Ivana Golub
Radovan Antonić
Đorđe Dobrota
Sveučilište u Splitu / *University of Split*
Pomorski fakultet / *Faculty of Maritime Studies Split*
Zrinsko-frankopanska 38
21000 Split
Hrvatska / *Croatia*

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OPTIMIZACIJA RADA SUSTAVA BRODSKOG SEPARATORA TEŠKOG GORIVA PRIMJENOM DIJAGNOSTIČKIH METODA ZAKLJUČIVANJA

OPTIMIZATION OF HEAVY FUEL OIL SEPARATOR SYSTEM BY APPLYING DIAGNOSTIC INFERENCE METHODS

SAŽETAK

Brodski dizelski motor je složen multivarijabilni nelinearni dinamički sustav. Njegova osnovna struktura se sastoji od međusobno povezanih podsustava i velikog broja različitih komponenti, te se kvarovi mogu pojaviti na bilo kojoj komponenti sustava. Stoga, za poboljšanje pouzdanosti i sigurnosti brodskih strojnih sustava metode dijagnostike kvarova imaju sve veću i veću važnost. Ovaj rad pruža poseban osvrt na dijagnostičke metode zaključivanja u funkciji pravovremene lokalizacije i izolacije kvarova. Analiza stabla kvarova prikazuje sve uzroke neispravnog rada separatora teškog goriva. Analiziran je utjecaj nečistoća u gorivu na okoliš i moguće kvarove u sustavu goriva kao izravna posljedica neispravnog rada separatora. Kvarovi u sustavu goriva su izvedeni na brodostrojarskom simulatoru Kongsberg Norcontrol. Ponašanje simptoma u vremenu prikazano je binarnom matricom. Analiza tablice izvedena je uz pomoć neizrazitih činjenica. Rezultati dobiveni simulacijom ukazuju na važnost dijagnostike kvarova u svrhu pravovremenog sprječavanja pojave kvarova, čime se doprinosi pouzdanosti i raspoloživosti brodskih strojnih sustava.

Ključne riječi: *brodski motor, dijagnostika kvarova, simulacija*

SUMMARY

Marine diesel engine is a complex multivariable nonlinear dynamic system. Its basic structure consists of interdependent and connected subsystems with a large number of different components. Faults can appear in any component of the system. Therefore, for improving reliability and marine engine systems safety fault diagnosis methods are more and more important. This paper gives an especial review on interference diagnosis methods in a function of timely localization and isolation of faults. Fault tree analysis shows all causes of heavy fuel oil separator incorrect operation. Influence of impurities in fuel oil on environment and possible fuel oil system faults as a direct consequence of separator incorrect operation has been analyzed. Fuel oil systems faults have been simulated using Full Mission Engine Room simulator Kongsberg Norcontrol. Symptom behavior in time has been presented by binary matrix. Table analysis has been conducted by fuzzy facts. Results obtained through simulation point to the importance of fault diagnosis for the timely prevention of the occurrence of faults, thereby contributing to the reliability and availability of marine engine systems.

Keywords: *marine diesel engine, fault diagnosis, simulation*

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1. UVOD

Brodski strojni sustavi su vrlo kompleksni. Sastoje se od velikog broja podsustava i elemenata čija je funkcionalnost i kvalitetna interakcija od elementarne važnosti za visoku efikasnost pozitivne eksploatacijske značajke broda. Kvarovi se mogu pojaviti na bilo kojoj komponenti procesa dizelskog motora i, naravno, na svim dijelovima postrojenja brodskog dizelskog motora kao objekta upravljanja [1]. Slika 1 prikazuje osnovnu strukturu brodskog dizelskog motora s podsustavima koji osiguravaju nužne uvjete za rad stroja.

Ispravan rad brodskih strojnih sustava izravno je ugrožen razvijanjem kvara na bilo kojoj komponenti sustava. Kao rezultat kvarova i pogrešaka, koji mogu biti pripisani mnogim različitim uzrocima, javlja se devijacija normalnog ponašanja.

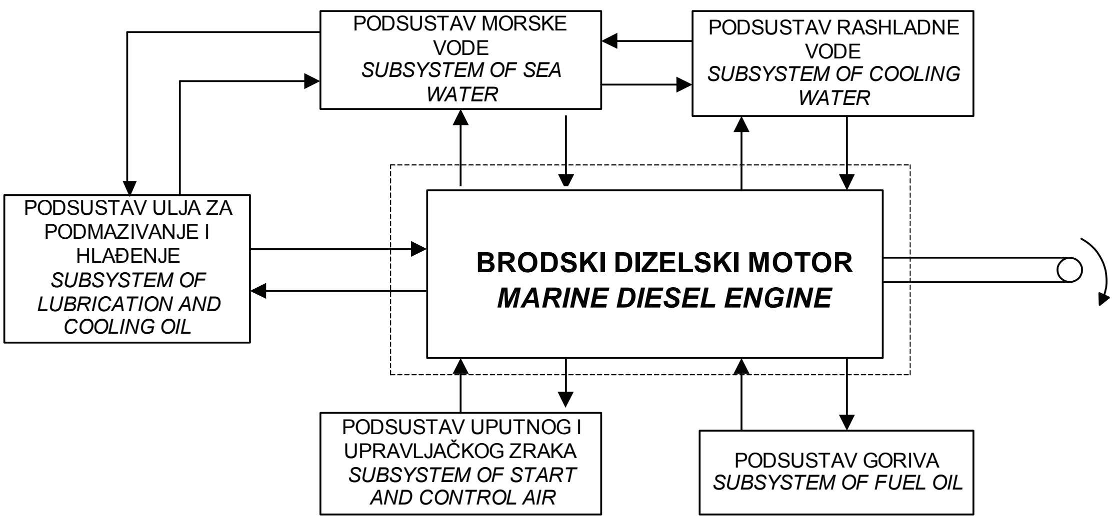
Dijagnozom kvara promatranog sustava analiziran je utjecaj pojedinačnih parametara na neželjeno stanje sustava. Takvim analizama moguće je izvršiti adekvatnu optimizaciju parametara. Navedenim pristupom mogu biti ostvareni bolji radni uvjeti pojedinih sustava. U svrhu optimizacije parametara u sustavu teškog goriva izvršena je simulacija na brodostrojarskom simulatoru Kongsberg Norcontrol, simuliranjem odgovarajućih kvarova u sustavu goriva dvotaktnog brodskog dizelskog motora MAN B&W 5L90MC. Ponašanje varijabli u vremenu detaljno je obrađeno korištenjem modernih dijagnostičkih metoda.

1. INTRODUCTION

Marine engine systems are very complex. They consist of a large number of subsystems and elements whose functionality and quality interaction are of essential importance for high efficiency and long operational lifetime. Faults may occur in any component of the diesel engine process and, of course, in all parts of the diesel engine plant as an object of control [1]. Figure 1 shows the basic structure of a marine diesel engine with subsystems that ensure essential conditions for engine operation.

A correct operation of marine engine systems is directly compromised by faults on any component of the system. As a result of faults and failures, that can be a result of many different causes, a deviation of the normal behavior occurs.

By fault diagnosis of the observed system, the influence of individual parameters on the undesired system behaviour, is analyzed. With such an analysis, it is possible to carry out an adequate parameter optimization. In such a way a better operation condition of a certain system can be accomplished. For the purpose of parameter optimization in heavy fuel oil system a simulation has been conducted on the Full Mission Engine Room simulator Kongsberg Norcontrol by simulating corresponding faults in the fuel system of a two stroke marine diesel engine MAN B&W 5L90MC. Behavior of the variables in time is processes in detail using modern diagnosis methods.



Slika 1. Brodski dizelski motor s podsustavima [1]
Figure 1 *Marine diesel engine with subsystems* [1]

2. DIJAGNOSTIKA KVAROVA

Poznato je da su radna pouzdanost i raspoloživost osnovni zahtjevi koji se stavljaju pred brodske strojne sustave. Danas se ti zahtjevi mogu postići korištenjem dijagnostičke tehnologije. Glavni ciljevi dijagnostike kvarova su detekcija, izolacija i analiza kvara [3], [4], [13], [15]. Sigurnost i pouzdanost su općenito postignute kombinacijom različitih djelovanja, kao što su [14]:

– izbjegavanje kvara

– uklanjanje kvara

– tolerancija kvara

– detekcija i dijagnoza kvara

– automatski nadzor i zaštita.

Zadatak dijagnostike kvarova je determiniranje tipa, veličine te lokalizacija kvara. Slika 2 prikazuje općenitu klasifikaciju kvara s obzirom na njegov oblik, opseg i ponašanje u vremenu.

Kako bi se ostvarili ciljevi procedure dijagnostike kvarova, prikazani na slici 3, postoje tri uzastopna koraka koja predstavljaju redoslijed

2. FAULT DIAGNOSIS

It is known that the operation reliability and availability are basic requirements that are put on the marine engine systems. Today, these requirements can be achieved by using diagnostic technology. The main objectives of fault diagnosis are detection, isolation and fault analyses [3], [4], [13], [15]. Security and reliability are generally achieved by a combination of different actions such as [14]:

- fault avoidance,

- fault removal,

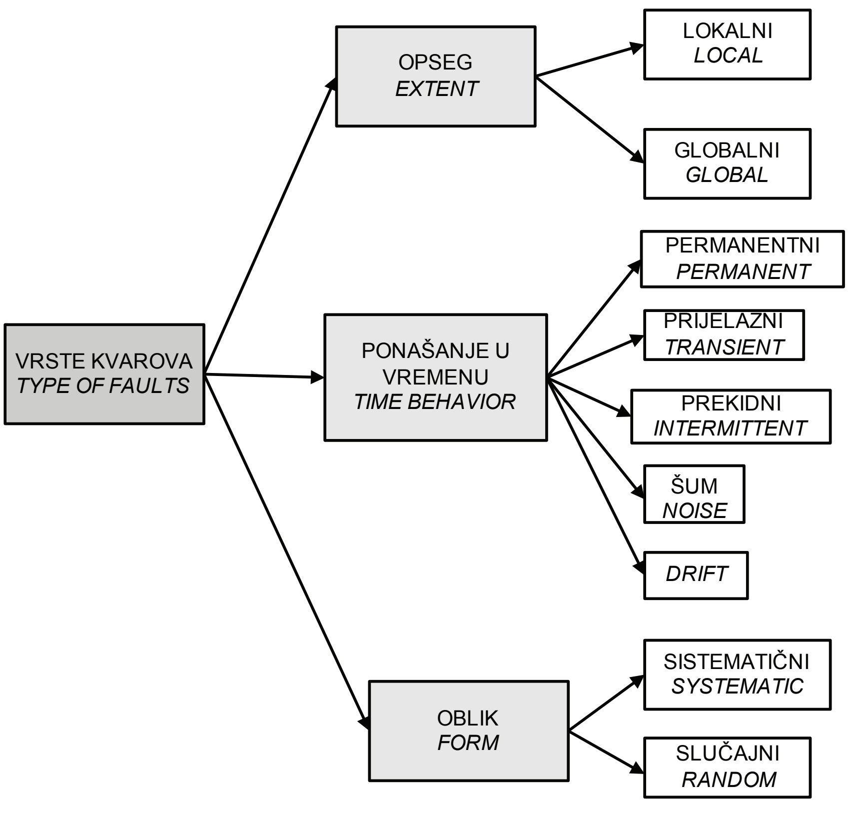
- fault tolerance,

- fault detection and diagnosis,

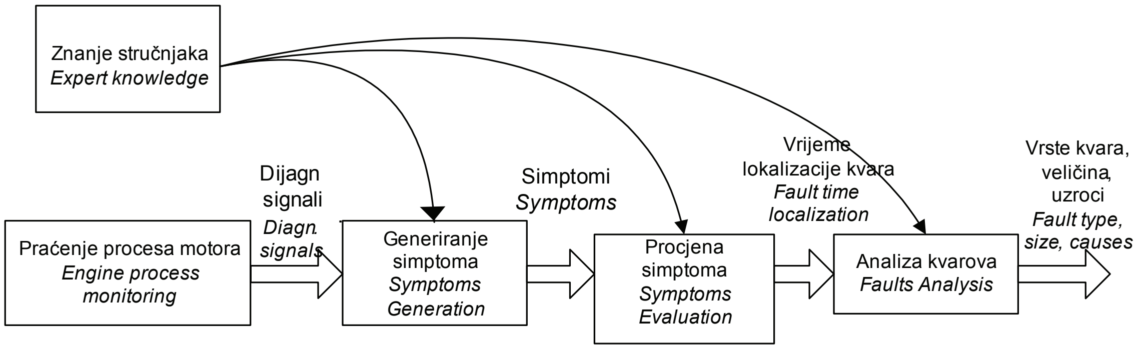
- automatic supervision and protection.

The task of fault diagnosis is the determination of type, size and localization of fault. Figure 2 shows a general fault classification regarding their form, extent and time behavior.

To realize the objectives of the fault diagnosis procedure, depicted in figure 3 and consisting of three consecutive steps, shows the order



Slika 2. Vrste kvarova [9]
Figure 2 *Type of faults* [9]



Slika 3. Procedura dijagnostike kvarova [2]
Figure 3 *Fault diagnosis procedure* [2]

zadataka koje treba obaviti u sustavu automatske dijagnoze [1],[16].

Procedura je zasnovana na promatranju simptoma. Simptomi prezentiraju promjene parametara u odnosu na normalno stanje sustava i indiciraju mogući kvar sustava. Simptomi mogu biti klasificirani kao [1], [8], [16]:

- analitički – promjena u rezidualu koji prelazi prag za detekciju kvara,
- heuristički – promatranje i stručna mjerenje te heurističke činjenice zasnovane na iskustvu eksperata,
- statistički simptomi – učestalost kvarova, vrijeme bez kvara i vrijeme trajanja kvara.

Promjena parametara procesa pod utjecajem kvara, u odnosu na normalnu referentnu vrijednost θ_0, prikazana je izrazom (1), [14]:

$$\boldsymbol{\Delta\theta} = \hat{\theta}(k) - \theta_0 , \qquad (1)$$

gdje je *k* parametar od interesa.

Parametri čije promjene prelaze pragove referiraju se kao simptomi i te su relacije prikazane izrazom (2), [14]:

$$\begin{aligned} \boldsymbol{\Delta\theta_s} &= \hat{\theta}(k) - (\theta_0 + \Delta\theta_{th}); \theta(k) > \theta_0 \\ \boldsymbol{\Delta\theta_s} &= \hat{\theta}(k) - (\theta_0 + \Delta\theta_{th}); \theta(k) < \theta_0 \end{aligned} \qquad (2)$$

Odnosi između dijagnostičkih signala/simptoma i kvarova su učinkovit način za dijagnozu i lokalizaciju kvara komponenti sustava. Mogu biti predstavljeni u različitim oblicima: pregledna tablica, analitički oblici, dijagnostička matrica simptoma/kvarova, kvalitativni modeli u neizrazitoj logici ili neuronskim mrežama, heurističke relacije zasnovan na iskustvu eksperata i operatera.

of tasks which should be performed in the automatic diagnosis system [1],[16].

The procedure is based on fault symptoms observation. Symptoms are presenting changes in parameters in regard to normal state of system and indicate possible system fault. Symptoms can be classified as [1], [8], [16]:

- analytical; change in the residual that exceed the threshold for fault detection,
- heuristic; observation and experts measurement and heuristic facts based on the experience of experts,
- statistical symptoms; frequency of faults, time without fault and time of fault duration.

Process parameters change under the influence of the fault, comparing to the normal referent value θ_0, as shown in expression (1), [14]:

$$\boldsymbol{\Delta\theta} = \hat{\theta}(k) - \theta_0 , \qquad (1)$$

where k is parameter of interest.

Parameter changes that exceed the thresholds referred to the symptoms and those relations are shown in expression (2), [14]:

$$\begin{aligned} \boldsymbol{\Delta\theta_s} &= \hat{\theta}(k) - (\theta_0 + \Delta\theta_{th}); \theta(k) > \theta_0 \\ \boldsymbol{\Delta\theta_s} &= \hat{\theta}(k) - (\theta_0 + \Delta\theta_{th}); \theta(k) < \theta_0 \end{aligned} \qquad (2)$$

Relations between diagnostic signals/symptoms and faults are an effective way for fault diagnosis and localization of system components. They can be expressed in various forms: look-up table, analytical forms, diagnostic matrix of symptoms/faults, qualitative models in fuzzy

Metode dijagnostike kvarova, koje obrađuju relacije između simptoma i kvarova, dijele se na klasifikacijske metode i metode zaključivanja. U ovom radu posebna pažnja je posvećena metodama zaključivanja u koje se, između ostalih, ubrajaju analiza stabla kvarova i neizrazite činjenice (if, then pravila).

2.1. Metode zaključivanja

Mogući kvarovi mogu biti definirani kako slijedi:

$$\boldsymbol{F} = \{ f_i : i = 1,2,...I \} \tag{3}$$

Stanje sustava $s(f_i)$ s obzirom na kvar f_i je definirano sljedećim izrazom:

$$s(f_i) = \begin{cases} 0\text{ - stanje bez kvara } f_i; \\ 1\text{ - stanje s kvarom } f_i \end{cases}$$

Osnova izolacije i dijagnostike kvarova je znanje o odnosima između dijagnostičkog signala i kvarova. Dijagnostički signal S može biti definiran kao:

$$\boldsymbol{S} = \{ s_j : j = 1,2,...J \} \tag{4}$$

$$R_{FS} \subset FXS$$

gdje je R_{FS} funkcija definirana kao Cartesian produkt FXS, za svaki par kvar-simptom.

Vrijednosti dijagnostičkih signala mogu biti u binarnom obliku {0,1}, kada dijagnostička shema može biti prezentirana u matričnom ili tabličnom obliku s kvarovima u stupcima i dijagnostičkim simptomima u recima, tablica1. Takva matrica omogućava procjenu mogućnosti detekcije i izolacije dobivenog kvara.

logic or neural networks, heuristic relations based on experience of expert and operator.

The fault diagnosis methods that process the relations between symptoms and faults are divided into classification methods and inference methods. In this paper a special attention is dedicated to inference methods that, among others, include fault tree analysis and fuzzy facts (if, then rules).

2.1. Inference methods

Possible faults can be defined as follows:

$$\boldsymbol{F} = \{ f_i : i = 1,2,...I \} \tag{3}$$

System state $s(f_i)$ related to fault f_i is defined with the following expression:

$$s(f_i) = \begin{cases} 0\text{ - stanje bez kvara } f_i; \\ 1\text{ - stanje s kvarom } f_i \end{cases}$$

The basis of fault isolation and diagnosis is the knowledge about the relation between diagnostic signal and faults. Diagnostic signal S can be defined as follows:

$$\boldsymbol{S} = \{ s_j : j = 1,2,...J \} \tag{4}$$

$$R_{FS} \subset FXS$$

where R_{FS} is a function defined as a Cartesian product set FXS, for each fault-symptom pair.

Diagnostic signals values can be in binary form {0,1}, when the diagnostic scheme may be presented in a matrix or table form with faults in columns and diagnostic symptoms in rows, table1. Such matrix enables the evaluation of the achieved fault detectability and isolability.

Tablica 1. Binarna matrica kvarova i odgovarajućih simptoma [1]
Table 1 *Binary matrix of faults and related symptoms* [1]

F/S	F1	F2	F3	F4	F5	F6	F7	F8
S1	1	0	1	1	1	0	1	0
S2	0	1	0	1	1	0	1	0
S3	1	0	0	0	1	1	0	0
S4	1	1	1	0	0	1	0	0
S5	0	0	1	1	0	0	1	0

Svaki element matrice je definiran kako slijedi:

$$r(f_i,s_j)=\begin{cases}0 & \Leftrightarrow \langle f_i,s_j\rangle \notin R_{FS}\\ 1 & \Leftrightarrow \langle f_i,s_j\rangle \in R_{FS}\end{cases} \quad (5)$$

Tablica 1 prikazuje identične simptome kvarova F4 i F7 (signatura kvara). U tom slučaju, kvarove je nemoguće izolirati te je potrebno promatrati ponašanje simptoma u vremenu.

Druga dijagnostička metoda zaključivanja je metoda stabla kvara. Koriste se dva pristupa, analiza stabla kvara − FTA i analiza stabla događaja − ETA. FTA ili rasuđivanje unazad je učinkovit način za analiziranje i predviđanje pouzdanosti i sigurnosti sustava, slika 4 a). Ovaj pristup predstavlja deduktivnu proceduru koja počinje s poznatim kvarom i istražuje odgovarajuće simptome koji uzrokuju istog.

Stablo kvara razvija se iz neželjenog događaja, a grane vode do slijeda događaja koji uzrokuje dotični kvar. Ako je analiza zasnovana na promatranju, stablo kvara starta od simptoma do kvarova i tada je to ETA ili unaprijedno rasuđivanje, slika 4 b).

FTA je najčešće korištena u procjeni sigurnosti sustava zaštite. Procjenjuje predviđanje vjerojatnosti da sigurnosni sustavi možda ne ispune svoje namijenjene zadatke ili smanjuje posljedice opasnih događaja.

Every matrix element is defined as follows:

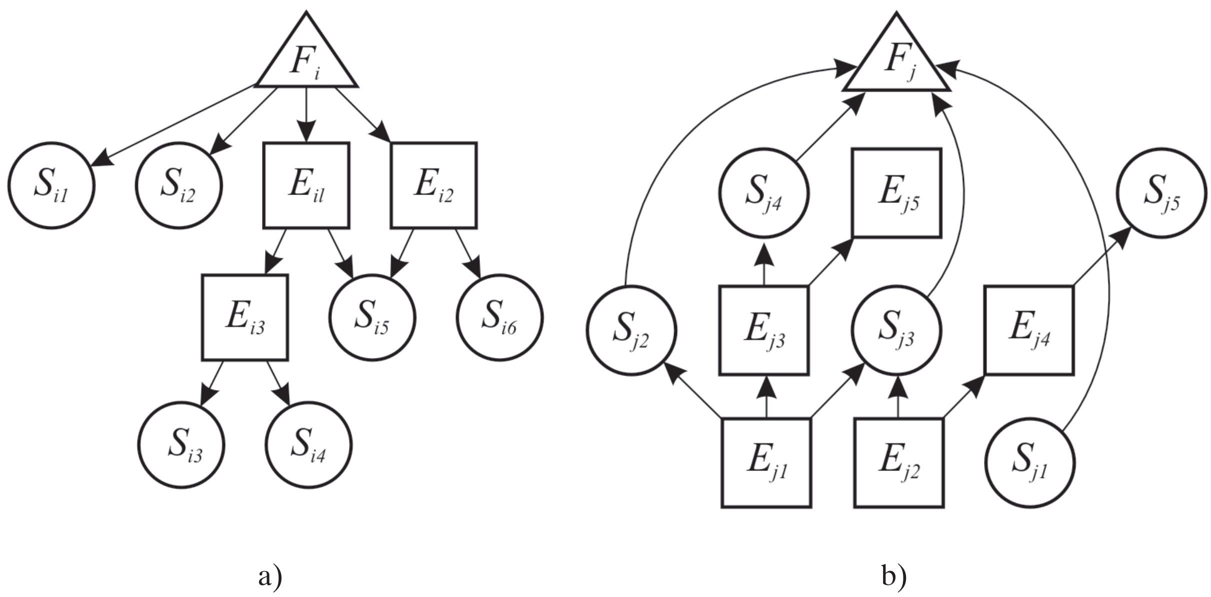
$$r(f_i,s_j)=\begin{cases}0 & \Leftrightarrow \langle f_i,s_j\rangle \notin R_{FS}\\ 1 & \Leftrightarrow \langle f_i,s_j\rangle \in R_{FS}\end{cases} \quad (5)$$

Table 1 shows that faults F4 and F7 have identical symptoms (fault signature). In such a case, faults are impossible to isolate and it is necessary to monitor the symptoms behavior in time.

Another diagnostics conclusion method is the fault tree method. Two approaches are used, fault tree analysis – FTA and event tree analysis ETA. FTA or backward chaining reasoning is an efficient way for analyzing and predicting system reliability and safety, figure 4a). This approach represents a deductive procedure that starts with a known fault and a search for symptoms that have caused the respective fault .

Fault tree develops from unwanted events, and the branches lead to event sequence that causes the respective fault. If the analysis is based on observing the fault tree, starting from the symptoms to the faults, then it is ETA or forward chaining reasoning, figure 4b).

FTA is the most frequently used in the assessment of the safety protection system design. The design is assessed by predicting the probability that safety systems might fail to perform their intended task of either preventing or reducing the consequences of hazardous events.



Slika 4. Stablo kvara – osnova heurističkog znanja [1]
Figure 4 *Fault tree – the basis of heuristic knowledge* [1]

Obje metode mogu biti izražene u obliku pravila: AKO <stanje> TADA <zaključak> / <akcija>. Simptomi su međusobno povezani pomoću logičkih I/ILI operacija u binarnom obliku ili u obliku neizrazite logike. Stanje (premisa) sadrži činjenice u obliku simptoma S kao ulaza, a zaključak sadrži kvar F kao logički uzrok činjenica. Pravila mogu biti dana u obliku (6):

$$ako < \left(\sigma_i \text{ I } \sigma_i{+}1 \text{ I...I } \sigma\delta\right) ILI \left(\sigma_i' \text{ I } \sigma_i'{+}1 \text{ I...I } \sigma\delta'\right)$$

$$\text{...}ILI\text{...} > tada < \phi_k > \qquad (6)$$

gdje su: $\sigma_i \in \left[E_k, S_i\right]$ skup događaja, simptoma (ulazi, tj. premise),

$\phi_k \in \left[E_k, F_j\right]$ skup događaja i kvarova (izlazi, tj. zaključci).

U binarnoj logici je: $\sigma_i = 0$ ili $\sigma_i = 1$, stoga ϕ_k može biti određen na ovaj način, izraz (7):

$$\phi_k = 1 - \prod_{j=1}^{\gamma}\left(1 - \prod_{i=1}^{\delta(j)} \sigma_i\right) \qquad (7)$$

gdje je: γ – broj konjunkcija (unija); δ(j) – broj elemenata konjunkcije.

Simptomi, događaji i kvarovi mogu biti prezentirani u neizrazitom obliku, što definira odgovarajuće funkcije i pripadnost, kao u izrazu (8), (najčešće je subjektivna procjena stručnjaka, operatera):

$$0 \le \mu(\sigma_i) \le 1 \text{ za simptome ;}$$
$$0 \le \mu(\varphi_k) \le 1 \text{ za kvarove} \qquad (8)$$

gdje je μ funkcija pripadnosti.

3. SIMULACIJA: PREDMET PROUČAVANJA

Ispravan rad separatora teškog goriva je od esencijalne važnosti za kvalitetu goriva. Slika 5 prikazuje presjek separatora teškog goriva i njegove komponente.

3.1. Analiza stabla kvara

Analiza mogućih uzroka nečistoća i vode u gorivu započinje provjeravanjem ispravnosti separatora goriva. Kako bi se promotrili svi even-

Both methods can be expressed in the form of rules: IF <condition> THEN <conclusions> / <action>. The symptoms are related to each other by means of logical AND/OR operations in binary or fuzzy logic form. Condition part (premise) contains facts in the form of symptoms S as input and the conclusion part includes fault F as a logic cause of the facts. Then, the rules could be given in the form (6):

$$ako < \left(\sigma_i \text{ I } \sigma_i{+}1 \text{ I...I } \sigma\delta\right) ILI \left(\sigma_i' \text{ I } \sigma_i'{+}1 \text{ I...I } \sigma\delta'\right)$$

$$\text{...}ILI\text{...} > tada < \phi_k > \qquad (6)$$

where: $\sigma_i \in \left[E_k, S_i\right]$ a set of events, symptoms (inputs i.e. premises),

$\phi_k \in \left[E_k, F_j\right]$ a set of events and faults (outputs i.e. conclusions).

In binary logic is: $\sigma_i = 0$ or $\sigma_i = 1$, so ϕ_k can be determined in this way, expression (7):

$$\phi_k = 1 - \prod_{j=1}^{\gamma}\left(1 - \prod_{i=1}^{\delta(j)} \sigma_i\right) \qquad (7)$$

where: γ – number of conjunction (union); δ(j) – number of elements by conjunction.

Symptoms, events and faults can be presented in the form of fuzzy set, which defines the respective functions and affiliation as in expression (8), (often subjective assessment of experts, operator):

$$0 \le \mu(\sigma_i) \le 1 \text{ for symptoms ;}$$
$$0 \le \mu(\varphi_k) \le 1 \text{ for faults} \qquad (8)$$

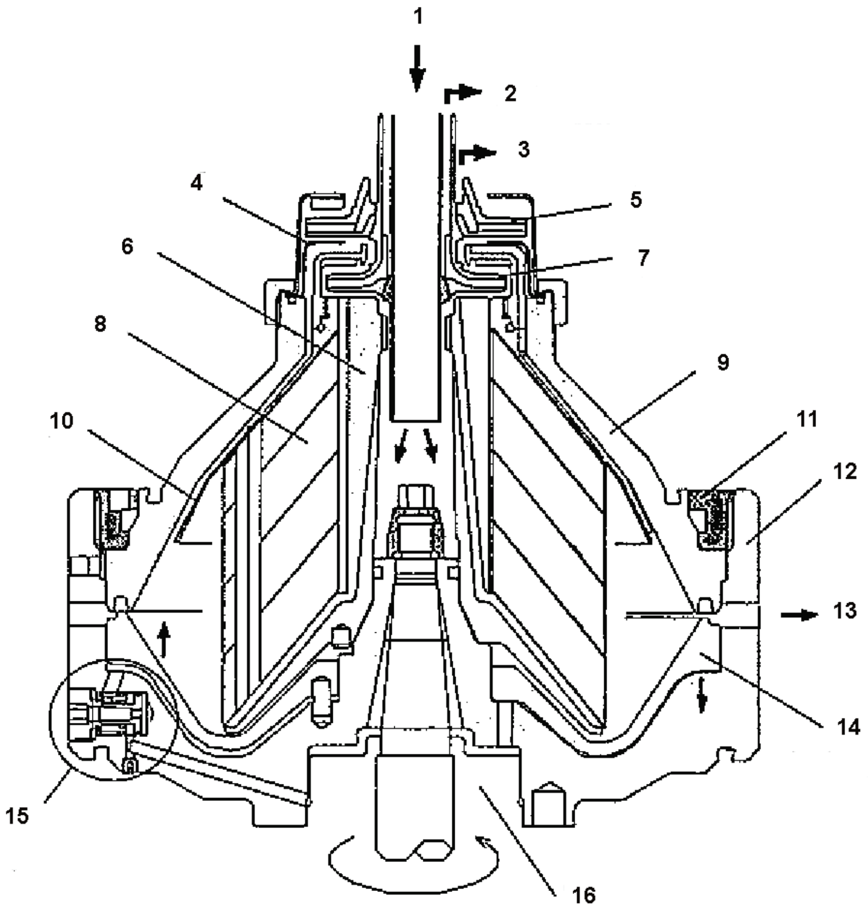
where μ is a membership function.

3. SIMULATION: CASE STUDY

A correct operation of heavy fuel oil separator is of essential importance for fuel oil quality. Figure 5 shows the cross section of a fuel oil separator and its components.

3.1. Fault tree analysis

The analysis of the possible causes of impurities and water in fuel oil starts by checking the fuel oil separator operation. To check all possible causes of the heavy fuel oil separator mal-



Slika 5. Presjek separatora teškog goriva [18]
gdje su: 1 – ulaz nečistog goriva; 2 – izlaz pročišćenog goriva; 3 – izlaz separirane vode; 4 – gravitacijski disk; 5 – komora teških tekućina; 6 – razvodnik; 7 – komora lakih tekućina; 8 – disk; 9 – kugla; 10 – gornji disk; 11 – tijelo kugle; 12 – tijelo kugle; 13 – mulj; 14 – glavni cilindar; 15 – skup pilot ventila; 16 – uređaj koji opskrbljuje vodom.

***Figure 5** Cross section of fuel oil separator* [18]
where: 1 – dirty fuel oil inlet; 2 – purified fuel oil outlet; 3 – separated water outlet; 4 – gravity disc; 5 – heavy liquid chamber; 6 – distributor; 7 – light liquid chamber; 8 – disc; 9 – bowl hood; 10 – top disc; 11 – bowl body; 12 – bowl body; 13 – sludge; 14 – main cylinder; 15 – pilot valve assembly; 16 – water supplying device.

tualni uzroci neispravnog rada separatora teškog dizelskog goriva, izvršena je analiza metodom stabla kvarova, slika 6.

Ovakva dijagnostička metoda zaključivanja pruža potpunije razumijevanje međusobnih funkcionalnih veza analiziranog sustava te jednostavnije identificiranje komponente koja uzrokuje eventualni kvar tehničkog sustava. Interaktivno povezivanje događaja i simptoma koji bi mogli dovesti do navedenog kvara, izvršeno je pomoći Booleovih logičkih izraza.

Nakon konstruiranja stabla moguće je izvršiti kvantitativnu analizu. Teorija vjerojatnosti je osnovna matematička tehnika koja je uključena u kvantitativnu procjenu stabla kvara. Pruža analitički tretman simptoma, a simptomi i događaji su temeljne komponente stabla kvarova.

function, an analysis by fault tree method has been made, figure 6.

Such diagnostic method of conclusion gives a better understanding of functional connections between the analyzed system's components and a more simple identification of the component that causes eventual fault of a technical system. The interactive connection of events and symptoms that could lead to the given fault has been inferred by Boole's logical expression.

After the fault tree construction, it is possible to make a quantitative analysis. The probability theory is the basic mathematical technique involved in the quantitative assessment of fault trees. It provides an analytical treatment of symptoms, symptoms and events are the fundamental components of fault trees.

Teorija skupova je opći pristup koji omogućuje organizaciju izlaznih događaja eksperimenata kako bi se utvrdila odgovarajuća vjerojatnost [17]. Koristeći teoriju skupova, koncepti stabla kvarova separatora teškog goriva mogu biti izraženi kao:

$$P(E)=P(E1)+P(E2)+P(E4)+P(E6)+P(E7)$$

$$P(E1)=P(A)+P(B)-P(A)P(B)$$

$$P(E2)=P(C)+P(D)+P(F)+P(E3)$$

$$P(E3)=P(G)+P(H)-2P(A\cap B)$$

$$P(E4)=P(E5) \quad (9)$$

$$P(E5)= P(I)+P(J)+P(K)+P(L)-P(I)P(J)P(K)P(L)$$

$$P(E6)=P(M)+P(N)-2P(M\cap N)$$

$$P(E7)=P(E8)+P(R)-2P(E8\cap R)$$

$$P(E8)=P(O)P(P)$$

gdje *P(E)* označava mogućnost pojave kvara *E* koja se, u ovom slučaju, ostvaruje prisutnošću kvarova *E1*, *E2*, *E4*, *E6* ili *E7*.

The set theory is a general approach which allows us to organize the outcome events of an experiment to determine the appropriate probabilities [17]. Using the set theory fault tree concepts of heavy fuel oil separator can be expressed as:

$$P(E)=P(E1)+P(E2)+P(E4)+P(E6)+P(E7)$$

$$P(E1)=P(A)+P(B)-P(A)P(B)$$

$$P(E2)=P(C)+P(D)+P(F)+P(E3)$$

$$P(E3)=P(G)+P(H)-2P(A\cap B)$$

$$P(E4)=P(E5) \quad (9)$$

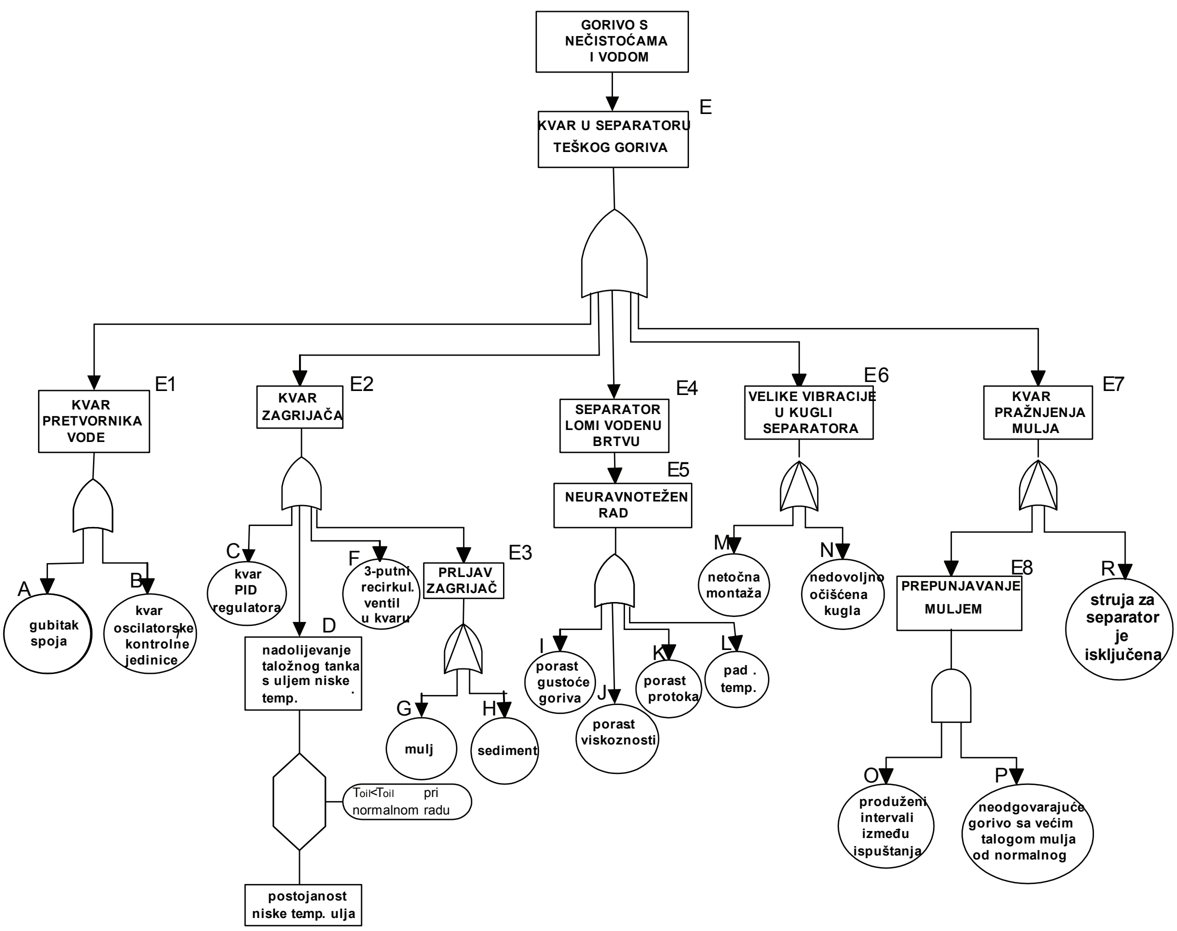
$$P(E5)=P(I)+P(J)+P(K)+P(L)-P(I)P(J)P(K)P(L)$$

$$P(E6)=P(M)+P(N)-2P(M\cap N)$$

$$P(E7)=P(E8)+P(R)-2P(E8\cap R)$$

$$P(E8)=P(O)P(P)$$

where *P(E)* indicates the possibility of fault *E* that, in this case, is gained with the occurrence of faults *E1*, *E2*, *E4*, *E6* or *E7*.



Slika 6. Stablo kvara sustava separatora teškog goriva

***Figure 6** Fault tree of heavy fuel oil separator system*

Ovakva analiza ukazuje da je za uspješno funkcioniranje sustava neophodna ispravnost svih elementa sustava. Također, olakšava pronalazak kvara u slučaju otkaza pojedine komponente te na taj način ubrzava postupak lokalizacije kvara i pravovremene reakcije.

Prikazanom analizom kvara u sustavu separatora teškog dizelskog goriva metodom stabla kvara, moguće je zaključiti koje mjere opreza trebaju biti poduzete kako bi separator učinkovitije funkcionirao. Jednostavnije rečeno, koje parametre sustava je potrebno kontinuirano pratiti kako bi se njihovom optimizacijom došlo do pouzdanijeg rada brodskih strojnih sustava. Veliku pažnju treba posvetiti na održavanje temperature ulaznog goriva, jer čak i malo smanjenje temperature reducirat će kvalitetu separacije. Temperatura utječe na viskoznost i gustoću goriva te je treba održavati stalnom tijekom separacije. Jednako je važno koristiti preporučenu brzinu protoka, jer se nižom brzinom protoka goriva kroz separator osigurava njegova veća učinkovitost.

3.2. Neizrazita pravila

Kako je već u ovom radu spomenuto neispravan rad separatora dovodi do velikog broja neželjenih događaja. Nečistoće u gorivu, koje su izravna posljedica nedovoljno pročišćenog goriva, izazivaju mnoge kvarove u sustavu teškog dizelskog goriva. Upravo zbog navedenog razloga, simulirani su neki od kvarova u sustavu goriva i promatrane su promjene parametara koje služe za procjenu ponašanja brodskog dizelskog motora i njegovih sustava.

Such analysis shows that, for a successful system function, it is necessary that all elements of the system are correct. Furthermore, it makes the fault detection easier in case of a single component fault and accelerates the procedure of the fault localization and timely reaction.

On the basis of the indicated fault analysis in heavy fuel oil by the fault tree method, it is possible to conclude which safety measures should be conducted for a more efficient function of the separator. In more simple terms, which parameters of the system are necessary to be monitored continually, so that their optimization leads to a more reliable operation of the marine engine system as a whole. Especial attention should be given on maintaining the input fuel oil temperature at a desired temperature, because, even the slight temperature fall is going to reduce the separation quality. Temperature influences on viscosity and fuel oil density should be held constant during the separation. It is also important to use the recommended flow fuel oil rate, because lower flow of fuel oil through the separator ensures higher efficiency [15].

3.2. Fuzzy rules

As previously mentioned, an incorrect operation of the separator leads to a great number of unwanted events. Fuel oil impurities, that are a direct consequence of insufficiently purified fuel oil, are responsible for many faults in the heavy fuel oil system. For this reason, some of the possible faults in the fuel oil system have been simulated and parameter changes that are used for the assessment of the marine diesel engine and its systems behavior have been monitored.

Tablica 2. Simulirani kvarovi i promatrani simptomi sustava teškog goriva
***Table 2** Simulated faults and observed symptoms of heavy fuel oil system*

KVAROVI *FAULTS*	SIMPTOMI *SYMPTOMS*
F1: Glavni filtar teškog goriva je zaprljan (puno) *F1: Main Fuel oil filter is dirty (high)* *F2*: Habanje pumpe za povećanje tlaka goriva (srednje) *F2: Booster pump wear (medium)* *F3*: Habanje dobavne pumpe (srednje) *F3: Supply pump wear (medium)*	*S1*: izlazni tlak pumpe za povećanje tlaka goriva *S1: fuel oil booster pump discharge pressure* *S2*: tlak goriva na glavnom motoru *S2: fuel oil pressure at main engine* *S3*: protok kroz zagrijač goriva 1 glavnog motora *S3: main engine fuel oil heater 1 flow* S4: tlak dobavne pumpe goriva *S4: fuel oil supply pump pressure* *S5*: tlak spremnika za odzračivanje goriva *S5: fuel oil venting tank pressure* *S6*: razlika tlakova na filtru goriva *S6: fuel oil filter difference pressure*

Simuliranjem tri kvara analizirana je promjena šest relevantnih simptoma u sustavu goriva brodskog dizelskog motora, tablica 2.

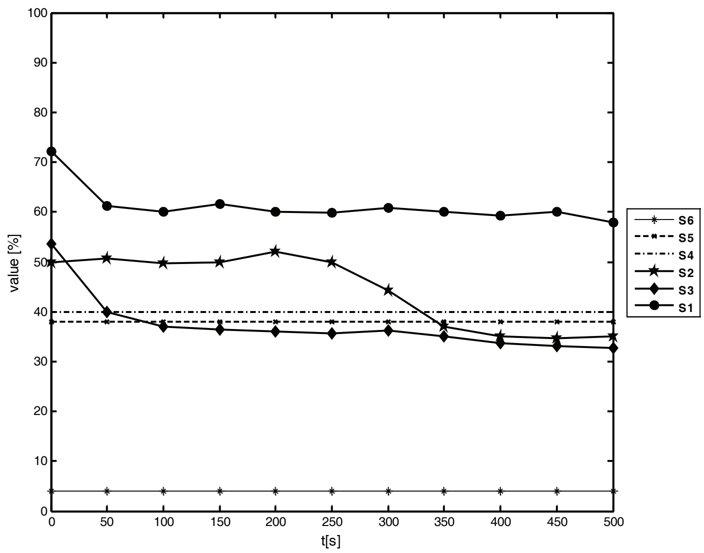
Rezultati simulacije zadanih kvarova pružaju analizu promatranja ponašanja simptoma u vremenu, slike 7, 8 i 9.

U svrhu jasnijeg uvida utjecaja simuliranih kvarova za relevantne simptome koristi se tablica 3, koja prezentira dijagnostičku matricu.

By simulating three faults, a change of six relevant symptoms in the marine diesel engine fuel oil system has been analyzed, table 2.

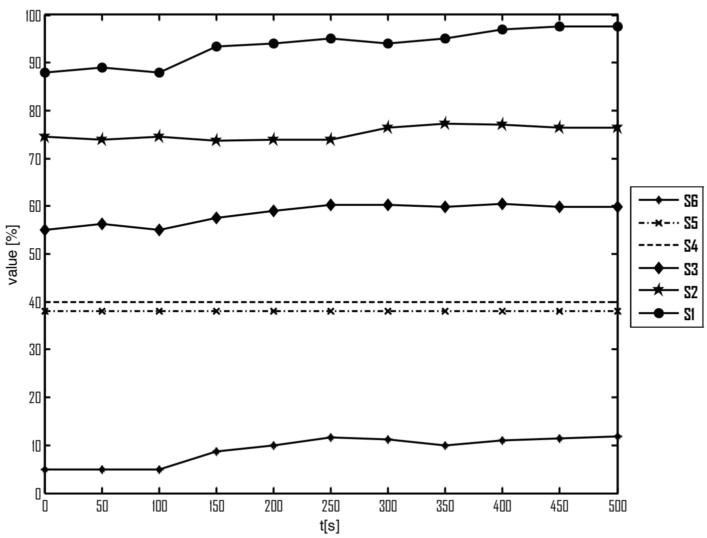
The results of the given faults simulation give us an observation analysis of the behavior of symptoms in time, figures 7, 8 and 9.

In order to gain a clearer insight into the impact of the simulated faults to the relevant symptoms, table 3 is used.



Slika 7. Zaprljan glavni filtar goriva
***Figure 7** Main fuel oil filter is dirty*

Izvor / *Source:* Pen Recorder, Full Mission Engine Room Simulator Kongsberg Norcontrol



Slika 8. Habanje pumpe za povećanje tlaka goriva
***Figure 8** Booster pump wear*

Izvor / *Source:* Pen Recorder, Full Mission Engine Room Simulator Kongsberg Norcontrol

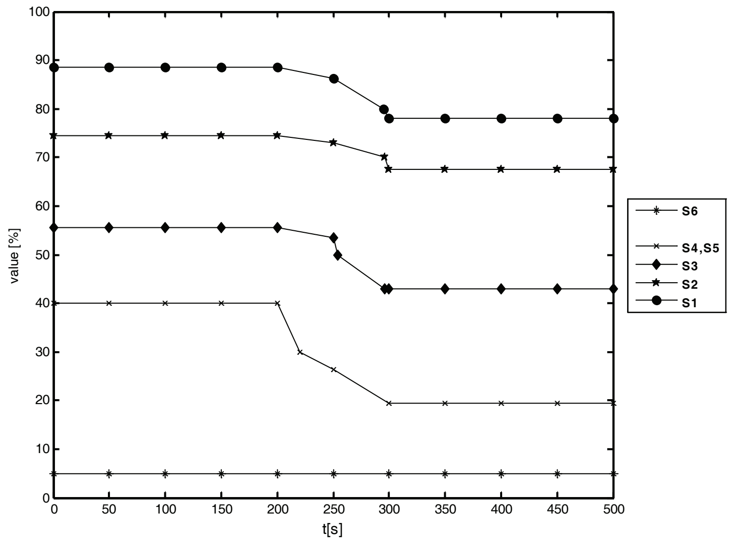


Figure 9. Habanje dobavne pumpe
Figure 9 *Supply pump wear*

Izvor / ***Source:*** Pen Recorder, Full Mission Engine Room Simulator Kongsberg Norcontrol

Tablica 3. Simptomi kvara za diskretne događaje i šest mjerenja
Table 3 *Fault symptoms table for discrete events and six measurements*

KVAROVI *FAULTS*	SIMPTOMI / *SYMPTOMS*						moguće izolirati *isolable*	nije moguće izolirati *not isolable*
	S1	S2	S3	S4	S5	S6		
F1	1	1	1	0	0	0	X	
F2	1	1	1	0	0	1	X	
F3	1	1	1	1	1	0	X	

Tablica prikazuje binarne odnose između simptoma i kvarova. Binarna vrijednost 0 indicira nepromijenjeno stanje promatranih parametara pod utjecajem zadanog kvara. U slučaju koji je prezentiran tablicom 3, sva tri zadana kvara mogu biti izolirana na osnovi promatranja ponašanja svih šest simptoma. Promatranjem simptoma pojedinačno, teško je zaključiti koji je kvar nastupio. Na primjer, simptomi *S1*, *S2*, *S3*, *S4* i *S5*, prema tablici 3, imaju identično ponašanje u slučaju kvara *F1* i kvara *F2*. Za bolju lokalizaciju, izolaciju i dijagnostiku koristi se tablica 4.

Table 3 presents a diagnostic matrix. Its goal is to produce binary relations between symptoms and faults. The binary value 0 indicates the unchanged state of the observed parameters under the influence of a given fault. In case that is presented in table 3, all three given faults can be isolated on the basis of observing the behavior of all six symptoms. By observing the symptoms individually, it is hard to conclude what is the fault. For example, symptoms *S1*, *S2*, *S3*, *S4* and *S5*, according to table 3, have an

Tablica 4. Promjena parametara u simulacijskom periodu
Table 4 *Changing of parameters of the simulation period*

KVAROVI *FAULTS*	SIMPTOMI / *SYMPTOMS*					
	S1	S2	S3	S4	S5	S6
F1	--	--	--	0	0	0
F2	++	+	+	0	0	+
F3	--	-	--	--	--	0

Gdje je: 0 nema značajne promjene; + porast; ++ veliki porast; – pad; -- veliki pad. / where is: 0 no significant change; + increase; ++ large increase; – decrease; -- large decrease.

Ovakav pristup promatranja ponašanja simptoma omogućava jednostavniju i točniju izolaciju kvara. Analiziranje tablice 4 očito je da kvar može biti izoliran nakon pojave simptoma *S2*. Pristup ovakvoj tablici može biti izveden neizrazitom logikom, koja pruža formalnu metodologiju za zastupanje, obradu i implementaciju ekspertnog znanja o problemu upravljanja procesima.

AKO S2 značajno pada I S6 nema značajne promjene, TADA je kvar F1.

AKO S3 značajno pada I S5 nema značajne promjene, TADA je kvar F1.

AKO S2 raste I S6 raste, TADA je kvar F2.

AKO S3 raste I S5 nema značajne promjene, TADA je kvar F2.

AKO S2 pada I S6 nema značajne promjene, TADA je kvar F3.

AKO S3 značajno pada I S5 značajno pada, TADA je kvar F3.

Ovaj pristup za analizu utjecaja odgovarajućih kvarova na relevantne simptome pruža doprinos u prevenciji katastrofalnih kvarova. Također utječe na brzinu i točnost identifikacije, izolacije i dijagnoze kvarova u različitim sustavima.

4. PRIMJENA MODELA SIMULACIJE

Ranija dijagnostika i izolacija kvarova sustava brodskog dizelskog motora je od esencijalne važnosti za realizaciju sigurnog rada i potrebne razine funkcionalnosti. Komponente brodskog dizelskog motora su predmet, a uzroci kvarova općenito mogu biti strukturalni (direktna konstrukcijska pogreška), produkcijski (pogreška u dizajnu i instalaciji) i eksploatacijski [5].

Inženjeri koriste mjerljive parametre motora za ispitivanje ponašanja brodskog dizelskog motora [6-7], [10]. Ali čak i s tim podacima u ruci, u mnogim slučajevima iznimno je teško utvrditi uzroke kvarova, jer svi ti parametri mogu imati sličan učinak [12]. Zbog navedenog razloga, u ovom radu je korišten simulacijski model u svrhu predviđanja karakteristika brodskog dizelskog motora u uvjetima različitih kvarova. Dijagnostičke metode zaključivanja primijenjene su s ciljem prikazivanja odnosa između kvarova i simptoma kao učinkovit nači-

identical behavior in case of fault *F1* and fault *F2*. For a better localization, isolation and diagnosis, table 4 has been used.

Such an approach to symptoms behavior monitoring allows as impler and more correct fault isolation. By analyzing table 4, it is obvious that a fault can be isolated after the appearance of *S2*. Access to such a table can be derived from the fuzzy logic, which provides a formal methodology for the representation, manipulation and implementation of the expert knowledge of the process control problem.

IF S2 significant drop AND S6 indicates no change, THEN fault F1.

IF S3 significant drop AND S5 indicates no change, THEN fault F1.

IF S2 rise AND S6 rise, THEN fault F2.

IF S3 rise AND S5 indicates no change, THEN fault F2.

IF S2 drop AND S6 indicates no change, THEN fault F3.

IF S3 significant drop AND S5 significant drop, THEN fault F3.

This approach to analyze the impact of the corresponding faults to the relevant symptoms provides a contribution to the prevention of disastrous faults. It also affects the speed and accuracy of identification, isolation and diagnosis of faults in different systems.

4. APPLICATION OF THE SIMULATION MODEL

Early diagnosis and isolation of the faults of themarine diesel engine systems is of essential importance for the realization of a safe operations and of the necessary level of functionality. The components of the marine diesel engine are subject to faults, and causes of faults can generally be structural (direct constructor errors), production (error in the design and installation) and exploitation ones [5].

Engineers make use of measurable engine parameters to examine the behavior of the marine diesel engine [6-7], [10]. But even after this data is in hand, it is extremely difficult, in many cases, to identify the cause of the faults since all these parameters may have a similar effect [12]. For this reason, in the presented paper, a simuna za brzu lokalizaciju, identifikaciju i izolaciju kvara odabrane komponente brodskih strojnih sustava. Simulacija je izvedena na simulatoru Kongsberg Norcontrol, koji omogućuje simulaciju blizu stvarnim uvjetima na brodu.

Ovaj rad analizira rad sustava separatora teškog goriva i njegov utjecaj na kvalitetu goriva. Prikazane su moguće posljedice goriva loše kvalitete na zagađenje okoliša te općenito na adekvatno funkcioniranje brodskih strojnih sustava.

4.1. Separator teškog goriva u funkciji zaštite okoliša i ljudskog zdravlja

Separator je esencijalan na razini redukcije katalitičkih čestica i drugih nečistoća koje mogu biti prisutne u gorivu. Loša kvaliteta goriva može dovesti do problema u radu kao što su:

- nestabilnost sustava goriva
- šteta na motoru uzrokovana kašnjenjem paljenja i prekomjernim habanjem
- zdravstveni aspekt i sigurnost posade zbog smjese otpadnih produkata
- ekološki aspekt, kao što je emisija NOx, SOx itd.

Krute čestice su neke od nečistoća u teškom dizelskom gorivu i uključuju prašinu, čađa, pepeo, metale itd. Ove čestice ne ostaju raspršene u zraku nego se postupno spuštaju na površinu zbog gravitacijske sile.

Čestice prašine mogu sadržavati brojne štetne polutante kao što su olovo (Pb), kadmij (Cd), živa (Hg) i ugljikovodici. Olovo ulazi u ljudsko tijelo respiratornim sustavom ili unosom hrane, akumulira se u organima i uzrokuje ozbiljne psihičke i mentalne probleme. Živa je bioakumulativni element i kao takav uzrokuje ozbiljne zdravstvene probleme. Kadmij uzrokuje kardiovaskularna oboljenja.

Čađa je opći pojam koji se odnosi na nečiste čestice ugljika koje proizlaze iz nepotpunog izgaranja ugljikovodika. Ugljični monoksid, ugljikovodik i ugljični dioksid su jedni od razloga globalnog zatopljenja.

Općenito, krute čestice mogu imati toksični utjecaj, mogu uzrokovati respiratorne i kardiovaskularne simptome te imaju globalno štetan utjecaj na okoliš.

lation model to predict the marine diesel engine performance under various fault conditions is used. Inference methods of fault diagnosis were applied with the aim of showing the relation between fault and symptoms as well as an efficient way for a rapid location, identification and isolation of selected components faults of the marine diesel engine system. Simulation was carried out on the Kongsberg Norcontrol simulator, which enables the simulation close to real conditions on board a ship.

This paper analyses the operation of the heavy fuel oil separator system and its influence on the fuel oil quality. Possible influences of the low quality fuel oil on the environment and human health, and, generally, on the adequate marine engine systems function, have also been presented.

4.1. Heavy fuel oil separator to promote environmental protection and human health care

A separator is essential at the level of reducing catalytic fines and other impurities that can be present in fuel oil. Bad fuel oil quality can lead to operational problems like:

- instability of the fuel oil system,
- engine damage caused by ignition delay and excessive wear;
- health aspect and safety of the crew because of a mixture of waste products;
- environmental aspect, such as emissions of NOx, SOx, etc.

Solid particles are some of the impurities in heavy fuel oil and include dust, soot, ash, metals, etc. These particles do not remain disperse in air but gradually settle down on the surface due to gravitational forces.

Dust particles may contain a number of harmful pollutants such as lead (Pb), cadmium (Cd), mercury (Hg) and hydrocarbons. Lead enters the human body by the respiratory system or by food intake, accumulates in the organs and causes serious physical and mental problems. Mercury is a bioaccumulative element and as such causes serious health problems. Cadmium causes cardiovascular diseases.

Soot is a general term that refers to impure carbon particles resulting from the incomplete combustion of a hydrocarbon. Carbon monox-

5. ZAKLJUČAK

Učestalost kvarova brodskih strojni sustava ovisi o brojnim faktorima, kao što su konstrukcija, održavanje, uvjeti plovidbe itd. Ako nisu poduzete adekvatne mjere, kvar može u kraćem ili dužem vremenu rezultirati neispravnim radom ili drastično većim oštećenjima, što često uzrokuje enormne troškove.

Posljednjih nekoliko godina dijagnostika kvarova doživljava rapidan razvoj. Primjena dijagnostičkih metoda na složenim brodskim strojnim sustavima jamči visoku učinkovitost i dugi eksploatacijski vijek.

Bilo bi idealno analizirati rad svih brodskih strojnih sustava u uvjetima različitih kvarova, ali zbog složenosti njihove interakcije to je gotovo nemoguće. U ovome radu analiziran je rad sustava separatora teškog goriva kao dijela brodskog dizelskog motora. Korištenjem analize stabla kvara prikazani su svi ozbiljni uzroci neispravnog rada separatora. Na temelju toga sugerirani su parametri sustava koji se trebaju kontinuirano pratiti, jer njihova optimizacija osigurava predviđanje budućih stanja brodskog stroja, vodi do poboljšanja radnih karakteristika i osigurava funkcionalnost sa minimalnim održavanjem i maksimalnom iskoristivošću.

Nečistoće u gorivu su izravno povezane s neispravnim radom separatora i mogu dovesti do ekoloških problema te radnih problema u sustavu teškog goriva.

Simulacija odgovarajućih kvarova u sustavu goriva, zbog nečistoća u gorivu, dvotaktnog brodskog dizelskog motora MAN B&W 5L90MC izvršena je koristeći brodostrojarski simulator Kongsberg Norcontrol. Implementacija simulatora u znanstvenim istraživanjima omogućuje simulaciju kvarova i njihovog utjecaja na cjelokupno radno ponašanje i to vrlo blizu realnim uvjetima na brodu, ali bez ikakvih posljedica. Rezultati simulacije omogućuju analizu ponašanja simptoma u vremenu. Relacije između simptoma i kvarova su prikazane dijagnostičkom matricom.

Dobiveni rezultati ukazuju na ponašanje komponenti brodskog dizelskog motora u slučaju kvarova i na neke degradirajuće karakteristike koje su bitne za pravovremenu prevenciju nastanka kvara, čime se pridonosi pouzdanosti propulziji brodskih dizelskih motora i sigurnosti broda na moru. Prikazane metode mogu po-

ide, hydrocarbon and carbon dioxide are one of the global warming reasons.

In general, solid particles can have a toxic influence, can cause respiratory and cardiovascular symptoms, and have an overall harmful effect on the environment.

5. CONCLUSION

Fault frequency in the marine diesel engine system depends on numerous factors, such as construction, maintenance, sailing conditions, etc. If adequate counter measures have not been taken, fault may, in a shorter or longer period of time, result in a faulty operation or drastically larger defect, which often cause enormous costs.

In a last few years, fault diagnosis is rapidly developing. The application of fault diagnosis methods on complex marine engine systems guarantees high efficiency and long operational lifetime.

It would be ideal to analyze the operation of all marine engine systems under different faults, but due to the complexity of their interaction that is practically impossible. This paper analyses the operation of the heavy fuel oil separator system as a part of the marine diesel engine. By using the fault tree analysis, all serious causes of the faulty operation of the separator have been treated. On this basis, system parameters, that should be continuously controlled, have been suggested, because their optimization ensures prediction of the marine engines future states, leads to improvements of operation characteristics and ensures functioning with a minimal maintenance and maximum usability.

Fuel impurities are directly connected with the faulty operation of the separator and can lead to environmental problems and operational problems in the heavy fuel oil system.

Simulation of the corresponding faults in the fuel oil system, due to fuel oil impurities, of the two-stroke MAN B&W 5L90MC marine diesel engine has been carried on by using the Kongsberg Norcontrol Full Mission Engine Room simulator. The implementation of the simulator in scientific researches enables the simulation of faults and their impact on the overall working behavior, very close to real conditions moći inženjerima za razumijevanje stvarnog učinka različitih kvarova na performanse motora.

on board the ship, but without any consequences. Simulation results enable the symptom behavior analysis at the time. Relations between symptoms and faults are shown in a diagnostic matrix.

The obtained simulation results indicate the performance of the marine diesel engine components in case of faults as well as some degradation performances which are important for the early prevention of a fault occurence, thereby contributing to the reliability of the marine diesel engine propulsion and ship's safety at sea. The proposed methods can hrlp the engineer to understand the actual effect of various faults on the engine performance.

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