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Modelling the Stages of Turbocharger Dynamic Reliability by Application of Exploitation Experience

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Abstract: Turbocharger is an important part of marine diesel engine installed as main propulsion on board. It is in operation from the outset and throughout the marine diesel engine exploitation. In order to meet high reliability criteria, a combination of mathematical, IT and simulation methods should be used. The original mathematical model of turbocharger has been shown in five stages. The paper presents database link from the AMOS maintenance software package, a mathematical model elaborated by using Markov chains and a systematic-dynamic simulation model elaborated in the POWERSIM simulation programme. Results will be used to monitor and predict reliability and availability of turbocharger in ship's propulsion system.

Keywords: AMOS (Administration of Maintenance, Operations and Spares); Markov models; system reliability; turbocharger in ship's propulsion system

1 INTRODUCTION

All ship's systems, including turbocharger, must fulfil all the requirements as prescribed, i.e. reliability and availability throughout the ship's period of exploitation. By regular monitoring of the operation and turbocharger maintenance through utilizing the AMOS maintenance software package, it is easy to fulfil the prescribed requirements [1-3]. Extended maintenance intervals may have very costly consequences but on the other hand, it may not be economical to perform it too frequently, [4]. Data for elaboration of the mathematical and simulation model have been collected from the AMOS database on the m/v Exp [5]. The results obtained by simulation with the programme package POWERSIM will be used to compare, monitor and predict reliability and availability of turbocharger while the ship is in exploitation [6-8].

2 TURBOCHARGER FAILURES AND THE EFFECT ON THE MODEL

Turbocharger is part of the ship's propulsion system which must meet high reliability and availability criteria at any stage of propulsion system operation. In order to meet the criteria the turbocharger must be maintained in accordance with the manufacturer's instructions and by applying the ships' systems maintenance software package AMOS.

To facilitate modelling the turbocharger is divided into three parts:

- compressor
- turbocharger housing
- turbine.

All three parts of the turbocharger are subject to the following failures:

1) mechanical failures
2) failures due to vibrations
3) failures due to insufficient lubrication
4) failures due to diesel engine operation.

Regular monitoring of certain parameters when in stand-by mode and during operation, is of utmost importance. All tests and measurements made are recorded in the log as well as the maintenance software package used. Measurement instruments must not be exposed to vibrations or any damages whatsoever. Otherwise, the measurement instrument must be replaced with a new one in order to proceed with monitoring of the turbocharger operation.

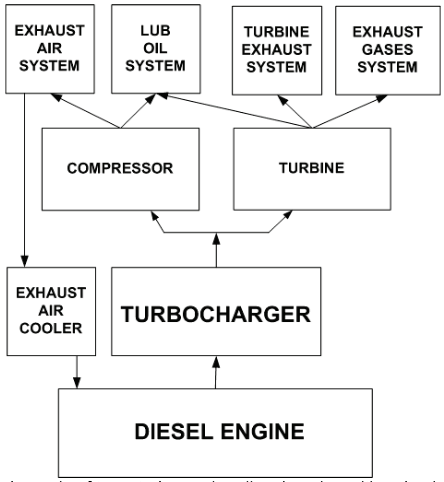

Figure 1 Schematic of two-stroke marine diesel engine with turbocharger MAN B&W

3 MATHEMATICAL RELIABILITY MODEL OF TURBOCHARGER

The Markov chains have been applied [9-11]. The Markov turbocharger model has been used to describe the possible turbocharger system statuses.

Meanings of symbols on Markov model in Fig. 2:

0 - turbocharger status in operation,
1 - status compressor failure,
2 - status turbocharger housing failure,
3 - status turbine failure,
4 - status restricted operation of diesel engine without turbocharger.

Frequency of shifting from status to status:

$\lambda_{01} = Lam\_01$ – frequency of shifting from status 0 in operation into status 1 compressor failure,

$\alpha_{14} = Alfa\_14$ – frequency of shifting from status 1 compressor failure into status 4 restricted operation of diesel engine without turbocharger,

$\lambda_{02} = Lam\_02$ – frequency of shifting from status 0 in operation into status 2 turbocharger housing failure,

$\alpha_{24} = Alfa\_24$ – frequency of shifting from status 2 turbocharger housing failure into status 4 restricted operation of diesel engine without turbocharger,

$\lambda_{03} = Lam\_03$ – frequency of shifting from status 0 in operation into status 3 turbine failure,

$\alpha_{34} = Alfa\_34$ – frequency of shifting from status 3 turbine failure into status 4 restricted operation of diesel engine without turbocharger,

$\mu_{40} = Mi\_40$ – frequency of return from status 4 into status 0 in operation,

$\lambda(t) = \dfrac{1}{\overline{T}_{ur}} = \lambda_{0n}$ – frequency of shifting from status in operation into status failure.

$\mu(t) = \dfrac{1}{\overline{T}_{uk}} = \mu_{n0}$ – frequency of repair or return from status failure into status in operation.

$\alpha(t) = \dfrac{1}{\overline{T}_{uog-r}} = \alpha_{nn}$ – frequency of shifting from status failure into status restricted which operation of diesel engine without turbocharger.

$Rn(t) = e^{-\lambda_{0n} t}$ – reliability of technical system

n = 1, 2, 3, 4 – status number.

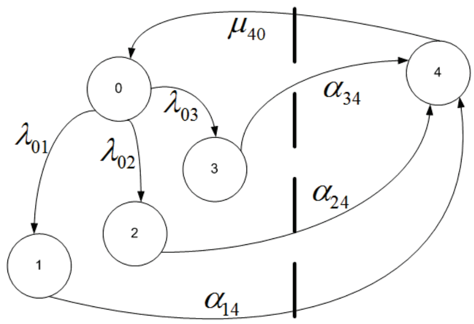

Figure 2 Markov model of turbocharger system status for two-stroke marine diesel engine MAN B&W 6L60MC of the propulsion system on board the m/v Exp

Since this is a series of all three statuses in case of failure on one of the statuses the system shifts into status 4, restricted operation of diesel engine without turbocharger.

Under status 4 restricted operation of diesel engine without turbocharger it is to be understood that only auxiliary blower is engaged and the engine is under reduced working load, i.e. the engine is working under special regime. Although the engine is working without turbocharger and under special regime its reliability is maintained, this being an advantage of the diesel engine.

In case of turbocharger failure, the turbocharger is to be blocked and auxiliary blowers to be engaged to enable the diesel engine operation at reduced rpm.

Once the failure on status 4 has been repaired the system returns into status 0 in operation, i.e. diesel engine operation with turbocharger under full load, and as soon as the scavenge air pressure is increased (over 0.5 bars) the auxiliary blowers are switched off.

Fig. 2 shows Markov model of turbocharger status in exploitation. Each status is described by linear differential equation.

Status 0:

$$\frac{\mathrm{d}P_0(t)}{\mathrm{d}t} = -(\lambda_{01} + \lambda_{02} + \lambda_{03})P_0(t) + \mu_{40}P_4(t) \tag{1}$$

Status 1:

$$\frac{\mathrm{d}P_1(t)}{\mathrm{d}t} = \lambda_{01}P_0(t) - \alpha_{14}\ P_1(t) \tag{2}$$

Status 2:

$$\frac{\mathrm{d}P_2(t)}{\mathrm{d}t} = \lambda_{02}P_0(t) - \alpha_{24}P_2(t) \tag{3}$$

Status 3:

$$\frac{\mathrm{d}P_3(t)}{\mathrm{d}t} = \lambda_{03}P_0(t) - (\mu_{30} + \alpha_{31})P_3(t) \tag{4}$$

Status 4:

$$\frac{\mathrm{d}P_4(t)}{\mathrm{d}t} = \alpha_{14}\ P_1(t) + \alpha_{24}P_2(t) + \alpha_{34}P_3(t) - \mu_{40}P_4(t) \tag{5}$$

Initial conditions determined at the moment $t = 0$ can be described as follows:

$$P_0(0) = 1;\ P_1(0) = 0;\ P_2(0) = 0;\ P_3(0) = 0;\ P_4(0) = 0 \tag{6}$$

At each moment the condition defined by the identity equation must be fulfilled:

$$P_{uk} = P_0 + P_1 + P_2 + P_3 + P_4 = 1 \tag{7}$$

Stationary solution to the Markov model linear differential equations system is sought.

$$\frac{\mathrm{d}P_n(t)}{\mathrm{d}t} = 0\ ;\quad n = 0,1,2,3,4 \tag{8}$$

Stationary solution to the Markov model linear differential equations system for stationary process status representing a system of linear equations with unknown variables.

$$P_j\ ;\quad j = 0,1,2,3,4 \tag{9}$$

where:

$P_0\,(t)$ – probability of finding the system in status 0 in operation,

$P_1\,(t)$ – probability of finding the system in status 1 compressor failure,

$P_2\,(t)$ – probability of finding the system in status 2 turbocharger housing failure,

$P_3\,(t)$ – probability of finding the system in status 3 turbine failure,

$P_4\,(t)$ – probability of finding the system in status 4 restricted operation of diesel engine without turbocharger.

By solving the equation system (9) probabilities for stationary statuses of marine propulsion systems are determined:

$$P_0(t) = \frac{1}{1 + \frac{\lambda_{01}}{\alpha_{14}} + \frac{\lambda_{02}}{\alpha_{24}} + \frac{\lambda_{03}}{\alpha_{34}} + \frac{\lambda_{01} + \lambda_{02} + \lambda_{03}}{\mu_{40}}} \tag{10}$$

$$P_1(t) = \frac{\lambda_{01} P_0(t)}{\alpha_{14}} \tag{11}$$

$$P_2(t) = \frac{\lambda_{02} P_0(t)}{\alpha_{24}} \tag{12}$$

$$P_3(t) = \frac{\lambda_{03} P_0(t)}{\alpha_{34}} \tag{13}$$

$$P_4(t) = \frac{(\lambda_{01} + \lambda_{02} + \lambda_{03}) P_0(t)}{\mu_{40}} \tag{14}$$

3.1 Cycle of Turbocharger Model Status in the Marine Propulsion System

By using the Markov model of turbocharger status for a two-stroke diesel engine MAN B&W 6L60MC on the m/v Exp propulsion system, following statuses are described:

0 – turbocharger status in operation (during normal diesel engine operation),
1 – status compressor failure, shifting into status restricted operation of diesel engine without turbocharger (auxiliary blowers in operation, reduced load and rpm),
2 – status turbocharger housing failure, shifting into status restricted operation of diesel engine without turbocharger (auxiliary blowers in operation, reduced load and rpm),
3 – status turbine failure, shifting into status restricted operation of diesel engine without turbocharger (auxiliary blowers in operation, reduced load and rpm),
4 – status restricted operation of diesel engine without turbocharger, (diesel engine shifting into status without turbocharger – auxiliary blowers in operation, reduced load and rpm).

By using the database of AMOS maintenance software package for marine diesel engine, model parameters are calculated, as well as the number of status shifts and the time spent under respective turbocharger statuses.

The data obtained is used to calculate the average times:

$\overline{T}_{01}$ – average time in status 0 until shifting into status 1,
$\overline{T}_{14}$ – average time in status 1 until shifting into status 4,
$\overline{T}_{02}$ – average time in status 0 until shifting into status 2,
$\overline{T}_{24}$ – average time in status 2 until shifting into status 4,
$\overline{T}_{03}$ – average time in status 0 until shifting into status 3,
$\overline{T}_{34}$ – average time in status 3 until shifting into status 4,
$\overline{T}_{04}$ – average time in status 0 until shifting into status 4,
$\overline{T}_{40}$ – average time in status 4 until shifting into status 0,

The table with calculations of average times for respective turbocharger statuses is used to calculate frequency parameters of status shifts. Average times are calculated according to failure frequencies, i.e. frequencies of status shifts. This being an exponential distribution, the failure frequencies or shifts are constant.

Frequency of failures $\lambda(t)$ is constant and it is calculated by expression (15), where frequency of shifts from status in operation into status failure reads λ_{0n}, n = 1, 2, 3.

$$\lambda(t) = \frac{1}{\overline{T}_{ur}} = \lambda_{0n} \tag{15}$$

Frequency of shifts from a status into a status which is not in operation $\alpha(t)$ and does not return into status in operation is calculated by expression (16), where α_{0n}, n = 1, 2, 3.

$$\alpha(t) = \frac{1}{\overline{T}_{st}} = \alpha_{0n} \tag{16}$$

Frequency of repairs $\mu(t)$ is constant and it is calculated by expression (17).

$$\mu(t) = \frac{1}{\overline{T}_{uk}} = \mu_{40} \tag{17}$$

$$Rn(t) = e^{-\lambda_{0n} t} \tag{18}$$

T_{srur_n} - average time in operation until the system reaches status n (status number n = 1, 2, 3, 4), average time in operation until the system reaches the status has been defined by status reliability $Rn(t) = e^{-\lambda_{0n} t}$ (18) and system failure frequency λ_{0n}.

$$T_{srur\_n} = \overline{T}_{ur\_n} = \int_0^\infty Rn(t)\,\mathrm{d}t = \int_0^\infty e^{-\lambda_{0n} t}\mathrm{d}t \tag{19}$$

T_{srur_n} or $\overline{T}_{ur\_n}$ is average time in operation until the system reaches status n.

The average times calculated shown in Tab. 1 have been obtained by measuring the time in operation t_{01} and time out of operation t_{10}, and the same has been done for each status being monitored t_{0n} and t_{n0}, where n = 1, 2, 3, 4. When describing shifts from status to status (failure or in operation) failures must be random and independent. The criteria that have to be satisfied are the time elapsed from system failure and the time required for repair. If a longer period is being monitored, the time in operation is taken as the average time in operation. This applies for each period since the components can be renewed:

$$\overline{T}_{0n} = \sum \frac{t_{0n}}{n_{0n}} \tag{20}$$

The same results are obtained for average time in the status failure (that is the average time under repair in the monitored interval)

$$\overline{T}_{n4} = \sum \frac{t_{n4}}{n_{n4}} \tag{21}$$

Frequency parameters of shifts from status to status in Markov model are calculated on the basis of data obtained from turbocharger in a marine propulsion system MAN B&W 6L60MC by application of AMOS maintenance software package database on the m/v Exp.

Frequency parameters of shifts from status to status in Markov model are calculated on the basis of data shown in Tab. 1 and these are inserted into Tab. 2.

Table 1 Average times calculated for respective statuses of turbocharger

$\overline{T}_{01}$ / h	$\overline{T}_{02}$ / h	$\overline{T}_{03}$ / h	$\overline{T}_{14}$ / h	$\overline{T}_{24}$ / h	$\overline{T}_{34}$ / h	$\overline{T}_{40}$ / h
42896,00	25965,00	36792,44	104,0000	46,0000	26,3895	51,2422
λ_{01}	λ_{02}	λ_{03}	α_{14}	α_{24}	α_{34}	μ_{40}
0,00002	0,00004	0,00003	0,0096	0,0217	0,0379	0,0195
P_0	P_1	P_2	P_3	P_4	P_{uk}	
0,9906	0,0024	0,0018	0,0007	0,0045	1,0000	

Table 2 Average frequencies calculated for respective statuses of turbocharger

Frequency of shifts from status in operation	Frequency of shifts from status to status (no return into status in operation)	Frequency of return into status in operation	Reliabilities for respective statuses
λ_{0n} / Lam_0n	$\alpha_{nn} = Alfa\_nn$	μ_{Z0} / Mi_n0	P_n
$\lambda_{01} / Lam\_01 = 0{,}00002$	$\alpha_{14} = Al\_14 = 0{,}0096$	$\mu_{40} / Mi\_40 = 0{,}0195$	$P_0 = 0{,}9906$
$\lambda_{02} / Lam\_02 = 0{,}00004$	$\alpha_{24} = Al\_24 = 0{,}0217$		$P_1 = 0{,}0024$
$\lambda_{03} / Lam\_03 = 0{,}00003$	$\alpha_{34} = Al\_34 = 0{,}0379$		$P_2 = 0{,}0018$
			$P_3 = 0{,}0007$
			$P_4 = 0{,}0045$
			$P_{uk} = 1{,}0000$

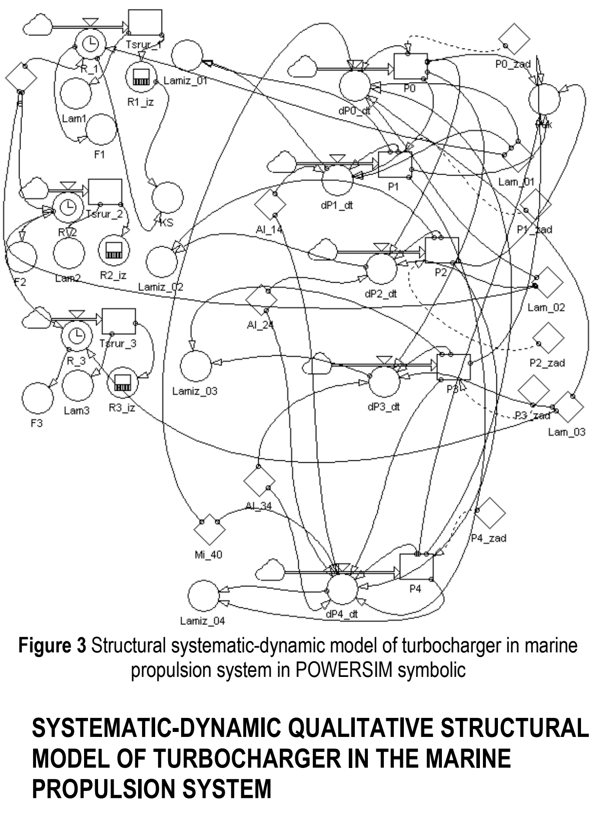

Figure 3 Structural systematic-dynamic model of turbocharger in marine propulsion system in POWERSIM symbolic

4 SYSTEMATIC-DYNAMIC QUALITATIVE STRUCTURAL MODEL OF TURBOCHARGER IN THE MARINE PROPULSION SYSTEM

Initial parameters utilized for elaboration of Markov model have been collected from Tab. 1 (AMOS database on the m/v Exp [5]).

Fig. 3 shows the structural systematic-dynamic model of the marine propulsion system for statuses: in operation, turbocharger failure (compressor failure, turbocharger housing failure, turbine failure) which is shifting into status restricted operation of diesel engine without turbocharger in POWERSIM symbols and systematic-dynamic qualitative structural model.

4.1 Result Analysis of Modelling of the Marine Propulsion Turbocharger Dynamic Reliability Statuses

Result analysis obtained by structural dynamic simulation model in POWERSIM symbols for turbocharger on the main propulsion system MAN B&W 6L60MC on the m/v Exp for 80.000 hours in operation is shown in Fig. 4, 5, 6, 7. On the basis of experimental data obtained the evaluation of the system operation will be made. Nevertheless, the simulation model must at all times fulfil the condition defined in the differentiation Eq. (7) and Fig. 7.

The results of the systematic-dynamic simulation model obtained for 80.000 hours in operation indicate that the reliability system corresponds to the exponential decay function, while unreliability and reliability take opposite direction ($1 = R_n + F_n$; $n = 1,2,3$).

Failure intensity (λ_n; $n = 1,2,3$) increases during the initial stage of system running in, while over time it tends to decrease and becomes constant. The simulation obtained for scenarios indicates that failure frequency corresponds to the bathtub curve, which confirms that the turbocharger reliability corresponds to the exponential distribution, where failure frequency after running in period is constant.

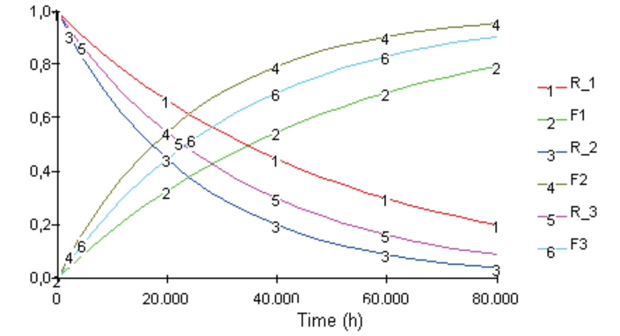

Figure 4 Diagram of reliability function “R_1, R_2, R_3“ and unreliability function “F1, F2, F3, F4, F5“

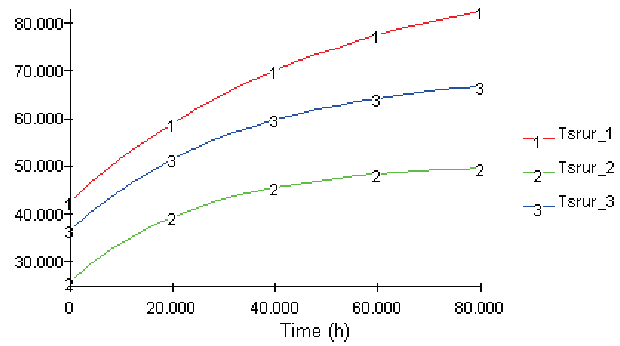

Figure 5 Diagram of functions of average times "in operation" until reaching one of the statuses “1, 2, 3“

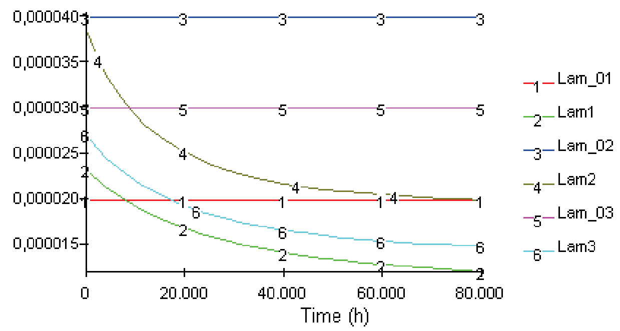

Figure 6 Diagram of failure intensity functions “Lam_1, Lam_2, Lam_3“

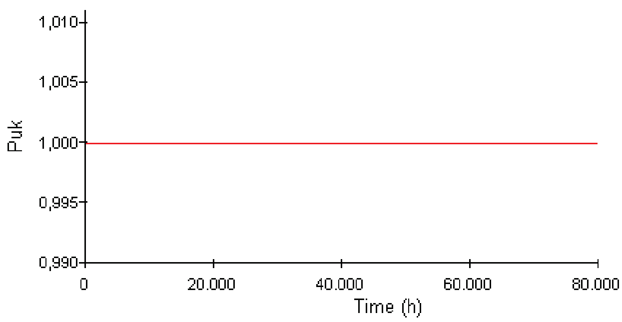

Figure 7 Condition to be satisfied at all times during observation. Summary of probability status

Regression equations, determination coefficients R^2 and regression coefficients R for all turbocharger statuses are shown in Tab. 3.

The results of reliability and shifting frequency regression show that the system reliability curves for each status are best approximated by the exponential curve, while the shifting frequency curves are approximated by the polynomial curve.

Table 3 Regression equations, determination coefficients and regression coefficients for turbocharger status

$Y = f(t)$	Regression Equation	R^2	R
$R\_1 = f(t)$	$Y1 = 0{,}999e^{-2E-0X}$	1	1
$Lam1\_1 = f(t)$	$Y1 = -3E - 10X + 2E - 0{,}5$	0,984	0,991
$R\_2 = f(t)$	$Y2 = 0{,}999e^{-4E-0X}$	1	1
$Lam2\_2 = f(t)$	$Y2 = -5E - 10X + 4E - 0{,}5$	0,947	0,973
$R\_3 = f(t)$	$Y3 = 1{,}000e^{-3E-0X}$	1	1
$Lam3\_3 = f(t)$	$Y3 = -3E - 10X + 3E - 0{,}5$	0,972	0,986

5 CONCLUSION

By integration of Markov models and systematic-dynamic models along with application of database, reliable parameters can be calculated to describe availability of technical systems such as turbochargers.

Regression analysis, determination coefficient and regression coefficient have been applied indicating the strong link between system reliability and time period.

By application of systematic dynamics modelling and analysis of complex technical systems the reliability and availability in realistic time periods have been made possible.

This process from the mathematical model to the systematic-dynamic simulation model and regression analysis provides possibilities to determine approximate reliability values with respect to time period for respective system statuses as well as frequencies of shifting from status to status.

This method of analysis increases the quality and facilitates planned maintenance. Moreover, the possibility to anticipate and correct the system status is provided thus enabling the system exploitation cost reduction.

6 REFERENCES

[1] Jurjević, M. & Bilić, B. (2009). Reliability Calculation of Marine Propulsion System Applying the Data from the Software Package AMOS. *Naše more, 56*(3-4).

[2] Jurjević, M., Bilić, B., Milić-Beran, I., & Zekić, H. (2008). Application of the software package AMOS in maintenance of the marine propulsion system. *2nd International Maritime Scientific Conference – IMSC*, Lumbarda, 151-159.

[3] Jurjević, M., Bilić, B., & Veža, I. (2007). Method of technical system reliability analysis by application of exploitation experience. *11th International scientific conference on production engineering – CIM2007*, Biograd, 175-180.

[4] Stazic, L., Komar, I., & Račić, N. (2017). Evalution Methodology for Ship’s Planned Maintenance System Database. *Transactions on maritime science, 6*(2), 109-116. https://doi.org/10.7225/toms.v06.n02.002

[5] (2008). Spec Tec: AMOS-Serving the World's Shipping: Database for marine propulsion system MAN B&W 6L60MC on the m/v Exp.

[6] Baliwangi, L., Arima, H., Ishida, K., & Artana, K. B. (2007). Simulation on System Operation and Maintenance Using System Dynamics. *Journal of the JIME, 42*(5), 129-133. https://doi.org/10.5988/jime.42.5_890

[7] Jurjević, M., Jurjević, N., & Koboević, N. (2012). Modelling of dynamic reliability stages of a ship propulsion

system with safety and exhaust emission. *Tehnički vjesnik – Technical Gazette, 19*(1), 159-165.
[8] Jurjević, M. (2009) Simulation modelling of technical system reliability by application of systematic dynamics, *Doctoral thesis*, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture (FESB), Split.
[9] Jurjević, M., Bilić, B., & Veža, I. (2007) Method of technical system reliability analysis by application of exploitation experience. *11th International scientific conference on production engineering – CIM2007*, Biograd.
[10] Bilić, B., Jurjević, M., & Barle, J. (2010). Reliability Estimation of Technical System Using Markov Models and System Dynamics. *Strojarstvo, 52*(3), 271-281.
[11] Chan, G. K. & Asgarpoor, S. (2006). Optimum maintenance policy with Markov processes. *Electric Power Systems Research, 76*, 452-456. https://doi.org/10.1016/j.epsr.2005.09.010
[12] Grabski, F. (2014). *Semi-Markov processes: applications in system reliability and maintenance*. Oxford, Elsevier

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