analysed equipment is important for starting and manoeuvring of the machinery; therefore, the significance index of the whole system is relatively high, both in safety and operational category.

Name	Maker's Reference	Default Location	Unit	Stock Class
Crankshaft	Ref 064 433 - 064 601 Compressor WP121 pos 2	1-STR-B19 - Store room - box 19	PCS	SPR
Connecting rod	Ref 064 568 - 064 601 Compressor WP121 pos 3	1-STR-B19 - Store room - box 19	PCS	SPR
Piston 1st stage	Ref 033 185 - 064 601 Compressor WP121 pos 6	1-STR-B19 - Store room - box 19	PCS	SPR
Piston 2nd stage	Ref 057 520 - 064 601 Compressor WP121 pos 7	1-STR-B19 - Store room - box 19	PCS	SPR
Piston 3rd stage	Ref 057 523 - 064 601 Compressor WP121 pos 8	1-STR-B19 - Store room - box 19	PCS	SPR
Cylinder with head and valve 1st stage	Ref 064 408 - 064 601 Compressor WP121 pos 9	1-STR-B19 - Store room - box 19	PCS	SPR
Cylinder with head and valve 2nd stage	Ref 064 409 - 064 601 Compressor WP121 pos 10	1-STR-B19 - Store room - box 19	PCS	SPR
Cylinder with head and valve 3rd stage	Ref 064 411 - 064 601 Compressor WP121 pos 11	1-STR-B19 - Store room - box 19	PCS	SPR
Cooler and air lines	Ref 064 412 - 064 601 Compressor WP121 pos 12	1-STR-B19 - Store room - box 19	PCS	SPR
Crankcase vent	Ref 064 423 - 064 601 Compressor WP121 pos 13	1-STR-B19 - Store room - box 19	PCS	SPR

Figure 4 Starting air compressor spare parts
Slika 4. Rezervni dijelovi kompresora zraka za upućivanje

Table 5 The Significance index (gradation of failure effects) [20]
Tablica 5. Indeks važnosti (stupnjevanje učinka kvara)

Class	Magnitude	SI	Possible failure effects
Safety	Catastrophic	1	deaths; loss of ship; environmental catastrophe
	Critical	0.1	critical injury; major ship damage
	Severe	0.01	minor injury; damage to ship; secondary damage
	Marginal	0.001	possible injury; possible damage to ship
	Negligible	<0.0001	no injury; no damage to ship or environment
Operation	Not available	0.01	the ship is unavailable for operation during some days
	Partially Available	0.001	the ship is unavailable for operation during some hours
	Reduced Performance	0.0001	the ship operates with reduced performance
	Available	<0.00001	the ship is fully operational

Table 6 Reliability of the system, calculated on initial maintenance plan (in %)

Tablica 6. Izračun pouzdanosti sustava na inicijalnom planu održavanja (u %)

Hours	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	65000	7000	7500	8000
Reliability	99.997	99.974	99.916	99.811	99.648	99.420	99.122	98.750	98.303	97.779	97.178	96.502	95.754	94.935	94.047	93.095

Considering the above, the parameters can be determined:

- Safety significance index SI(S) > 0.01
- Operational significance index SI(O) > 0.0001

Expected Life Failure Frequency (ELFF) [4], [20] is defined as the number of failures occurring during the life of equipment. The life span of the ship and its equipment today ranges from 20 to 30 years, depending on the type and purpose of the ship [7], i.e. an average of 25 years. This value will be used as a parameter for the following calculations. In nine years, only two failures were recorded, and the ELFF of the corrective maintenance can be calculated:

$$\mathrm{ELFF} = \mathrm{F(T)}\frac{\mathrm{L}}{\int_0^{\mathrm{T}} \mathrm{R(t)dt}} = 5.5556 \quad (1)$$

where:

F(T) – probability of failure within T

L – Component lifetime, in this case ship's lifetime

$\int_0^{\mathrm{T}} \mathrm{R(t)dt}$ - reliability weighted cycler of interval T

Risk index (RI) [4], [20] is a product of the Expected Life Failure Frequency and the Significance index:

$$RI = SI * ELFF \quad (2)$$

By entering the equation, the following values are obtained:

$RI_{(S)} = 0.055556$

$RI_{(O)} = 0.00055556$

Redundancy reduces the risk index because it considers the probability that the backup device will fail when the main device has already been broken down. In the case of three compressors, the risk index reduction is defined by equation:

$$RI(T) = RI * FS_1 * FS_2 \quad (3)$$

where:

FS1 – the probability that the backup device will fail during the repair of the first device.

FS2 – the probability that the second backup device will fail during the repair of the first and backup device.

FS1 = FS2 = 0.000231

The probability that the backup device will fail during the repair of another device is calculated according to the equation [4], [20]:

$$FS(Tr) = 1\text{-}e^{\frac{Tr}{\lambda}\sum_{i=1}^{n} lnRI(L)} \quad (4)$$

Where:

Tr – time needed to repair the device

λ – failure rate

Same value can be calculated if the median downtime is divided by the median time between failures and the average daily operating time of the compressor.

As values FS_1 and FS_2 are very small, the overall risk index will be negligible:

$RI(T) < 0.055556 * 2.31*10^{-4} * 2.31*10^{-4}$

$RI(T) < 0.2965*10^{-8}$

The risk analysis considers the overall risk index and assesses the level of risk for the system in the event of a failure. According MA-CAD method, when the risk index is less than 0.0005, no further analysis is required [4]. In this case, the risk is several times smaller than the above, i.e. the total risk is negligible, and there is no need for further analysis.

According MA-CAD method and in view of the above, if no other requirements exist, the analysed equipment could be maintained in this case by a corrective method.

Reliability analysis of Initial Maintenance Plan is one of the requirements of the MA-CAD method. In this case, the analysed sample is small as well as the number of failures, therefore results should be taken with a degree of distrust [19]. An exponential method is used as the simplest method of calculating reliability.

Failure rate is calculated according to the equation 5 and amounts to $66.007 * 10^{-6}$ [h^{-1}], when entered data from Table 2.

$$\lambda = \frac{n}{t} \quad (5)$$

where:

λ – failure rate

n – number of failures

t – running time of the component (equipment)

Reliability of the parallel system [3] is calculated per equation:

$$R_{sys}(t) = 1 - \prod_{i=1}^{n}[1 - R_i(t)] = 1 - [(1 - R_1) * (1 - R_2) * (1 - R_3)] \quad (6)$$

where:

$R_{sys}(t)$ – reliability of system in time

R_1 – reliability of the first component

R_2 – reliability of the second component

R_3 – reliability of the third component

Results are presented in the Table 6.

The MA-CAD method usually uses a multiparameter Weibull analysis when analysing system reliability. As already mentioned, the analysed sample and the number of failures is small, and the results of one-parameter analysis should be taken with a certain dose of reserve. Similar to one-parameter analysis, Weibull's multiparameter distribution has a limited degree of confidence with a smaller number of failures. Therefore, the Γ-exponential method with custom reliability data was used for the multi-parameter reliability calculation [8]. To minimize the impact of a small sample and a small number of failures of the observed system, the calculation includes data of failures from one of the reliability databases. When considering which values to include in a multiparametric analysis, the values of two generic databases are reviewed (Table 7).

Table 7 Air compressor's failure index in generic databases

Tablica 7. Indeks kvara kompresora u generičkim bazama podataka

Failure rate OREDA-2002 [17]	$\lambda=166.07*10^{-6}$	[h^{-1}]
Failure rate NPRD-2011 [14]	$\lambda=90.383*10^{-6}$	[h^{-1}]
Failure rate NPRD-2011 (military ships) [14]	$\lambda=114.469*10^{-6}$	[h^{-1}]

The data in the OREDA DB was obtained by collecting data on the operation of equipment on ships and platforms mostly in aggressive marine environment. NPRD database data contains data from systems operating in the marine environment, as well as from land-based equipment. As devices, analysed in this paper, are used on board, data from the OREDA database [17] are taken for the calculation of the parameter λ.

Table 8 Analytical solution of estimation of parameter λ [8]

Tablica 8. Analitičko rješenje procjene parametra λ [8]

Failure n_i	Time T_i [h]	α_i	β_i	λ_i
0	0.000	1.0	6021	$166.07*10^{-6}$
1	13382	2.0	19403	$103.08*10^{-6}$
2	20217	3.0	26238	$114.34*10^{-6}$

Notes: αi – i[th] number of failures
βi – i[th] running time of the equipment
$\boldsymbol{\lambda}_i$ – i[th] estimation of failure rate

With new, estimated values of λ, new reliability values were obtained for the initial maintenance plan (Table 9).

5. MA-CAD METHOD RECOMMENDATION / *Preporuke MA-CAD metode*

Considering the analysed parameters, and in view that both calculated risk indexes are negligible, the MA-CAD method recommends corrective maintenance. In this case there are other reasons limiting the maximum maintenance interval. Since the starting air system is one of the important systems of the ship, its maintenance is prescribed and controlled by Classification Societies. The rules of the Classification Societies, e.g. Lloyds Registry [12], for a compressed air system prescribe maintenance period not exceeding 60 months, except in special cases of condition monitored based maintenance.

Adapting to the requirements of the Classification Societies, the result of the MA-CAD analysis would recommend maintaining this system every 60 months.

The longest average daily operation had compressor No. 3 in the amount of 3.3 hours per day or converted to a five-year period of 6022.5 hours. This can be rounded to lower value, 6000 running hours.

Consequently, according to this analysis, the MA-CAD maintenance period recommendation would be 60 months or 6000 hours.

6. SITUATION AFTER THE MAINTENANCE PLAN MODIFICATION / *Stanje nakon modifikacije plana održavanja*

The reliability analysis after the maintenance interval modification is made by the exponential method and compared to the situation before the change. Changing the maintenance interval also changed the number of system failures and other parameters. In this case the Failure rate is $83.764 * 10^{-6}$ [h^{-1}].

The reliability comparison based on the original maintenance plan and the modified maintenance plan is shown in Figure 5, which compares Tables 6, 9 and 10.

Table 9 Reliability of the system, calculated by Γ-exponential method (in %)

Tablica 9. Izračun pouzdanosti sustava Γ-eksponencijalnom metodom

Hours	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	65000	7000	7500	8000
Reliability	99.983	99.874	99.609	99.146	98.463	97.552	96.413	95.055	93.493	91.744	89.828	87.766	85.578	83.286	80.91	78.468

Table 10 Reliability of the system, calculated on modified maintenance plan (in %)

Tablica 10. Izračun pouzdanosti sustava na modificiranom planu održavanja (u %)

Hours	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	65000	7000	7500	8000
Reliability	99.993	99.948	99.835	99.633	99.326	98.903	98.359	97.692	96.903	95.994	94.969	93.836	92.599	91.268	89.850	88.354

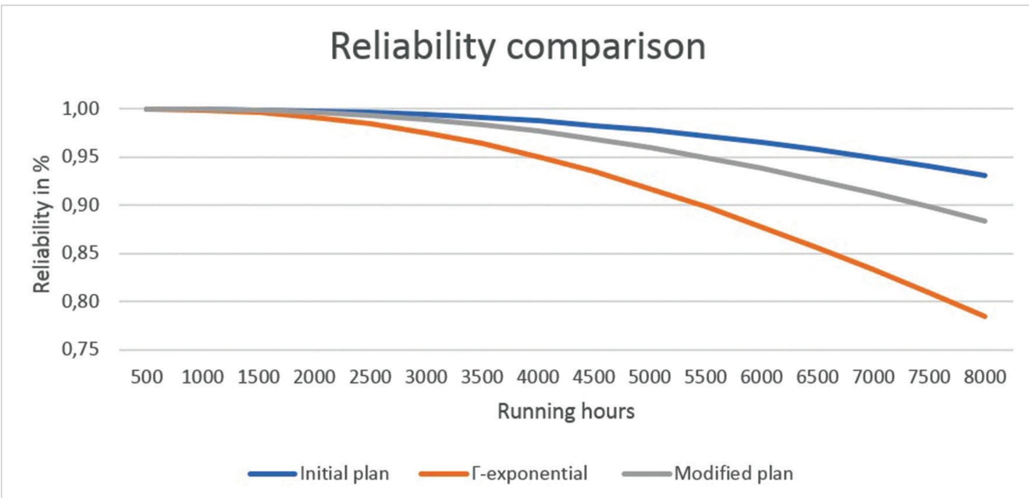

Figure 5 Comparison of system reliability

Slika 5. Usporedba pouzdanosti sustava

7. CONCLUSION / *Zaključak*

Reliability calculation presented in the Table 6 showed reliability of 98.75% at the end of the Maintenance period (4000 running hours) and confirmed the need to implement the modification of the maintenance plan. Result of the reliability calculation by Γ-exponential method, presented in the Table 9 have significantly lower reliability of 95.055% at same moment, adding a note of caution on the modification of the maintenance plan. The results of the MA-CAD analysis showed that the maintenance period extension is limited with the rules of the Classification Societies (Chapter 6) and the maximum maintenance period extension can be 5 years (60 months) in which the compressor will run approximately 6000 running hours. MA-CAD analysis is fully supporting the crew's request that the maintenance interval should be increased by 50%. The proposed increase will produce a reduction of the maintenance costs, while at the same time the reliability of the system will drop to 96.502% (only 2.2%) at the end of the new maintenance period of 6000 running hours (Figure 5).

Modification of the Maintenance plan i.e. increase of the Maintenance period by 25%, although not as much as required, should be marked as positive as it has led to significant maintenance savings. Projected decrease of the reliability of the system, calculated by exponential method should be just 1% lower (97.779%) at the end of the maintenance period of 5000 running hours. At the same time Γ-exponential method projects decrease of the reliability of more than 3% (to 91.744%) at the end of the maintenance period.

Analisys of the reliability of the system performed after the modification showed that the reliability at the end of the maintenance period dropped to 95.994%, which is more than 1,5% lower than predicted in the Table 6 (97.779%). Obtained result is still much higher than the result calculated by Γ-exponential method (91.744%).

During the research for the paper and inspection of company databases, the following shortcomings were noted:

- The maintenance interval adjustment procedure was completed after two maintenance cycles, although analysis and adjustment could have been made after the first cycle. Therefore, the maintenance resources on the initial plan were spent unnecessarily.
- The procedure for setting the interval was not preceded by a systematic analysis of the maintenance plan, it was performed experimentally, thus missing the opportunity to achieve the optimal interval adjustment effect.
- After the interval adjustment, no analysis of the performed procedure was carried out, therefore, results of the action on the reliability of the system were not observed and the maintenance interval was not readjusted.
- Although inventory and updating of quantities in the computer system were performed on a regular basis, the shipowner failed to activate the option of a computer system that would automatically monitor the minimum quantities of key spare parts. Turning on this option will further increase system reliability and decrease risk.

Although the crew's request for the modification of Maintenance plan was fully in accord with the results of the MA-CAD analysis, the question remains whether this case is an educated guess or a simple coincidence. It will remain unanswered due to the lack of available data and no similar case is present in the company database.

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