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Fault Tree Analysis as a tool for modelling the marine main engine reliability structure

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Key words: Fault Tree Analysis (FTA), main engine, reliability, weak link, Reliability Block Diagram (RBD), qualitative analysis, minimal cut sets

Abstract

The introduction to the Fault Tree Analysis has been presented in this article. Selected publications on the Fault Tree Analysis have been listed. The usefulness of the method in marine engineering application has been indicated. Reliability testing facility has been presented, that is typical two-stroke, slow-speed ship crosshead Diesel engine intended to power the ship. The way of creating system model with the Fault Tree Analysis application has been presented. Reliability structure of tested engine has been modelled using Reliability Block Diagrams, as well as the Fault Tree Analysis. Main tree describing the object reliability structure analysis and the sub-tree structure modelling crank system, subsystem of the cam shaft, cylinder exemplary system and turbocharger have been built. Qualitative analysis of the tree has been conducted – the minimal cut sets of the system has been determined. The directions for further research have been indicated.

Introduction

The Fault Tree Analysis – FTA is one of the basic methods of assessing reliability. The FTA method was first used by the HA Watson at Bell Telephone Laboratories in 1961 in the United States, Watson with the US Air Force have analyzed the reliability of the control system of the Minuteman missiles [1]. The first publications on Fault Tree Analysis emerged in the mid-60s of the last century, the method in the following years has been improved [2, 3, 4].

The FTA method allows detailed examination of the system operation principles during the design, operation and during accident investigations [5]. Using fault tree potential system weak links can be located [6], and thus avoid serious and expensive design errors and construction [7, 8]. Fault tree are successfully used to diagnose the state of the reliability of the existing system [9]. Among many applications of this method analysis of vessel system operation can be mentioned [10, 11, 12, 13]. A detailed description of the method can be found in handbooks [3, 14, 15, 16].

Assess the validity of the components are associated with the issue of searching for the "weak links" that are the most unreliable components. Severity level of the component in the system is dependent on two factors: the reliability of the component that is part of the system and on what place it occupies in the structure of reliability. The influence of the first factor is obvious, however, relating to the location of the component in the structure of the reliability it should be noted that the component is the more important, the more it resembles a separate component connected in series to the system reliability structure. Its importance decreases with increasing level of its reserving [17].

Fault tree reflects the behaviour of the tested system, depending on the status of the individual sub-systems or individual components. The FTA model shows graphically and logically different combinations of possible adverse and normal events, which may occur during the operation of the system, leading to its failure.

Prior to the creation of the fault tree one should carefully consider the system, the first step is to define the purpose of the analysis (system down) or top event. The constructor of the tree must keep in mind that the tree should be clear and understandable to other people.

Fault tree is built based on a set of symbols of events interconnected with cause and effect relation. Intermediate event presented graphically as a rectangle represent the states of the subsystems of the analyzed object and their correlations cause emerging subsequent intermediate events leading to the top event in question, which is the purpose of the analysis [6, 16].

To the most prominent primary events are included:

1. Basic events, presented graphically using circles, are components faults of the system in question. Considering the case of the main engine parts these are the failed components. Events can also represent the basic operator errors and reflect the influence of the environment.
2. Undeveloped events, presented graphically using diamonds, are faults not fully defined, that is, not fully known. Undeveloped events can be further improved by conducting appropriate tests allowing for a quantitative estimation of the event, becoming the elementary events.

Apart from FTA model events, transfer symbols are used that are presented using triangles – they allow a clear division of the system into subsystems causing the fault tree easier survey.

Logic gates combine events according to cause-effect relations recorded by the designer. Each gate has any number of inputs but only one output. Gates can be distinguished as: AND which requires the simultaneous occurrence of signals on all inputs to get an output signal, OR is a gate that requires the existence of only one of the input signal to get an output signal and gate "k-out-of-n" requiring occurrence at least *k* out of *n* of all input events.

Object of analysis

Presented later in this article, block diagrams of reliability and fault trees model main engine reliability structure of HYUNDAI MAN B&W Mk8 7S50MC-C which is a two-stroke marine engine, perpetual, crosshead, unilateral actions driven turbo exhaust gases for direct drive of variable pitch propeller. Table 1 shows the main parameters of the main engine subjected to analysis.

During the analysis of the object the possibility of one cylinder system off as a partial possibility of achieving goals was assumed. The engine is an example of the threshold structure. The view of engine from upper platform of engine room is shown in figure 1.

The oldest but still very popular graphic description of system structure is Reliability Block Diagram (RBD), the diagram can be easily transformed to equivalent binary model or fault tree [6, 18].

Table 1. Basic data subjected to the analysis of the main engine

Main engine data for MAN B&W 7S50MC-C		
Parameter	Value	Unit
Cylinder number	7	–
Cylinder bore	500	mm
Piston stroke	2000	mm
Nominal speed	117	rpm
Maximum speed	127	rpm
Nominal power	9076	kW
Maximum continuous power	11635	kW

Fig. 1. Engine MAN B&W 7S50MC-C from upper platform of engine room

Block diagrams of reliability and fault trees

When building RBD model some simplifications during the object analysis are made which affects the accuracy of the results [19]. Usually, each block corresponds to exactly one component of the system, however, in the case of complex structures it may prove as impracticable. In this situation, the blocks that correspond to the same element are equally described.

Modern vessel engines have complex structure [20, 21, 22, 23]. Shown in figure 2 block diagram of the reliability of the main engine consists of a serial structure and threshold, the individual components are mapped by blocks of reliability. In the serial part are common components to engine, while, in the threshold part are components associated with the cylinder block. Implemented node 6 of 7 in the presented model opens the threshold structure and means that 6 of 7 systems must remain without any fault to the system was able to pursue its goals.

For the analyzed object cause and effect relationships are modelled corresponding to analyzed structure [22] using the methodology of fault tree

Table 2. Conventions used during the construction of the main engine fault trees

Tag	Description	Tag	Description
P	Transfer	I1	Fuel injector 1
ME	Main engine failure	I2	Fuel injector 2
AB1	Auxiliary blower 1	HP1	Fuel high pressure pipe 1
AB2	Auxiliary blower 2	HP2	Fuel high pressure pipe 2
CCF	Common components failure	FP	Fuel pump
CF	Cylinder frame	TF	Turbocharger failure
BP	Bedplate	SD	Shaft failure
CD	Chain drive	HD	Housing failure
AR	Scavenge air receiver	EF	Exhaust side components failure
ER	Exhaust gas receiver	TBE	Thrust bearing
SP	Starting air pipe	RBE	Radial bearing
AC	Air cooler	EI	Exhaust side impeller
CU	Cylinder unit failure	ES	Exhaust side seal
CPL	Cylinder cover – piston – liner group failure	AF	Air side components failure
CC	Cylinder cover	TBA	Thrust bearing
PN	Piston	RBA	Radial bearing
PR	Piston rings	AI	Air side impeller
LR	Liner	AS	Air side seal
CJ	Cylinder jacket	CKCF	Crankshaft components failure
PC	Piston rod – connecting rod group failure	MBF	Main bearings failure
PRO	Piston rod	MB	Main bearing
SB	Stuffing box	CS	Crankshaft
CB	Crosshead bearings	TB	Thrust bearing
CR	Connecting rod	CMCF	Camshaft components failure
CRB	Crankpin bearing	FCF	Fuel cams failure
CSC	Combustion and starting air components failure	FC	Fuel cam
		BF	Bearings failure
EV	Exhaust valve	B	Bearing
SV	Air starting valve	ECF	Exhaust valve cams failure
FS	Fuel supply components failure	EC	Exhaust valve cam

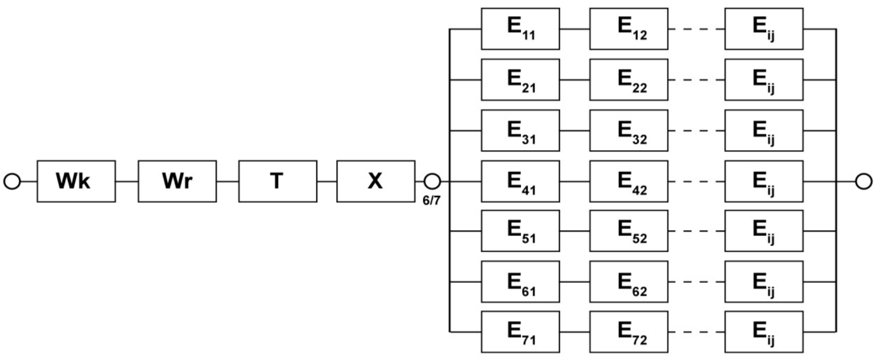

Fig. 2. Reliability Block Diagram of engine MAN B&W 7S50MC-C; Wk – crankshaft, Wr – camshaft, T – turbocharger, X – other elements like cylinder frame, bedplate, chain drive, starting air manifold, scavenge air receiver, air cooler and exhaust manifold, E_{ij} – is j element i-of cylinder system

analysis (FTA). In table 2 a list of symbols used in the construction of fault trees is provided.

The main components of the main engine's fault tree (Fig. 3) are faults of the cylinder, failure to the turbocharger and common components which include, among others, cylinder frame, bedplate, chain drive, starting air manifold, scavenge air receiver, air cooler and exhaust manifold.

FTA model of components associated with the engine cylinder system is shown in figure 4. In the model transfer symbols to the main groups of faults due to the significant expansion of the model are

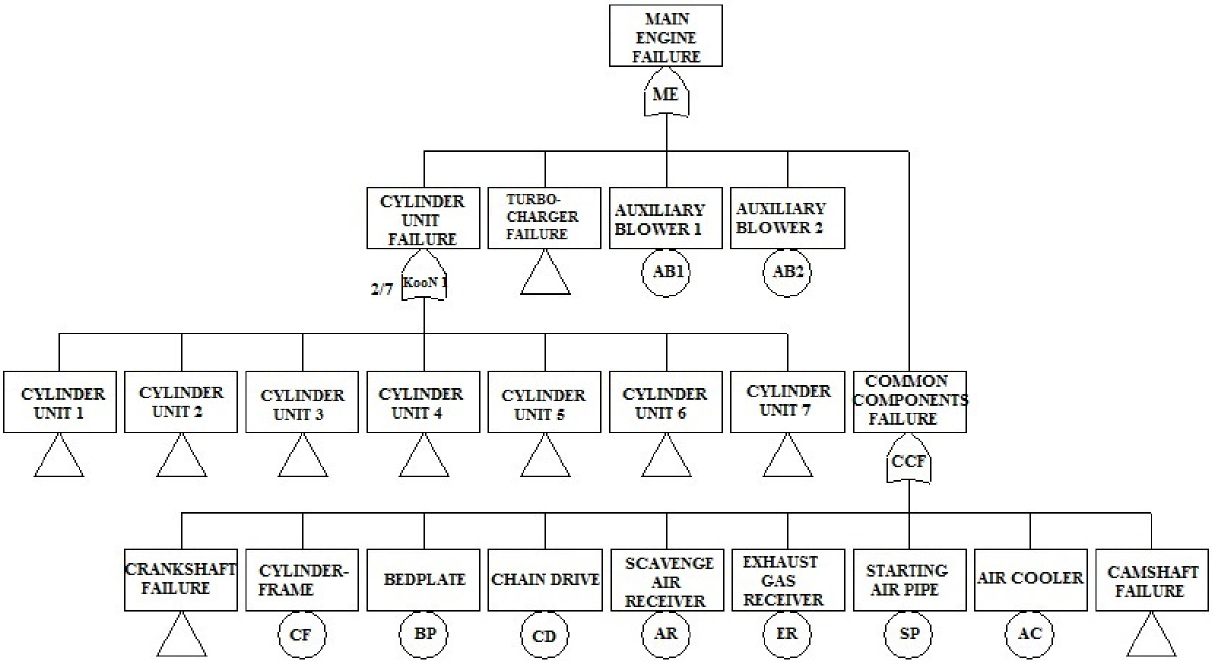

Fig. 3. The fault tree of analyzed main engine

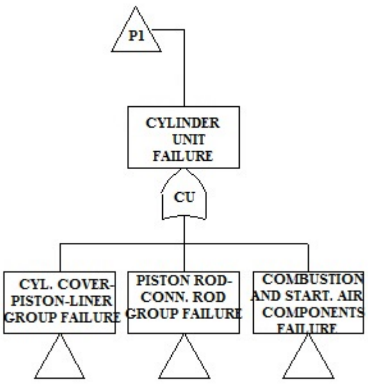

Fig. 4. Fault tree of cylinder system of analyzed main engine of a ship

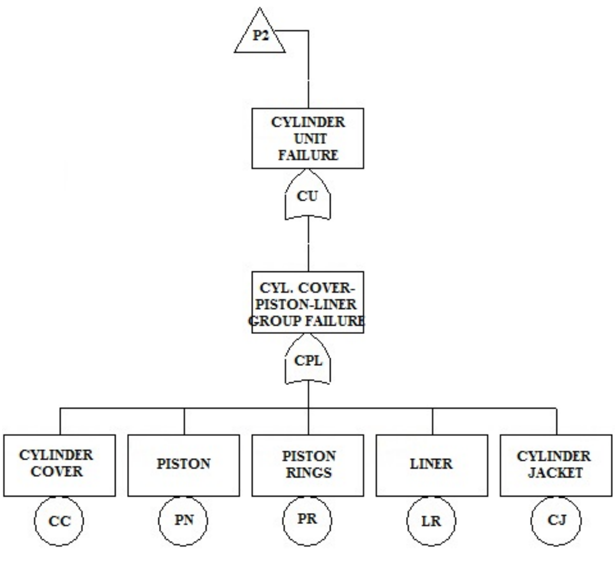

Fig. 5. The fault tree of piston-cylinder group of analyzed engine's cylinder system

used, making it easier for the recipient to understand presented system decomposition.

Figure 5 shows the fault of piston-cylinder group of cylinder system, main faults in this group include failures of: cylinder head, piston, piston rings, liner and jacket.

The faults of piston-crank group are illustrated in figure 6, among the specified components are: the piston rod, the stuffing box, crosshead bearings, a connecting rod and crankpin bearings.

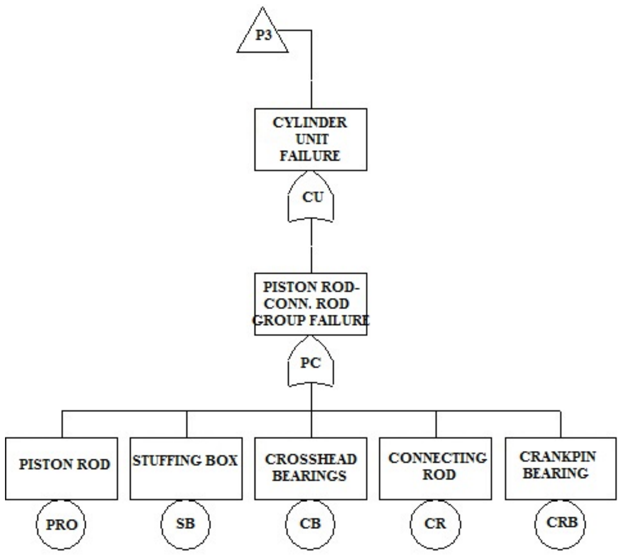

Fig. 6. The fault tree of piston-crank group of analyzed engine's cylinder system

The last group highlighted in the decomposition of the cylinder system is a group of components

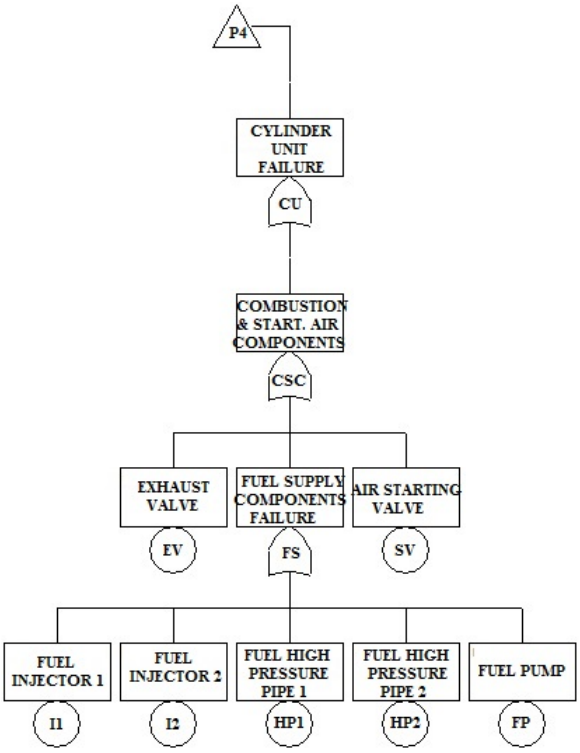

Fig. 7. The fault tree of group of components realizing the start and combustion process in the analyzed engine's cylinder system

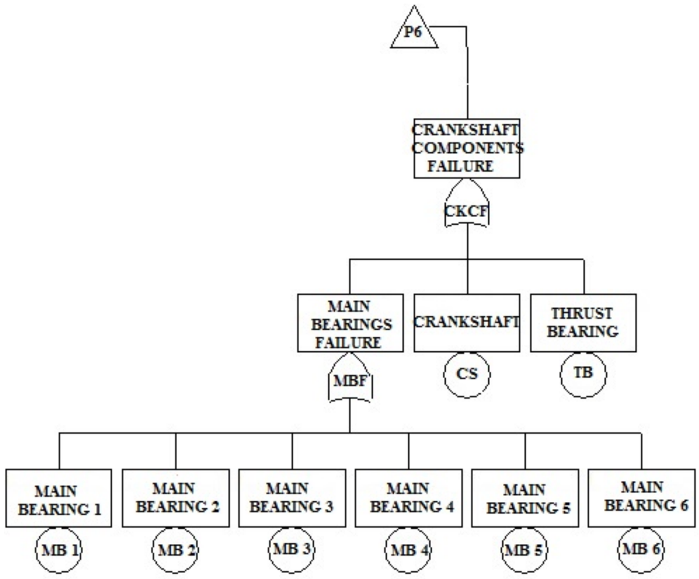

Fig. 9. The fault tree of analyzed engine's crank system

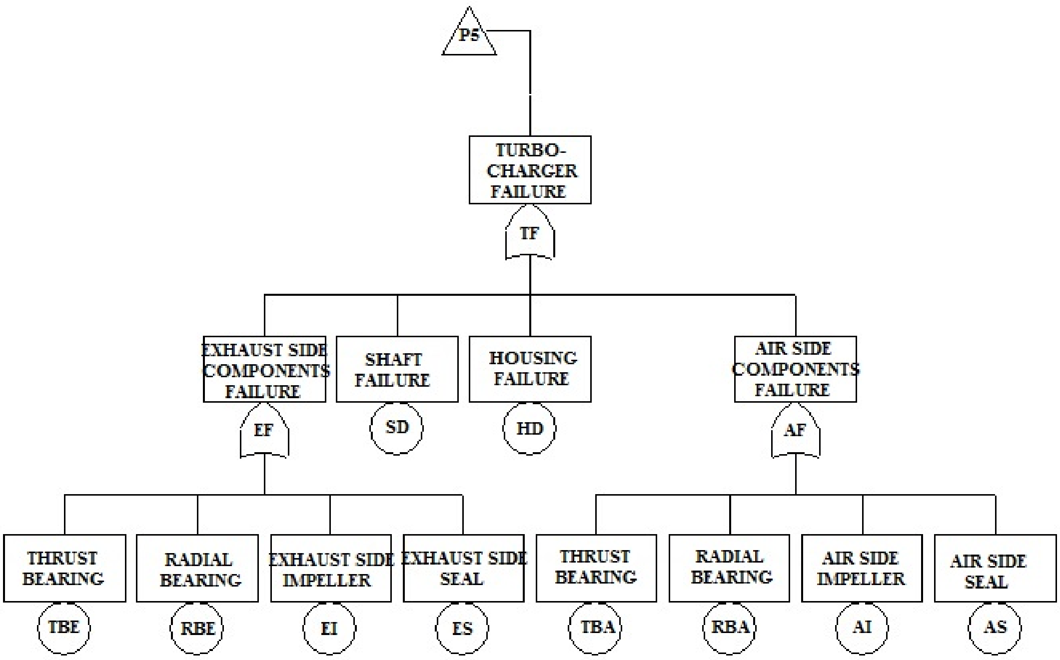

Fig. 8. The fault tree of analyzed engine's turbocharger

responsible for the realization of the starting and combustion process shown in figure 7. This group includes fault to the exhaust valve, the air starting valve, fuel injectors with high pressure pipes and fuel pump.

The fault tree of turbocharger was divided into fault of turbine functioning components, compressor and common elements (Fig. 8).

Similarly, models for crank system presented in figure 9 containing damages to main bearings, thrust bearing and the shaft.

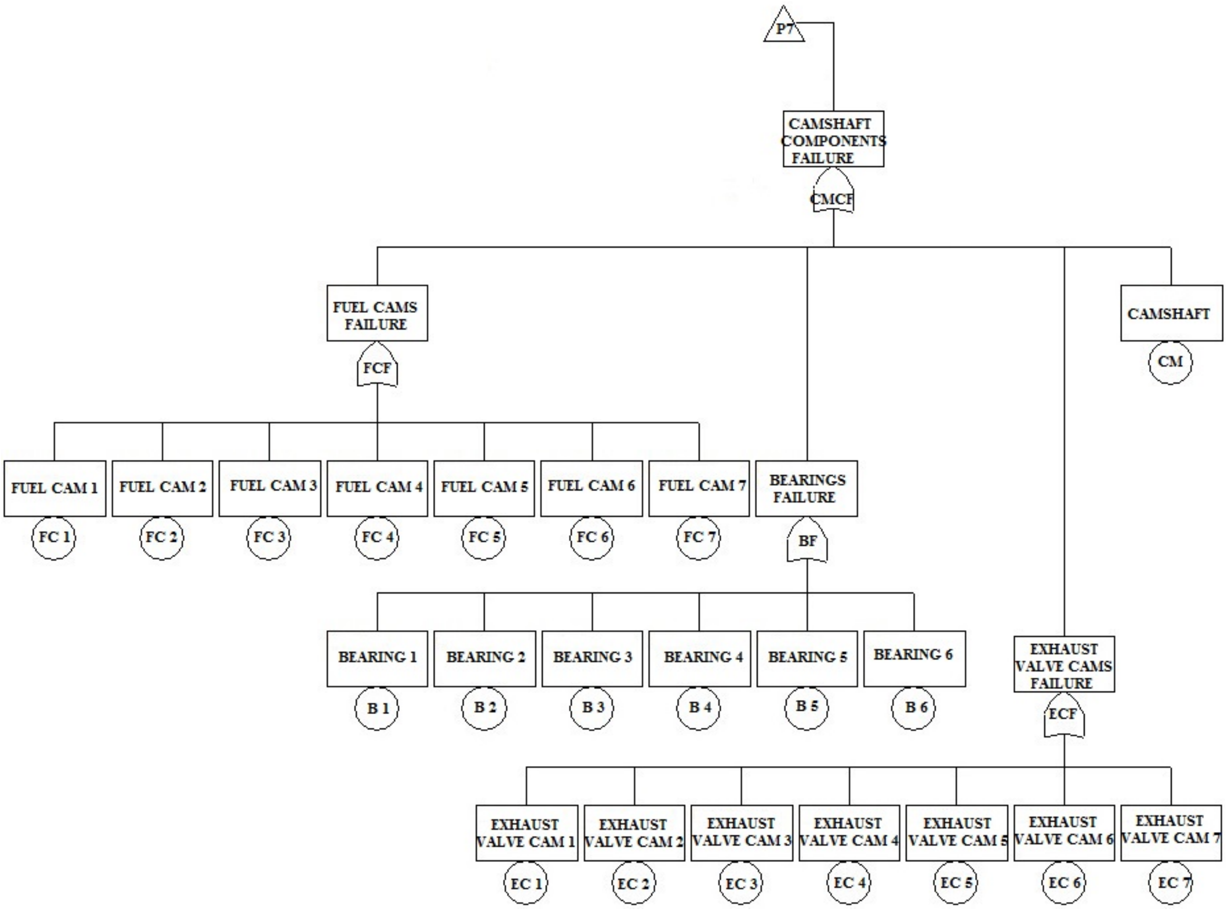

Fig. 10. The fault tree of analyzed engine's camshaft

The last shown fault sub-tree of analyzed main engine is the tree of camshaft (Fig. 10). Main failures include following components: fuel and exhaust valves cams, bearings and shaft.

Conclusions

Presented fault trees are source of information about relation / combinations of events which in critical situation lead to occurrence of top event causing prevention of goal achievement by system it was made for. For built fault tree the minimal cut sets are searched under qualitative analysis of tree [12, 16, 24]. The size of the minimal cut set is called row section.

In case of small fault tree the minimal cut set is searched by tree inspection while for large and complex fault trees appropriately selected procedures and algorithms are used [24].

The validity of the minimal cut set depends on the number of items included in the system. With the increase of row section the validity of component decreases, if the component is contained in the minimum number of sections in the analysis than first sections of the lowest row are taken into account. However, the more important component is the more often it occurs as a component of a larger quantity of minimal cut set [6].

The computer programme *CARA- FaultTree 4.1. Academic Version* made by *Sydvest Software* was used to model fault trees and to search for tracks, and the minimal cut set.

As a result of qualitative analysis of the main engine's fault tree the minimal cut set of first order are obtained, which consist of individual components in the number of 47 events of the original, events are shown in table 3. This means that the failure of any component of this set will cause failure of the system. The number printed at the marking component is cylinder arrangement in which it is located.

As a result of further qualitative analysis of the main engine fault tree, the minimum dimensions of disablement of the second order is obtained, which includes 5453 cut sets consisting of a combination of two components, due to the large number of these combinations just a few examples of cut sets are presented in table 3.

Above-mentioned means, that failure of two components belonging to any minimal cut sets of 5453 cut set will bring the system into down state.

Table 3. Main Engine's fault tree the minimal cut sets of first and second order

Name	First order	Second order
Events	{TBE}, {RBE}, {EI}, {ES}, {TBA}, {RBA}, {TBA}, {RBA}, {AI}, {AS}, {SD}, {HD}, {SD}, {HD}, {MB1}, {MB2},{MB3}, {MB4}, {MB5}, {MB6}, {CS}, {TB}, {FC 1}, {FC 2}, {FC 3}, {FC 4}, {FC 5}, {FC 6}, {FC 7}, {B 1}, {B 2}, {B 3}, {B 4}, {B 5}, {B 6}, {EC 1},{EC 2}, {EC 3}, {EC 4}, {EC 5}, {EC 6}, {EC 7}, {CF}, {BP}, {CD}, {AR}, {ER}, {SP}, {AC}, {AB1}, {AB2}.	{CC1,CC2}, {CC1,PN2}, {CC1,PR2}, {CC1,LR2}, {CC1,CJ2}, {CC1,PRO2}, {CC1,SB2}, {CC1,CB2}, {CC1,CR2}, {CC1,CRB2}, {CC1,I12}, {CC1,I22}, {CC1,HP12}, {CC1,HP22}, {CC1,FP2}, {CC1,EV2}, {CC1,SV2}, {PN1,CC2}, {PN1,PN2}, {PN1,PR2}, {PN1,LR2}, {PN1,CJ2}, {PN1,PRO2}, {PN1,SB2}… .

In the analyzed fault tree there are no minimal cut sets with more than two components. As a result of the analysis the total of 5500 minimal cut sets.

Please note that the component is the more important, the more it resembles independent component, the significance of components decreases with increasing level of its reserve [18]. From the reliability point of view, the most important components are the ones that make up the minimum of the first order sections (47 components).

Presented article is a part of the analysis of data collected on the main engine helpful to write a doctoral dissertation on *the validity of the analysis of marine engine components, taking into account the consequences of damage.*

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