ISSN 1330-3651
UDC/UDK [629.5.054.03:629.5.017]:519.217

MODELLING OF DYNAMIC RELIABILITY STAGES OF A SHIP PROPULSION SYSTEM WITH SAFETY AND EXHAUST EMISSION

Mate Jurjević, Nataša Jurjević, Nikša Koboević

Preliminary notes

This paper elaborates on the efficacy of application of the combination of Markov chains and systematic-dynamic modelling during research on technical systems reliability problem. The original mathematical model of a ship propulsion system has been shown in six stages. The very combination of Markov model with systematic-dynamic model contributes to original solution to the problem of the ship propulsion system reliability. By the application of systematic-dynamic simulation model it is possible to quantify the system structure maintenance efficacy parameters and enable better reliability and availability of a specific technical system. Simulation programme POWERSIM has been used to simulate the subject simulation model. AMOS maintenance programme package data base has been applied, which is being used on board the m/v Explorer. On the basis of the results obtained it is possible to plan and timely and efficiently influence a higher quality ship propulsion systems management.

Keywords: *AMOS (Administration of Maintenance, Operations and Spares), maintenance, Markov models, ship propulsion systems, simulation modelling, system reliability, systematic dynamics*

Modeliranje dinamičkih stanja pouzdanosti brodskog porivnog sustava sa zaštitnom i ispušnom emisijom

Prethodno priopćenje

U radu je prikazana uspješnost primjene spoja Markovljevih lanaca i sustavno dinamičkog modeliranja pri istraživanju problema pouzdanosti tehničkih sustava. Prikazan je originalni matematički model brodskog porivnog sustava sa šest stanja. Sam spoj Markovljevog modela sa sustavno dinamičkim simulacijskim modelom, doprinosi originalnosti rješavanja problema pouzdanosti brodskog porivnog sustava. Primjena sustavno dinamičkog simulacijskog modela omogućuje kvantifikaciju parametara efektivnosti održavanja strukture sustava i utječe na poboljšanje pouzdanosti i raspoloživosti konkretnog tehničkog sustava. Izrađeni simulacijski model simuliran je pomoću simulacijskog programa POWERSIM. Korištena je baza podataka programskog paketa održavanja AMOS, koji se koristi na M/B Explorer. Na temelju dobivenih rezultata može se planirati te pravodobno i učinkovito utjecati na kvalitetnije upravljanje brodskim porivnim sustavima.

Ključne riječi: *AMOS (Administration of Maintenance, Operations and Spares), brodski porivni sustavi, Markovljevi modeli, održavanje, pouzdanost sustava, sustavna dinamika, simulacijsko modeliranje*

1 Introduction

To enable successful monitoring of a ship propulsion system status it is necessary to collect sufficient data on the monitored systems. The statistical evaluation and analysis of data collected alone is no longer sufficient for a successful maintenance of modern ship propulsion systems, but, on the other hand, the process of research on real systems can be very expensive, long-lasting and uncertain [1]. Consequently, it is to be concluded that the data collected on a technical system operation, besides statistical evaluation and analysis of the results, could also be used for research and operation monitoring as well as the technical system reliability model analysis. By the application of the simulation model it will be possible in the very design stage, i.e. in the preliminary stage of the technical system design, to make changes in design and construction and during operation to optimise exploitation of a ship propulsion system. We are experiencing the wakening of human conscience, man is paying more attention to environmental standards in order to remedy the damages and return the balance. He is being directed on that path by the IMO (International Maritime Organisation) and EPA (Environmental Protection Agency) rules. Designers and technicians comply with these rules [2]. Many manufacturers of marine diesel engines, such as MAN B&W are implementing the programme for monitoring and reduction of exhaust emission in accordance with the IMO rules. Thus, reliability and availability will be increased and environmental requirements for marine propulsion system during its working life will be met.

2 Mathematical model of a ship propulsion system with the status of pollution by exhaust emission obtained by Markov model

After manufacture of diesel engine, and prior to installation on board, a workshop trial is performed to avoid any faults that may cause breakdowns during operation, and consequently engine malfunction [3]. The trial reduces the running-in period, i.e. the period of initial malfunctions, and assists the engine manufacturer in reducing the percentage of initial malfunctions to the minimum.

Ship propulsion system is very often, for cleaning purposes, dismantled earlier than scheduled, which is not recommended, since during dismantling and re-assembly certain malfunctions may occur leading to the system breakdown. Obviously, many malfunctions cannot be foreseen, but by proper maintenance they can be reduced to the minimum. For easier monitoring and timely reaction it is necessary to divide the diesel engine into sub-systems, Fig. 1.

Emission control was performed on the ship propulsion system, main emission components of exhaust gases CO, CO_2, NO_x, SO_2, CH and O_2 were monitored, as well as diesel engine working parameters [4]. Fig. 2 shows sample collecting and analytical equipment for measurement of exhaust emission during normal operation. Sample collection is done by tubes, and exhaust gases pass through (sintered) cheramic filter and through heated line are brought to the measuring spot in gas analysers and auxiliary instruments. The relation between produced NO_x and engine load is measured during workshop trial. The ratio obtained is used for exhaust emission control [4]. NO_x

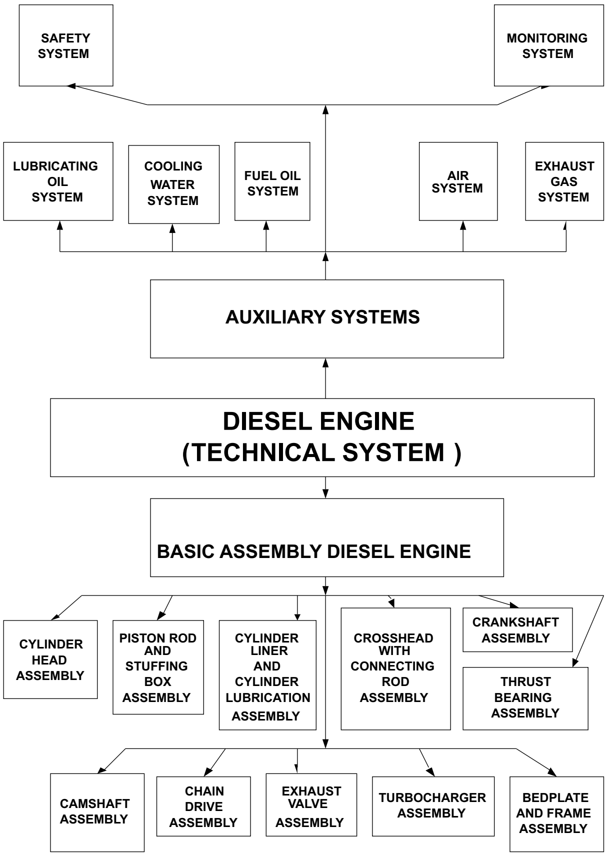


Figure 1 Schematic of ship propulsion system with relevant systems and sub-systems [3]

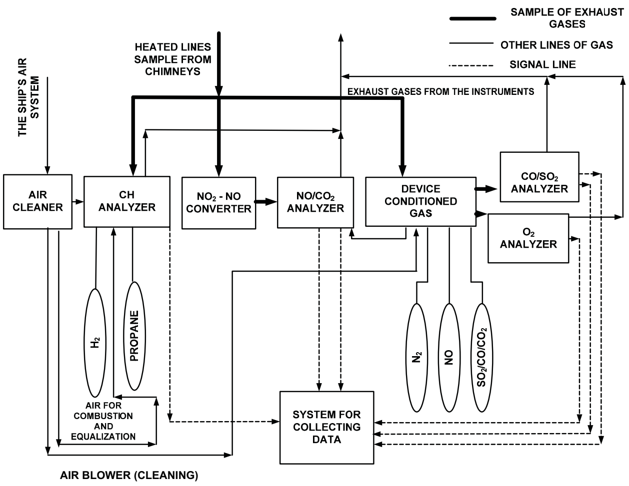


Figure 2 Schematic of data sampling for control and measurement of exhaust gas emission [3]

emission must be measured at various loads following the schedule prescribed by ISO 81781.

The two additional situations - status *safety* and status *exhaust emission*, occuring when the system exits status 0 *in operation*, are the following:

- reduction of the number of revolutions due to malfunction of the system (e.g. turbocharger malfunction), or of components without which the system can function, although at reduced rpm (e.g. the function of turbocharger is assumed by auxiliary chargers) and status of the propulsion automatic control system in case of malfunction of any of the components that are necessary for normal operation of the system (prevents further damage to engine).
- situation when due to excessive wear or fracture the system does not return to initial position 0 *in operation* but blocks. Due to malfunction the emergency system is automatically activated and exhaust emission is increased.

Markov model of the ship propulsion system for statuses *in operation*, *malfunction*, *out of operation* (total breakdown), with respect to the regular inspection, safety and pollution by exhaust emission is shown in Fig. 3. At the same time minor system malfunctions are neglected (leakages, fractures of seal rings, change of filter on oil mist detector, replacement of inserts on filters and cleaning, the system assuming malfunction status due to automatics,...).

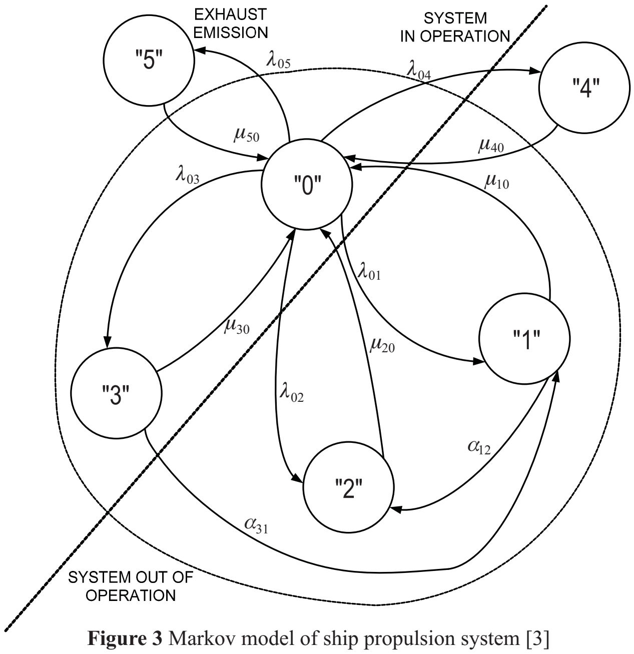


Figure 3 Markov model of ship propulsion system [3]

Symbols in Fig. 3 have the following meanings:

0 – system status *in operation*,
1 – system status *malfunction*,
2 – system status *out of operation* (total breakdown),
3 – system status *regular inspection*,
4 – system status *safety* (*reduced rpm and shut-down*),
5 – system status *pollution by exhaust emission*,
$\lambda_{01} = Lam\_01$ – frequency of shifting from status 0 *in operation* into status 1 *malfunction*,
$\mu_{10} = Mi\_10$ – frequency of system return from status 1 *malfunction* into status 0 *in operation*,
$\lambda_{02} = Lam\_02$ – frequency of shifting from status 0 *in operation* into status 2 *out of operation*,
$\mu_{20} = Mi\_20$ – frequency of return from status 2 *out of operation* into status 0 *in operation*,
$\lambda_{03} = Lam\_03$ – frequency of shifting from status 0 *in operation* into status 3 *regular inspection*,
$\mu_{30} = Mi\_30$ – frequency of return from status 3 *regular inspection* into status 0 *in operation*,
$\lambda_{04} = Lam\_04$ – frequency of shifting from status 0 *in operation* into status 4 *safety*,
$\mu_{40} = Mi\_40$ – frequency of system return from status 4 *safety* into status 0 *in operation*,
$\lambda_{05} = Lam\_05$ – frequency of shifting from status 0 *in operation* into status 5 *exhaust emission*,
$\mu_{50} = Mi\_50$ – frequency of system return from status 5 *exhaust emission* into status 0 *in operation*,
$\alpha_{12} = Al\_12$ – frequency of shifting from status 1

malfunction into status 2 *out of operation*,
$\alpha_{31} = Al\_31$ – frequency of shifting from status 3 *regular inspection* into status 1 *malfunction.*

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

$\lambda(t)$ – frequency of shifting from status z

$$\mu(t) = \frac{1}{\overline{T}_{uk}} = \mu_{0z} \tag{2}$$

$\mu(t)$ – frequency of repairs or return into status *in operation*

$$\alpha(t) = \frac{1}{\overline{T}_{st}} = \alpha_{0z} \tag{3}$$

$\alpha(t)$ – frequency of shifting from a status into status which is not in operation

$$Rz(t) = \mathrm{e}^{-\lambda_{0z} t} \tag{4}$$

$Rz(t)$ – reliability of technical system

$z = 1, 2, 3, 4, 5$ – status number.

The system from status 3 *regular inspection* (routine inspection recommended by the manufacturer) returns into status 0 *in operation* if the component is functioning. If during inspection the component is found to be defective the system shifts to position 1 *malfunction*. Once the malfunction has been repaired the system returns again into status 0 *in operation*. If the malfunction cannot be repaired, the system shifts into status 2 *out of operation* (total breakdown status) where repairs cannot be performed by the ship's crew but help from shore is requested (servicing and purchase of new components that are not stored on board). After each change of status when the system is not in status 0 *in operation* the status 4 *safety* and status 5 *increased exhaust emission* automatically respond. The system returns back to allowed or normal limits once it is in balance, i.e. normal exploitation status (status *in operation*).

In Fig. 3, Markov model is described by the system of linear differential equations. Each status is described by one linear differential equation [3].

Status 0:

$$\frac{\mathrm{d}P_0(t)}{\mathrm{d}t} = -(\lambda_{01} + \lambda_{02} + \lambda_{03} + \lambda_{04} + \lambda_{05}) P_0(t) + \mu_{10} P_1(t) + \\ + \mu_{20} P_2(t) + \mu_{30} P_3(t) + \mu_{40} P_4(t) + \mu_{50} P_5(t) \tag{5}$$

Status 1:

$$\frac{\mathrm{d}P_1(t)}{\mathrm{d}t} = \lambda_{01} \cdot P_0(t) - (\mu_{10} + \alpha_{12}) P_1(t) + \alpha_{31} \cdot P_3(t) \tag{6}$$

Status 2:

$$\frac{\mathrm{d}P_2(t)}{\mathrm{d}t} = \lambda_{02} \cdot P_0(t) + \alpha_{12} \cdot P_1(t) - \mu_{20} \cdot P_2(t) \tag{7}$$

Status 3:

$$\frac{\mathrm{d}P_3(t)}{\mathrm{d}t} = \lambda_{03} \cdot P_0(t) - (\mu_{30} + \alpha_{31}) P_3(t) \tag{8}$$

Status 4:

$$\frac{\mathrm{d}P_4(t)}{\mathrm{d}t} = \lambda_{04} \cdot P_0(t) - \mu_{40} \cdot P_4(t) \tag{9}$$

Status 5:

$$\frac{\mathrm{d}P_5(t)}{\mathrm{d}t} = \lambda_{05} \cdot P_0(t) - \mu_{50} \cdot P_5(t) \tag{10}$$

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

$$P_0(0) = 1;\ P_1(0) = 0;\ P_2(0) = 0;\ P_3(0) = 0;\ P_4(0) = 0;\ P_5(0) = 0.$$

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

$$P_{uk} = P_0 + P_1 + P_2 + P_3 + P_4 + P_5 = 1 \tag{11}$$

Stationary solution to the linear differential equations system of Markov model is given in expression (12).

$$\frac{\mathrm{d}P_n(t)}{\mathrm{d}t} = 0\,; \quad n = 0, 1, 2, 3, 4, 5. \tag{12}$$

By solving the equation system 6 probabilities for stationary statuses of marine propulsion systems are determined:
P_0 – probability of finding the system in status 0 *in operation*,
P_1 – probability of finding the system in status 1 *malfunction*,
P_2 – probability of finding the system in status 2 *out of operation* (total breakdown),
P_3 – probability of finding the system in status 3 *regular inspection*,
P_4 – probability of finding the system in status 4 *safety*,
P_5 – probability of finding the system in status 5 *exhaust emission.*

2.1 Cycle of the ship propulsion system model status

The numbers of shiftings and time periods in certain ship propulsion statuses are calculated for each interval separately, and the results are shown in Tab. 1.

For the model parameters to be calculated it is necessary to include the following data obtained from the programme package AMOS [5, 6] data base.

By the application of the stated data average times are calculated:
$\overline{T}_{0\_1}$ – average time spent in status 0 until shift into status 1,
$\overline{T}_{1\_0}$ – average time spent in status 1 until shift into status 0,
$\overline{T}_{0\_2}$ – average time spent in status 0 until shift into status 2,
$\overline{T}_{2\_0}$ – average time spent in status 2 until shift into status 0,
$\overline{T}_{0\_3}$ – average time spent in status 0 until shift into status 3,
$\overline{T}_{3\_0}$ – average time spent in status 3 until shift into status 0,
$\overline{T}_{0\_4}$ – average time spent in status 0 until shift into status 4,
$\overline{T}_{4\_0}$ – average time spent in status 4 until shift into status 0,
$\overline{T}_{0\_5}$ – average time spent in status 0 until shift into status 5,
$\overline{T}_{5\_0}$ – average time spent in status 5 until shift into status 0,
$\overline{T}_{1\_2}$ – average time spent in status 1 until shift into status 2,
$\overline{T}_{3\_1}$ – average time spent in status 3 until shift into status 1.

$$Tsrur\_z = \overline{T}_{ur\_z} = \int_0^\infty Rz(t)\,\mathrm{d}t \tag{13}$$

$Tsrur\_z$ – average time in operation until the system reached status z (status number $z = 1, 2, 3, 4, 5$).

Frequency parameters of shifts from one status into another in Markov model have been calculated on the basis of data given in Tab. 1. Frequency of system shifts from

Table 1 Calculated frequencies for statuses of individual marine propulsion system MAN B&W 6L60 MC by the application of AMOS data base on the m/v Explorer

Frequencies of shifts from status in operation	Frequencies of returns into status in operation	Frequencies of shifts from status into status (without return into status in operation)	Reliabilities for individual statuses
λ_{0Z} / Lam_0z	μ_{Z0} / Mi_z0	$\alpha_{ZZ} = Al\_zz$	P_z
$\lambda_{01} / Lam\_01 = 0{,}00003$	$\mu_{10} / Mi\_10 = 0{,}00253$	$\alpha_{31} = Al\_31 = 0{,}00861$	$P_0 = 0{,}9493$
$\lambda_{02} / Lam\_02 = 0{,}00004$	$\mu_{20} / Mi\_20 = 0{,}00241$	$\alpha_{12} = Al\_12 = 0{,}01695$	$P_1 = 0{,}0024$
$\lambda_{03} / Lam\_03 = 0{,}00005$	$\mu_{30} / Mi\_30 = 0{,}01037$		$P_2 = 0{,}0313$
$\lambda_{04} / Lam\_04 = 0{,}00011$	$\mu_{40} / Mi\_40 = 0{,}01668$		$P_3 = 0{,}0024$
$\lambda_{05} / Lam\_05 = 0{,}00010$	$\mu_{50} / Mi\_50 = 0{,}01173$		$P_4 = 0{,}0062$
$\lambda_{05} / Lam\_05 = 0{,}00010$	$\mu_{50} / Mi\_50 = 0{,}01173$		$P_5 = 0{,}0085$

status in operation into another status has been calculated by expression 1 [2, 3] Fig. 8, and frequency of returns from a status into status has been calculated by expression (2) in operation by [2, 3] .

Frequencies of system shiftings from status 1 into status 2 and from status 3 into status 1 have been calculated by expression (3).

Reliability of individual statuses has been calculated by expression 4 [2, 3], Fig. 6. Calculated average times by expression (12), Fig. 7 and frequencies for individual statuses of marine propulsion system are shown in Tab. 1.

3 Systematic-dynamic qualitative structural model of the ship propulsion system reliability

Frequency parameters of shiftings from one status into another in Markov model are calculated by the application of initial data given in Tab. 1.

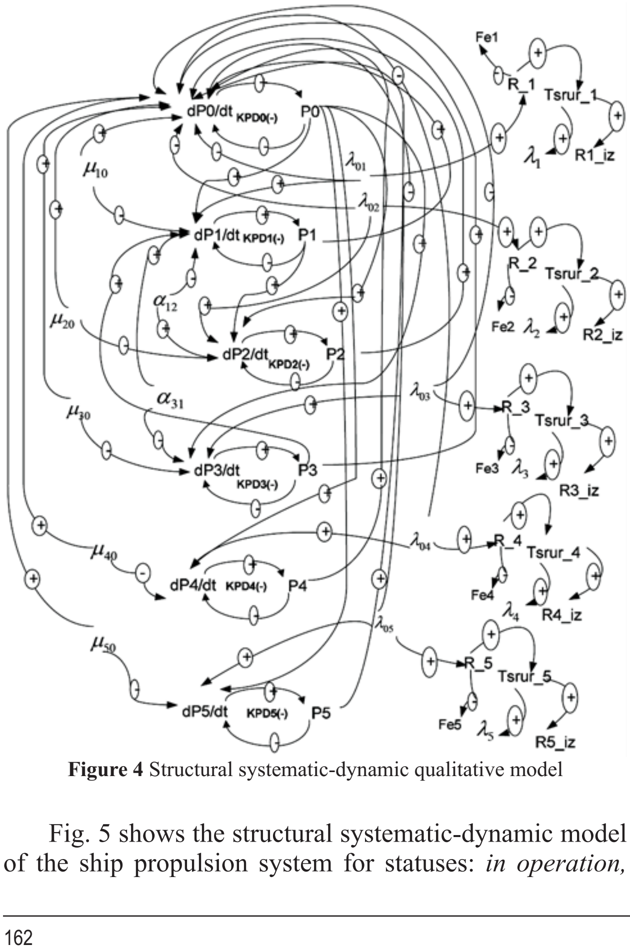


Figure 4 Structural systematic-dynamic qualitative model

Fig. 5 shows the structural systematic-dynamic model of the ship propulsion system for statuses: *in operation, malfunction, out of operation, regular inspection, safety* and *excessive exhaust emission* in POWERSIM symbolics by the application of expressions 5, 6, 7, 8, 9, 10 and systematic-dynamic qualitative struc tural model Fig. 4.

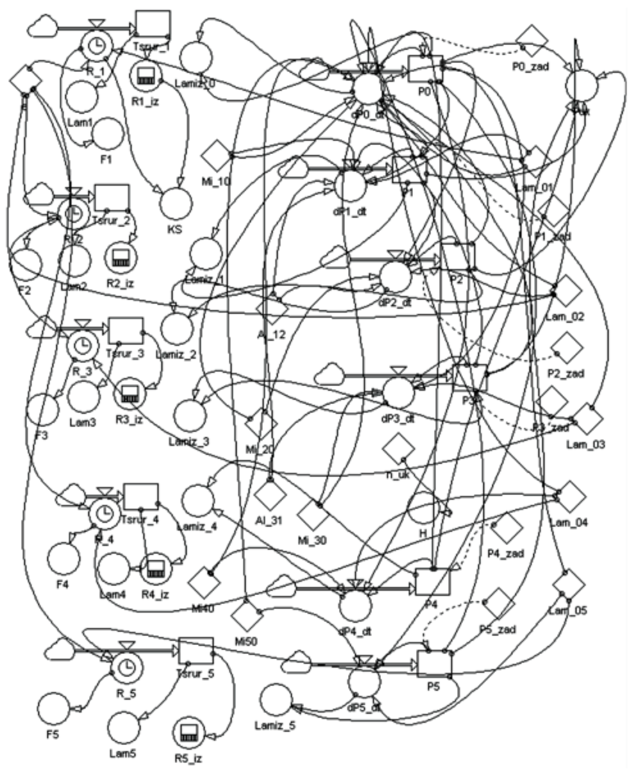


Figure 5 Structural systematic-dynamic model of ship propulsion system in POWERSIM symbolics for statuses: in operation, malfunction, out of operation, regular inspection, safety and excessive exhaust emission

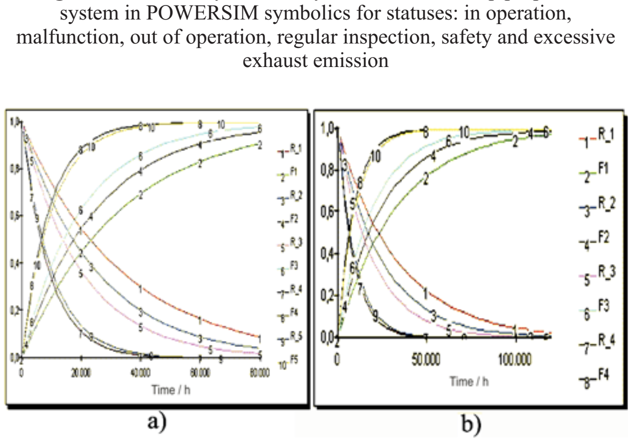
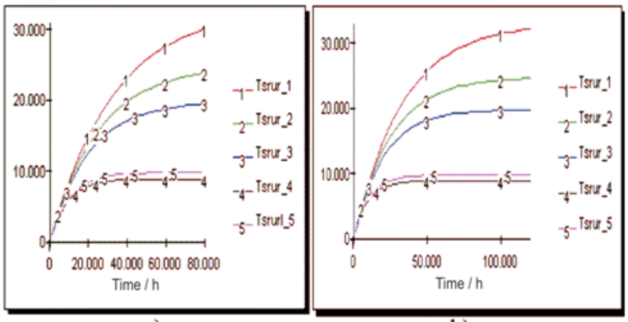
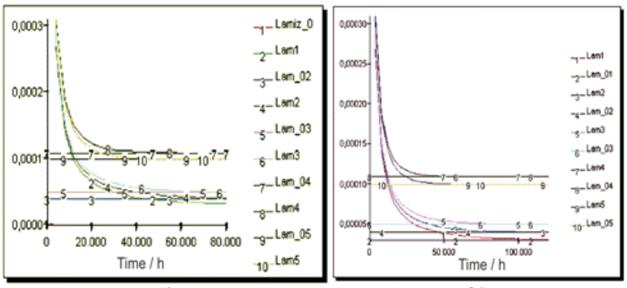


Figure 6 Diagram of reliability function "R1, R2, R3, R4, R5" and unreliability "F1, F2, F3, F4, F5" of ship propulsion system for
a) scenario I (80 000 hours in operation)
b) scenario II (120 000 hours in operation)



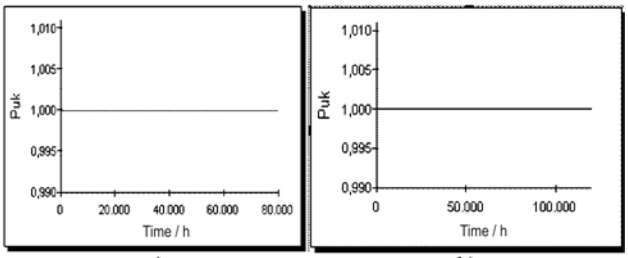
a) b)

Figure 7 Diagram of functions of average times "in operation" until reaching one of the statuses "1, 2, 3, 4, 5" of ship propulsion system for
a) scenario I (80 000 hours in operation)
b) scenario II (120 000 hours in operation)



a) b)

Figure 8 Diagram of malfunction intensity functions "Lam1, Lam2, Lam3, Lam4, Lam5" of ship propulsion system obtained by simulation and application of average times for
a) scenario I (80 000 hours in operation)
b) scenario II (120 000 hours in operation)



a) b)

Figure 9 Condition which should be satisfied at all times during observation. Summary of probabilities of ship propulsion system status must equal one for
a) scenario I (80 000 hours in operation)
b) scenario II (120 000 hours in operation)

Table 2 Overview of reliability values "R1, R2, R3, R4, R5" of ship propulsion system (times in hours) for
a) scenario I (80 000 hours in operation)
b) scenario II (120 000 hours in operation)

a)

Time	R 1	R 2	R 3	R 4	R 5
0	1,00	1,00	1,00	1,00	1,00
4.000	0,887	0,852	0,819	0,644	0,67
8.000	0,787	0,726	0,67	0,415	0,449
12.000	0,698	0,619	0,549	0,267	0,301
16.000	0,619	0,527	0,449	0,172	0,202
20.000	0,549	0,449	0,368	0,111	0,135
24.000	0,487	0,383	0,301	0,0714	0,0907
28.000	0,432	0,326	0,247	0,046	0,0608
32.000	0,383	0,278	0,202	0,0296	0,0408
36.000	0,34	0,237	0,165	0,0191	0,0273
40.000	0,301	0,202	0,135	0,0123	0,0183
44.000	0,267	0,172	0,111	0,00791	0,0123
48.000	0,237	0,147	0,0907	0,00509	0,00823
52.000	0,21	0,125	0,0743	0,00328	0,00552
56.000	0,186	0,106	0,0608	0,00211	0,0037
60.000	0,165	0,0907	0,0498	0,00136	0,00248
64.000	0,147	0,0773	0,0408	0,000876	0,00166
68.000	0,13	0,0659	0,0334	0,000564	0,00111
72.000	0,115	0,0561	0,0273	0,000363	0,000747
76.000	0,102	0,0478	0,0224	0,000234	0,000501
80.000	0,0907	0,0408	0,0183	0,000151	0,000336

b)

Time	R 1	R 2	R 3	R 4	R 5
0	1,00	1,00	1,00	1,00	1,00
4.000	0,887	0,852	0,819	0,644	0,67
8.000	0,787	0,726	0,67	0,415	0,449
12.000	0,698	0,619	0,549	0,267	0,301
16.000	0,619	0,527	0,449	0,172	0,202
20.000	0,549	0,449	0,368	0,111	0,135
24.000	0,487	0,383	0,301	0,0714	0,0907
28.000	0,432	0,326	0,247	0,046	0,0608
32.000	0,383	0,278	0,202	0,0296	0,0408
36.000	0,34	0,237	0,165	0,0191	0,0273
40.000	0,301	0,202	0,135	0,0123	0,0183
44.000	0,267	0,172	0,111	0,00791	0,0123
48.000	0,237	0,147	0,0907	0,00509	0,00823
52.000	0,21	0,125	0,0743	0,00328	0,00552
56.000	0,186	0,106	0,0608	0,00211	0,0037
60.000	0,165	0,0907	0,0498	0,00136	0,00248
64.000	0,147	0,0773	0,0408	0,000876	0,00166
68.000	0,13	0,0659	0,0334	0,000564	0,00111
72.000	0,115	0,0561	0,0273	0,000363	0,000747
76.000	0,102	0,0478	0,0224	0,000234	0,000501
80.000	0,0907	0,0408	0,0183	0,000151	0,000336
84.000	0,0805	0,0347	0,015	0,0000971	0,000225
88.000	0,0714	0,0296	0,0123	0,0000625	0,000151
92.000	0,0633	0,0252	0,0101	0,0000403	0,000101
96.000	0,0561	0,0215	0,00823	0,0000259	0,0000677
100.000	0,0498	0,0183	0,00674	0,0000167	0,0000454
104.000	0,0442	0,0156	0,00552	0,0000108	0,0000304
108.000	0,0392	0,0133	0,00452	0,00000693	0,0000204
112.000	0,0347	0,0113	0,0037	0,00000446	0,0000137
116.000	0,0308	0,00966	0,00303	0,00000287	0,00000917
120.000	0,0273	0,00823	0,00248	0,00000185	0,00000615

Table 3 Overview of malfunction intensity values "Lam1, Lam2, Lam3, Lam4, Lam5" of ship propulsion system obtained by simulation and application of average times (in hours) for
a) scenario I (80 000 hours in operation)
b) scenario II (120 000 hours in operation)

a)

Time	Lam1	Lam2	Lam3	Lam4	Lam5
0	=?	=?	=?	=?	=?
4.000	0,000265	0,000271	0,000276	3,09e-4	0,000303
8.000	0,000141	0,000146	0,000152	1,88e-4	0,000182
12.000	0,0000992	0,000105	0,000111	1,5e-4	0,000143
16.000	0,0000787	0,0000846	9,08e-5	1,33e-4	0,000125
20.000	0,0000665	0,0000726	7,91e-5	1,24e-4	0,000116
24.000	0,0000585	0,0000648	7,155e-5	1,18e-4	0,00011
28.000	0,0000528	0,0000594	6,636e-5	1,15e-4	0,000106
32.000	0,0000486	0,0000554	6,265e-5	1,13e-4	0,000104
36.000	0,0000454	0,0000524	5,99e-5	1,12e-4	0,000103
40.000	0,0000429	0,0000501	5,782e-5	1,11e-4	0,000102
44.000	0,0000409	0,0000483	5,623e-5	1,11e-4	0,000101
48.000	0,0000393	0,0000469	5,499e-5	1,11e-4	0,000101
52.000	0,000038	0,0000457	5,401e-5	1,1e-4	0,000101
56.000	0,0000369	0,0000448	5,324e-5	1,1e-4	0,0001
60.000	0,0000359	0,000044	5,262e-5	1,1e-4	0,0001
64.000	0,0000352	0,0000434	5,212e-5	1,1e-4	0,0001
68.000	0,0000345	0,0000428	5,172e-5	1,1e-4	0,0001
72.000	0,0000339	0,0000424	5,14e-5	1,1e-4	0,0001
76.000	0,0000334	0,000042	5,114e-5	1,1e-4	0,0001
80.000	0,000033	0,0000417	5,093e-5	1,1e-4	0,0001

b)

Time	Lam1	Lam2	Lam3	Lam4	Lam5
0	=?	=?	=?	=?	=?
4.000	0,000265	0,000271	0,000276	0,000309	0,000303
8.000	0,000141	0,000146	0,000152	0,000188	0,000182
12.000	0,0000992	0,000105	0,000111	0,00015	0,000143
16.000	0,0000787	0,0000846	0,0000908	0,000133	0,000125
20.000	0,0000665	0,0000726	0,0000791	0,000124	0,000116
24.000	0,0000585	0,0000648	0,0000715	0,000118	0,00011
28.000	0,0000528	0,0000594	0,0000664	0,000115	0,000106
32.000	0,0000486	0,0000554	0,0000626	0,000113	0,000104
36.000	0,0000454	0,0000524	0,0000599	0,000112	0,000103
40.000	0,0000429	0,0000501	0,0000578	0,000111	0,000102
44.000	0,0000409	0,0000483	0,0000562	0,000111	0,000101
48.000	0,0000393	0,0000469	0,000055	0,000111	0,000101
52.000	0,000038	0,0000457	0,000054	0,00011	0,000101
56.000	0,0000369	0,0000448	0,0000532	0,00011	0,0001
60.000	0,0000359	0,000044	0,0000526	0,00011	0,0001
64.000	0,0000352	0,0000434	0,0000521	0,00011	0,0001
68.000	0,0000345	0,0000428	0,0000517	0,00011	0,0001
72.000	0,0000339	0,0000424	0,0000514	0,00011	0,0001
76.000	0,0000334	0,000042	0,0000511	0,00011	0,0001
80.000	0,000033	0,0000417	0,0000509	0,00011	0,0001
84.000	0,0000326	0,0000414	0,0000508	0,00011	0,0001
88.000	0,0000323	0,0000412	0,0000506	0,00011	0,0001
92.000	0,000032	0,000041	0,0000505	0,00011	0,0001
96.000	0,0000318	0,0000409	0,0000504	0,00011	0,0001
100.000	0,0000316	0,0000407	0,0000503	0,00011	0,0001
104.000	0,0000314	0,0000406	0,0000503	0,00011	0,0001
108.000	0,0000312	0,0000405	0,0000502	0,00011	0,0001
112.000	0,0000311	0,0000405	0,0000502	0,00011	0,0001
116.000	0,000031	0,0000404	0,0000502	0,00011	0,0001
120.000	0,0000308	0,0000403	0,0000501	0,00011	0,0001

3.1 Result analysis of modelling of the ship propulsion system dynamic reliability statuses with safety and exhaust emission for scenario I and II

Structural dynamic simulation model in POWERSIM symbolics for the ship propulsion system model with safety and exhaust emission and two scenarios of operation (80 000 and 120 000 hours in operation) are shown in Figs. 3, 4, 5, 6 and 7. Fig. 3 shows Markov model of the ship propulsion system statuses: *in operation, malfunction, out of operation, regular inspection, safety* and *excessive exhaust emission*, Fig. 5 shows the structural dynamic model and Fig. 4 structural qualitative model with two scenarios of operation. By the application of systematic-dynamic simulation models results for scenarios I and II will be obtained. The results have been used as experimental data on the basis of which evaluation of the system operation will be performed [1]. Simulation models at all times fulfil the conditions defined in the identity equation expression (11), i.e., for the ship's propulsion system model Fig. 9.

Tabs. 2 and 3 show the values obtained by simulation of the ship propulsion system reliability model for scenarios I and II. From Figs. 6, 7, 8 and 9 it is obvious that the results obtained by the dynamic simulation model (for both scenarios) behave according to exponential distribution. Frequency of malfunctions in the initial interval of system operation is increased, and eventually it falls and becomes constant. This is best shown in Figs. 6 and 8 and Tabs. 4 and 5, where frequency of malfunctions has been obtained by simulation for both scenarios I and II by the application of average times in a specific status Fig. 7. Shape of the curves corresponds to the bathtub curve, which coincides with the choice of exponential distribution where frequency of malfunctions is constant. Reliability of the ship's propulsion system is shown in Fig. 6. It can be concluded from the figure that with the increase of the ship's propulsion system operation period the reliability decreases, and unrealiability increases. By prompt intervention of maintenance service the system is returned from status *malfunction* into status *in operation*.

3.1.1 Regression result analysis of dynamic status modelling for scenarios I and II

Results obtained by dynamic status modelling for scenario I and II are shown in tables and have been used for regression analysis.

Tab. 4 shows reliability values (*R*_1, *R*_2, *R*_3, *R*_4 i *R*_5) obtained by simulation in the function of the time of operation of the ship propulsion system for individual system statuses.

Table 4 Review of reliability values of various ship propulsion system statuses obtained by simulation

t/h	*R*_1	*R*_2	*R*_3	*R*_4	*R*_5
1	2	3	4	5	6
4 000	0,887	0,852	0,819	0,644	0,67
8 000	0,787	0,726	0,67	0,415	0,449
12 000	0,698	0,619	0,549	0,267	0,301
16 000	0,619	0,527	0,449	0,172	0,202
20 000	0,549	0,449	0,368	0,111	0,135
24 000	0,487	0,383	0,301	0,0714	0,0907
28 000	0,432	0,326	0,247	0,046	0,0608
32 000	0,383	0,278	0,202	0,0296	0,0408
36 000	0,340	0,237	0,165	0,0191	0,0273
40 000	0,301	0,202	0,135	0,0123	0,0183
44 000	0,267	0,172	0,111	0,0079	0,0123
48 000	0,237	0,147	0,091	0,0051	0,0082
52 000	0,210	0,125	0,074	0,0033	0,0055
56 000	0,186	0,106	0,061	0,0021	0,0037
60 000	0,165	0,091	0,05	0,0014	0,0025
64 000	0,147	0,077	0,041	0,0009	0,0017
68 000	0,130	0,066	0,033	0,0006	0,0011
72 000	0,115	0,056	0,027	0,0004	0,0007
76 000	0,102	0,048	0,022	0,0002	0,0005
80 000	0,091	0,041	0,018	0,0002	0,0003

Table 5 Frequency of shiftings into various ship propulsion system statuses obtained by simulation

t /h	*Lam*1_1	*Lam*2_2	*Lam*3_3	*Lam*4_4	*Lam*5_5
1	2	3	4	5	6
4 000	0,0002650	0,000271	0,000276	0,000309	0,000303
8 000	0,0001410	0,000146	0,000152	0,000188	0,000182
12 000	0,0000992	0,000105	0,000111	0,00015	0,000143
16 000	0,0000787	0,0000846	0,0000908	0,000133	0,000125
20 000	0,0000665	0,0000726	0,0000791	0,000124	0,000116
24 000	0,0000585	0,0000648	0,0000715	0,000118	0,000110
28 000	0,0000528	0,0000594	0,0000664	0,000115	0,000106
32 000	0,0000486	0,0000554	0,0000626	0,000113	0,000104
36 000	0,0000454	0,0000524	0,0000599	0,000112	0,000103
40 000	0,0000429	0,0000501	0,0000578	0,000111	0,000102
44 000	0,0000409	0,0000483	0,0000562	0,000111	0,000101
48 000	0,0000393	0,0000469	0,000055	0,000111	0,000101
52 000	0,0000380	0,0000457	0,000054	0,00011	0,000101
56 000	0,0000369	0,0000448	0,0000532	0,00011	0,000100
60 000	0,0000359	0,000044	0,0000526	0,00011	0,000100
64 000	0,0000352	0,0000434	0,0000521	0,00011	0,000100
68 000	0,0000345	0,0000428	0,0000517	0,00011	0,000100
72 000	0,0000339	0,0000424	0,0000514	0,00011	0,000100
76 000	0,0000334	0,000042	0,0000511	0,00011	0,000100
80 000	0,0000330	0,0000417	0,0000509	0,00011	0,000100

Tab. 5 shows the frequency values of shiftings (*Lam*1_1, *Lam*2_2, *Lam*3_3, *Lam*4_4 i *Lam*5_5) obtained by simulations in the function of the time of operation of the ship propulsion system for individual system statuses.

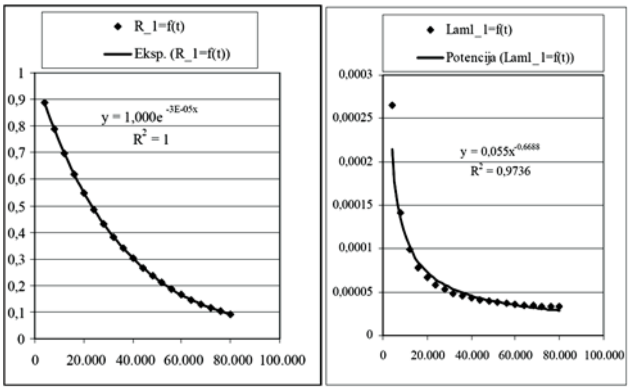
By the application of data in Tab. 4, by means of regression analysis the interconnection between the monitored time of operation of a ship propulsion system and reliability value for each system status is defined. By the application of data from Tab. 5 the interconnection between the monitored time of operation of the ship propulsion system and frequency of shiftings is defined.

Regression equations, determination coefficients R^2 and regression coefficients *r* for all ship propulsion system statuses analysed are shown in Tab. 6.

Table 6 Regression equations, determination coefficients and regression coefficients for ship propulsion system statuses

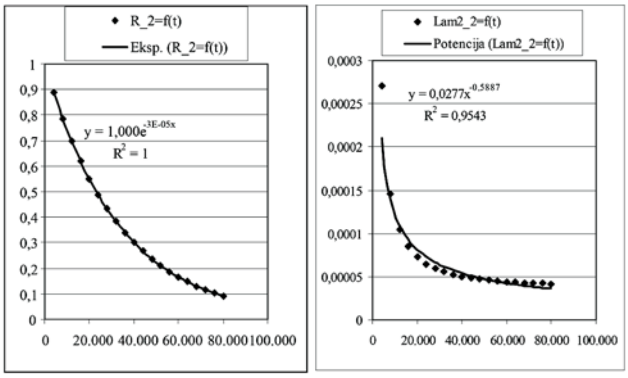
$Y = f(t)$	Regression equation	R^2	r
$R\_1 = f(t)$	$Y1 = 1{,}000 \cdot \mathrm{e}^{-3E-05X}$	1	1
$Lam1\_1 = f(t)$	$Y1 = 0{,}055 \cdot X^{-0{,}6688}$	0,9763	0,9881
$R\_2 = f(t)$	$Y2 = 1{,}000 \cdot \mathrm{e}^{-3E-05X}$	1	1
$Lam2\_2 = f(t)$	$Y2 = 0{,}0277 \cdot X^{-0{,}5887}$	0,9543	0,9768
$R\_3 = f(t)$	$Y3 = 1{,}000 \cdot \mathrm{e}^{-3E-05X}$	1	1
$Lam3\_3 = f(t)$	$Y3 = 0{,}0157 \cdot X^{-0{,}5212}$	0,9324	0,9656
$R\_4 = f(t)$	$Y4 = 0{,}9746 \cdot \mathrm{e}^{-0{,}0001X}$	0,9992	0,9996
$Lam4\_4 = f(t)$	$Y4 = 0{,}0022 \cdot X^{-0{,}2779}$	0,7898	0,8887
$R\_5 = f(t)$	$Y5 = 1{,}000 \cdot \mathrm{e}^{-0{,}0001X}$	0,9999	0,9999
$Lam5\_5 = f(t)$	$Y5 = 0{,}0027 \cdot X^{-0{,}305}$	0,8127	0,9015

Results of regression analysis for various statuses of a ship propulsion system are shown in Figs. 10÷14.



a) b)

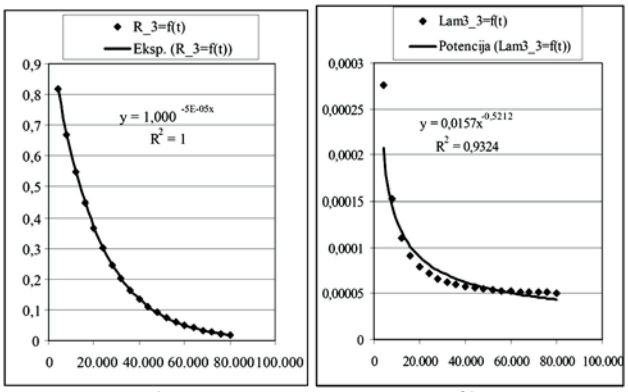
Figure 10 Regression analysis for model II of ship propulsion system for status 1
a) change of system reliability *R*_1 in the time function *t*/h
b) change of frequency of shifting *Lam*1_1 in the time function *t*/h



a) b)

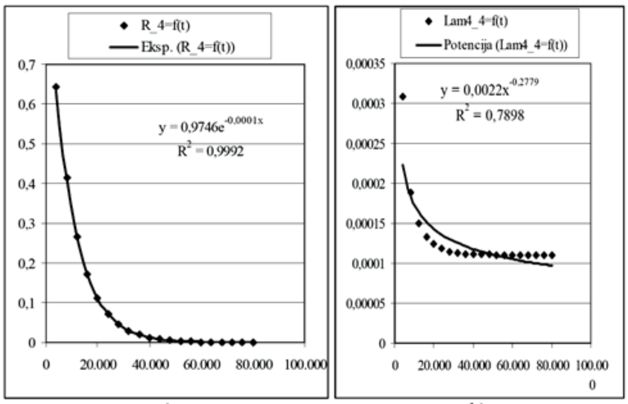
Figure 11 Regression analysis for model II of ship propulsion system for status 2
a) change of system reliability *R*_2 in the time function *t*/h
b) change of frequency of shifting *Lam*2_2 in the time function *t*/h

Regression equations shown in Tab. 6 for the ship propulsion system model with safety and exhaust emission enable approximate values of reliability on time dependence for individual system statuses and frequency of shiftings from status to status to be determined. Such analysis makes regular inspection, prediction and system status correction easier and exerts a large influence onto reduction of the ship propulsion system exploitation costs, in particular in reduction of pollution by exhaust emission.



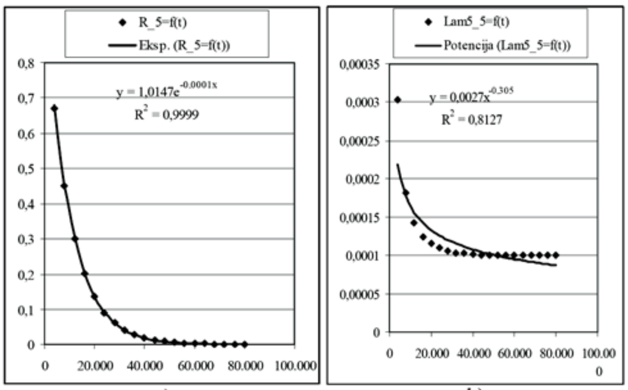
a) b)

Figure 12 Regression analysis for model II of ship propulsion system for status 3
a) change of system reliability R_3 in the time function t/h
b) change of frequency of shifting $Lam3\_3$ in the time function t/h



a) b)

Figure 13 Regression analysis for model II of ship propulsion system for status 4
a) change of system reliability R_4 in the time function t/h
b) change of frequency of shifting $Lam4\_4$ in the time function t/h



a) b)

Figure 14 Regression analysis for model II of ship propulsion system for status 5
a) change of system reliability R_5 in the time function t/h
b) change of frequency of shifting $Lam5\_5$ in the time function t/h

From the results of regression for reliability and frequency of shiftings (Tab. 6 and Figs. 10÷14) it is to be noted that system reliability curves for each status are best approximated by exponential curve, and frequency of shiftings curve approximate the general potential curve.

4 Conclusion

By quantification of technical system reliability and availability parameters it is possible to determine the influence of certain values in the technical system support chain in individual stages of its working life. For the purpose of prevention from pollution by exhaust emission timely measures have been taken by IMO by adoption of Annex VI to MARPOL on prevention of marine air pollution. By the application of Markov models, a mathematical ship propulsion system reliability model with safety and exhaust emission has been elaborated in this paper. On the basis of empirical data, parameters for frequency of system shifting from status in operation into another status have been calculated, as well as for frequency of system return from a status into status *in operation* and probability of the system being in one of the statuses. By the application of systematic dynamics modelling and analysis of complex technical systems reliability and availability in realistic time periods have been made possible. This refers to the time required for renewal of the system components and return of the system into initial reliability and availability status. Thus, it is possible to detect weak spots in the system, and by preventive actions failures are reduced and consequently reliability and availability of the system increased, and at the same time pollution by exhaust emission is reduced.

5 References

[1] Barle, J. Authorised lectures (text-book in print), FESB, Split 2008.
[2] Lovrić, J. Basic Ship's Terotechnology, Maritime Faculty in Dubrovnik, Dubrovnik 1989.
[3] Jurjević, M. Simulation modelling of technical system reliability by application of systematic dynamics, doctoral thesis, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture (FESB), Split, 2009.
[4] Jurjević, M.; Prce, I.; Jurjević, N. Measuring & reducing two-stroke low speed diesel engine exhaust gas emissions. // Proceeding of the 3rd DAAAM International Conference on Advanced Technologies for Developing Countries ATDC'04, Split, 2004.
[5] Jurjević, M.; Bilić, B.; Milić-Beran, I.; Zekić, H.: Application of the software package AMOS in maintenance of the marine propulsion system; 2nd International Maritime Scientific Conference – IMSC, Lumbarda, 2008.
[6] Jurjević, M.; Bilić, B.; Veža, I. Method of technical system reliability analysis by application of exploitation experience; 11th International Scientific Conference on Production Engineering – CIM2007, Biograd, 2007.

Authors' addresses

Mate Jurjević
Sveučilište u Dubrovniku,
Ćira Carića 4,
20000 Dubrovnik, Croatia
e-mail: mjurjevic@unidu.hr

Nataša Jurjević
Sveučilište u Dubrovniku,
Ćira Carića 4,
20000 Dubrovnik, Croatia
e-mail: njurjevic@unidu.hr

Nikša Koboević
Sveučilište u Dubrovniku,
Ćira Carića 4,
20000 Dubrovnik, Croatia
e-mail: niksa@unidu.hr