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Application of External Events Vectors for Defining Reliability Structure of Fishing Vessels Power, Propulsion and Technological Plants

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Abstract

In the paper an overview of various ways of reliability structure complex technical systems have been presented. In order to do that both literature devoted to most frequently encountered systems has been overviewed as well as the basic types of reliability structures have been pointed out. A possibility of general structure function for the assumed group of construction solutions of the systems in question as well as application of external events vectors for precise definition of structure and configuration of cooperating system components have been suggested. Moreover, basic operational states of fishing vessels with their hypothetical configurations showing adequate external events vectors have been described. Results of calculations of values of system reliability measures based on presented reliability structure models have been presented.

Keywords: fishing vessel, technological plant, power plant, reliability structure, external events vector

Introduction

The main objective of the technical reliability systems analysis is determining reliability measures in order to assess the system with regard to the demands the system is to fulfill [1, 9].

Before the calculation stage it is necessary to carry out several actions like: formulating assumptions, defining the system boundaries and selecting components, specifying and describing the system reliability structure, choosing a mathematical model of system reliability structure and defining reliability measures describing the system components [3, 8, 10].

The starting point of all reliability assessment methods is the analysis of the system reliability structure in order to transform it into the required shape for making the calculations. The system structure represents specified interactions between the system constituent components.

From the cybernetic point of view in every system we may outline several types of structures [11]; these are: general, construction, functional, reliability and diagnostic structures. The system reliability depends upon the system reliability structure and the reliability of system components. That is why the knowledge of the analyzed system reliability structure turns out to be usually indispensable to determine its reliability (except of experimental reliability research).

The number of all possible structures corresponding with the number of all possible logical functions of a two-state system (up state – down state) built of two-state components equals 2^n [10]. Not all structures seem to be useful for the existing systems analysis. The system state may be independent of the state of one or more components. Such components are called passive and such structures are known as reducible structures because in such cases for defining the system components states and the system states a function with fewer arguments (system components states) is enough [10].

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Among irreducible structures there are such whose one component damage may lead to the whole system restoration. Such structures do not correspond with really existing objects (they are very rare exceptions) – they are so called incoherent structures [7, 8, 10]. When analyzing two-state object structures most frequently the following structures can be outlined [8-10, 13, 15]: series, parallel, threshold (*k*-out-of-*n*), series-parallel, parallel-series. According to the literature [9] it is possible to outline also the following structures: bridge, relay (cascade), series-relay, threshold-relay, parallel-relay.

System reliability structure may be presented in various forms if needed. The system reliability structure may be described with the use of three equivalent methods: positive (analysis limited to the system up state description), negative (analysis limited to the system down state description) and combined (with the use of both positive and negative descriptions) [12]. For each of the methods we may enumerate the following ways of defining the system reliability structure [12, 13]: verbal, logical (using logical signs, functions, tables and Venn's diagrams representations) and mathematical (probability methods, statistical and random functions theory). In [14] there has been presented a slightly different division which distinguishes the following: verbal description, analytical (using mathematical formulas), graphic (using conventional signs and symbols) and combined description (at the same time using several ways of structure description).

In both quoted above classifications the ways of defining permeate one another since the basis of their division constitute slightly different criteria. Each of the structure defining methods has many solutions and modifications. Among the analytical ways of defining the reliability structure we may distinguish: binary structure function which may be presented in arithmetic form, Boolean form, logical table, up states vectors list, minimal path-sets list, minimal cut-sets list etc. [9, 10, 12, 14]. Currently the most frequently used form of system reliability structure description are graphic form such as graphs, fault tree, reliability block diagram etc., [7, 8]. In literature we encounter several equivalent ways of system structure description, which means that one model can be transformed into another one.

There exist systems consisting of basic components whose destiny in each of the systems is the same. Due to different requirements and detailed solutions in particular cases the systems vary in number and configuration of certain components. An example of that are marine vessel power, propulsion and technological plants (*SENiT*) [2, 5, 6]. A considerable number of particular construction solutions can be encountered on fishing vessels [2] where depending upon the size of the ship and applied solutions the systems may vary considerably. Apart from that the system structure sometimes changes considerably in various ship's operational states which is connected with switching on or off certain system components depending upon the need for the functions the components should play in a specific operational state [4].

In case of such systems it is useful to make use of general models allowing for their application in many various solutions. This may be useful for accelerating reliability and availability analyses of many systems composed of similar systems. The presented in the paper application of external events vectors for modeling of the system structure changing has been worked out by the author as a part of the project reported in [5, 6]. Such form of the approach has not been found in literature yet. The presented in [3, 8, 10, 16] ways of structure description refer to the system in its specific selected operational state. Regarding the need for fishing vessels reliability and availability analysis *SENiT*, the systems reliability structure has been modeled in the shape of a binary model. The model presents the general aspects of the system with its proper function system components switched off in case of the lack of the right components in a system specific construction solution or in case of their switching off in a specific operational state. The information about the components belonging to a specified system in a given state is presented in the form of external events vector [5, 6] modeling the configuration and the system working conditions.

Construction of Fishing Vessel *SENiT*

Particular system components may be switched off and on depending on the vessel operational state [2]. The analysis has been devoted to the *general system* presented in Fig. 1. The system contains many detailed solutions (*specific systems*) connected with specific system components configuration. The presented general system does not exhaust all possibilities of real encountered configurations *SENiT* but only their most frequently applied subgroup. Additionally, not all presented components must appear in specific systems, which depend on the concrete technological solution applied to the vessel design.

Power, propulsion and technological plants of fishing vessels presented in the general way in Fig. 1 consist of the following components: 1 – the main engine with auxiliary operating installations (*ME*); 2 – the main engine exhaust manifold; 3 – air supercharging system (air filter, air cooler, turbocharger); 4 – clutch of the main engine intermediate shaft; 5 – gear box, 6 – shaft line (intermediate and propeller shafts, bearings and the stern tube sealing); 7 – fixed or controllable pitch propeller; 8 – the propeller Kort's nozzle; 9 – alternating current shaft generator; 10 – direct current shaft generator; 11 – pump No. 1 driven by the main engine propulsion gear; 12 – pump No. 2 driven by the main engine propulsion gear; 13 – hydraulic propulsion system (pump-motor) of the trawl winch driven by the main engine propulsion gear; 14 – the trawl winch gear driven by the system 13; 15 – the trawl winch pulley driven by the system 13; 16 – hydraulic propulsion system (pump-motor) of the net winch driven by the main engine propulsion gear; 17 – the net winch gear driven by means of system 16; 18 – the net winch pulley driven by system16; 13a – electromotor of the trawl winch; 14a – the trawl winch gear driven by the system 13a; 15a – the trawl winch pulley driven by the system 13a; 16a – electromotor of the net winch; 17a – the net winch gear driven by means of system 16a; 18a –

the net winch pulley driven by system16a; 19 – the sea water pump(s) for power and technological systems operation; SAC – clutch of the alternating current generator shaft; SDC – clutch of the direct current generator shaft; SP1 – clutch of pump No. 1; SP2 – clutch of pump No. 2; SW1 – clutch of hydraulic pump of winch 15 propulsion system; SW2 – clutch of hydraulic pump of winch 18 propulsion system; SH1 – clutch of hydraulic pump of winch 15 propulsion system; SH2 – clutch of the hydraulic engine of the winch 18 propulsion system; SWL – clutch of the propulsion shaft; x – diesel generating set; y – other electrical consumers.

For the technical system containing n components ($n > 0$) with the set of components $C = \{c_1, c_2, ..., c_n\}$ after assuming random variables defining the state of X_i system components and the state of the system φ in the shape of:

$$X_i = \begin{cases} 1 \text{ if } c_i \text{ is in up state} \\ 0 \text{ if } c_i \text{ is in down state} \end{cases};\ \varphi = \begin{cases} 1 \text{ if the system is in up state} \\ 0 \text{ if the system is in down state} \end{cases} \quad (1)$$

the binary vector of the components state can be shown as [12]:

$$\vec{X} = [\mathrm{X}_1, \mathrm{X}_2, ..., \mathrm{X}_n] \quad (2)$$

For a specified system structure, the system state is unambiguously defined by the state vector. Assuming the set of all system components binary state vectors are:

$$S = \{0,1\}^n = \{\ \vec{X} : \vec{X} = [\mathrm{X}_1, \mathrm{X}_2, ..., \mathrm{X}_n],\ X_i \in \{0,1\},\ i = 1,2,...,\mathrm{n}\} \quad (3)$$

it is possible to define function φ specified in the set S and taking the values $\{0,1\}$:

$$\varphi : \mathrm{S} \rightarrow \{0,1\} \quad (4)$$

A classical mathematical system reliability model is represented by an ordered pair $\langle \mathrm{C}, \varphi \rangle$ [13, 17]. C-denotes the set of system components whereas φ is the function defining the system state depending upon its components state.

The function φ is used for analytical presentation of the reliability structure. It is called the system structure function [8]. In case the function φ is bivalent as it has been presented above $\varphi(x) = \{0,1\}$, from the reliability point of view the such system is called binary or two-states system (up state, down state). Generally for multi-state systems the value of the function is normalized within the range <0,1>. In the further part of the paper it is assumed that the analyzed system is a two-states system.

For *SENiT* presented in Fig. 1, the binary vector of random variables X_i, which described the state of system components C_i can be presented as follows:

$$\vec{X} = [X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}, X_{15}, X_{16}, X_{17}, X_{13a}, X_{14a}, X_{15a}, X_{16a}, X_{17a}, X_{18a}, X_{19}, X_{SAC}, X_{SDC}, X_{SP1}, X_{SP2}, X_{SW1}, X_{SW2}, X_{SH1}, X_{SH2}, X_{SWL}, X_x, X_y] \quad (5)$$

The structure function for *SENiT* can be presented in form:

$$\varphi = \varphi(X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11}, X_{12}, X_{13}, X_{14}, X_{15}, X_{16}, X_{17}, X_{13a}, X_{14a}, X_{15a}, X_{16a}, X_{17a}, X_{18a}, X_{19}, X_{SAC}, X_{SDC}, X_{SP1}, X_{SP2}, X_{SW1}, X_{SW2}, X_{SH1}, X_{SH2}, X_{SWL}, X_x, X_y) \quad (6)$$

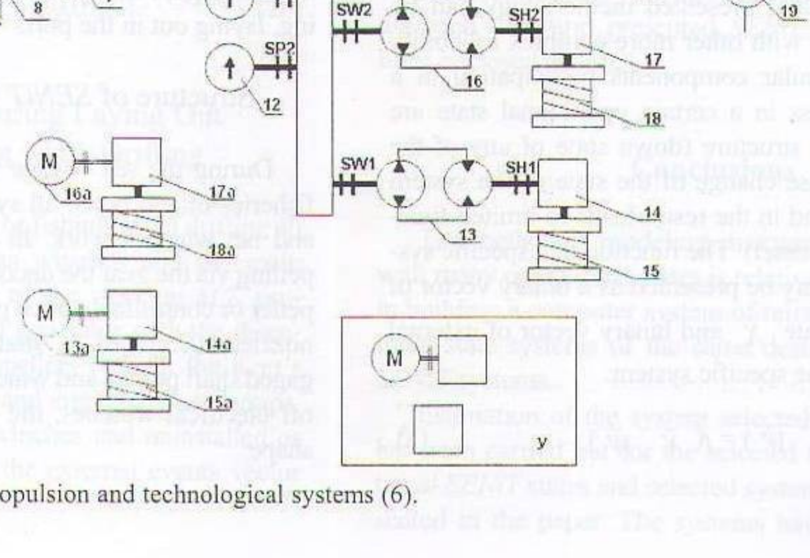

Fig. 1. Components of power, propulsion and technological systems (6).

Since the model is to be adequate to various configurations of components contained by the power, propulsion and technological systems, several conditions allowing for system configuration modeling by means of joining and excluding the parts of the model adequate to the components have been introduced. The conditions have been realized due to the use of external events. The model comprises the following conditions: W_1 – Does the propeller have a nozzle?, W_{2a} – Is the shaft clutched type?, W_{2b} – Is the shaft engaged with the engine?, W_{3a} – Is there an *AC* shaft generator installed?, W_{3b} – Is the *AC* generator clutched type?, W_{4a} – Is there an *DC* shaft generator installed?, W_{4b} – Is the *DC* generator clutched type?, W_{5a} – Is there a shaft pump No. 1 installed?, W_{5b} – Is the pump No. 1 engaged?, W_{6a} – Is there a shaft pump No. 2 installed?, W_{6b} – Is the pump No. 2 engaged?, W_{7a} – Is there a trawl winch driven by the main engine installed?, W_{7b} – Is the trawl winch hydraulic pump engaged?, W_{8a} – Is there a net winch driven by the *ME* installed?, W_{8b} – Is the net winch hydraulic pump engaged?, W_{8c} – Is the net winch hydraulic engine engaged?, W_9 – Is there an electric trawl winch installed?, W_{10} – Is there an electric net winch installed?,

The system structure presented by means of vector (5) is suggested to be modified using the binary vector:

$$\vec{W} = [W_1, W_{2a}, W_{2b}, W_{3a}, W_{3b}, W_{4a}, W_{4b}, W_{4b}, W_{5a}, W_{5b}, W_{6a}, W_{6b}, W_{7a}, W_{7b}, W_{8a}, W_{8b}, W_{8c}, W_9, W_{10}] \quad (7)$$

whose components define the fulfillment or unfulfilment of particular external events adequate to the presented conditions W_i. The vector components have the value of 0 and 1 consistently when the external events occur or does not occur. Depending upon the value of the particular external events, particular components of the general system are contained in the components set of a specific system or they are not. Such approach allows for an unambiguous determining system configuration for a specified analyzed state of work.

In presented analysis has been used exemplary system features reliability series structure whose appropriate parts may be included or excluded from the structure depending upon the technological solution applied to a vessel or the system operational state. Presented methodology can by used also for systems with other more complex reliability structures. The particular components participating in a ship's working process in a certain operational state are connected in a series structure (down state of any of the components shall cause change of the state of the system into the down state and in the result leads to limited functionality of a fishing vessel). The function of a specific system structure φ_{SENiT} may be presented as a binary vector of the general system state $\vec{X}$ and binary vector of external events $\vec{W}$ defining the specific system:

$$\varphi_{SENiT} = \psi(\varphi, \vec{W}) = f(\vec{X}, \vec{W}) \quad (8)$$

Since the presented case of general structure *SENiT* has a series reliability structure, the structure function of the system φ_{SENiT} and structure functions of subsystems φ_i based on the presented vectors can have the following shape:

$$\varphi_{SENiT} = X_1 \wedge X_2 \wedge X_3 \wedge X_{19} \wedge X_x \wedge X_y \wedge \varphi_1 \wedge \varphi_5 \quad (9)$$

subsystem of the marine shaft line:

$$\varphi_1 = \varphi_2 \wedge X_4 \wedge (X_{SWL} \vee W_{2a}) \wedge \{[X_6 \wedge X_7 \wedge (X_8 \vee W_1)] \vee W_{2b}\} \quad (10)$$

subsystem of gear box:

$$\varphi_2 = \{[X_{SAC} \wedge (X_9 \vee W_{3b})] \vee W_{3a}\} \wedge \{[X_{SDC} \wedge (X_{10} \vee W_{4b}) \vee W_{4a}]\} \wedge \{[X_{SP1} \wedge (X_{11} \vee W_{5b})] \vee W_{5a}\} \wedge \{[X_{SP2} \wedge (X_{12} \vee W_{6b})] \vee W_{6a}\} \wedge X_5 \wedge \varphi_3 \wedge \varphi_4 \quad (11)$$

subsystem of trawl winch driven by the *ME*:

$$\varphi_3 = \{X_{SW1} \wedge \{\{X_{13} \wedge X_{SH1} \wedge [(X_{14} \wedge X_{15}) \vee W_{7c}]\} \vee W_{7b}\}\} \vee W_{7a} \quad (12)$$

subsystem of the net winch driven by the *ME*:

$$\varphi_4 = \{X_{SW2} \wedge \{\{X_{16} \wedge X_{SH2} \wedge [(X_{17} \wedge X_{18}) \vee W_{8c}]\} \vee W_{8b}\}\} \vee W_{8a} \quad (13)$$

subsystem of the electrically driven trawl and net winches:

$$\varphi_5 = [(X_{13a} \wedge X_{14a} \wedge X_{15a}) \vee W_9] \wedge [(X_{16a} \wedge X_{17a} \wedge X_{18a}) \vee W_{10}] \quad (14)$$

SENiT Reliability Structure Change in Various Operational States

Depending upon the operational state of a fishing vessel *SENiT* changes its structure including and excluding certain components from the series reliability structure of the system. The basic operational states of a fishing vessel are: a sea voyage, casting and hauling in the nets, trawling, drifting, laying out in the port.

Structure of *SENiT* during the Sea Voyage

During the sea voyage when a vessel moves between fisheries or/and ports, all system components except trawl and net winches work. In case of the working *ME* propelling via the gear the uncoupled propeller shaft, fixed propeller or controllable pitch propeller equipped with a Kort's nozzle, an engaged *AC* shaft generator, installed but disengaged shaft pumps and winches and uninstalled or switched off electrical winches, the external events vector has the shape:

$$\vec{W} = [1,0,1,1,1,0,0,0,0,0,0,1,0,0,1,0,0,0,0] \quad (15)$$

In the case above with the propulsion system without the Kort's nozzle, the vector has the shape:

$$\vec{W} = [0,0,1,1,1,0,0,0,0,0,0,1,0,0,1,0,0,0,0] \quad (16)$$

Structure of *SENiT* during Casting and Hauling in the Nets

During casting and hauling in the nets all *SENiT* components work. In case of the working *ME* propelling via the gear the uncoupled propeller shaft, fixed propeller or controllable pitch propeller equipped with a Kort's nozzle, an engaged *AC* shaft generator, installed and engaged shaft pumps and shaft winches and uninstalled electrical winches, the external events vector has the shape:

$$\vec{W} = [1,0,1,1,1,0,0,1,1,1,1,1,1,1,1,1,1,0,0] \quad (17)$$

In case the system are equipped with both electrical as well as shaft driver winches, the external events vector has the shape:

$$\vec{W} = [1,0,1,1,1,0,0,1,1,1,1,1,1,1,1,1,1,1,1] \quad (18)$$

Structure of *SENiT* during Trawling Operation

During trawling all *SENiT* components work. In case of the working *ME* propelling via the gear the uncoupled propeller shaft, fixed propeller or adjustable pitch propeller equipped with a Kort's nozzle, an engaged *AC* shaft generator, installed and engaged shaft pumps, installed and engaged trawl winch and installed but disengaged shaft net winch and uninstalled electrical winches, the external events vector has the shape:

$$\vec{W} = [1,0,1,1,1,1,0,0,1,1,1,1,1,1,1,0,0,0,0] \quad (19)$$

In case the system turns out to be without the Kort's nozzle, the vector has the shape:

$$\vec{W} = [0,0,1,1,1,1,0,0,1,1,1,1,1,1,1,0,0,0,0] \quad (20)$$

Structure of *SENiT* During Laying Out in the Port or Fishing when Drifting

During laying out in the port or fishing when drifting all power generators work whereas winches and the main propulsion unit do not. In case of the working *M/E* propelling via the gear the *AC* shaft generator with the disengaged propeller shaft, fixed propellers without the Kort's nozzles, installed in the system and engaged shaft pumps, installed and disengaged shaft winches and uninstalled or switched off electrical winches the external events vector has the shape:

$$\vec{W} = [0,1,0,1,1,0,0,1,1,1,1,0,0,1,0,0,0,0,0] \quad (21)$$

In case of the system equipped with a *DC* shaft generator, the vector has the shape:

$$\vec{W} = [0,1,0,0,0,1,1,1,1,1,1,0,0,1,0,0,0,0,0] \quad (22)$$

Examples of the Models Application

For the presented above operational states of the defined *SENiT* configurations according to the presented external events vectors the exemplary analysis of *SENiT* reliability (selected reliability measures calculation) have been carried out. Literature data have been taken as input measures for system components. Values of availability and failure intensity have been taken on the basis of the information presented in [7].

In case of a sea voyage *SENiT* reliability defined by means of the vector (15), the system availability coefficient equals 0,98233. The set of the system minimal cut sets may be presented as follows:

$$\Omega = \{\{1\},\{2\},\{3\},\{4\},\{5\},\{6\},\{7\},\{8\},\{9\},\{19\},\{SAC\},\{SW1\},\{SW2\},\{x\},\{y\}\} \quad (23)$$

In case of casting and hauling in the nets *SENiT* reliability defined by means of the vector (18) system availability coefficient equals 0,95403. The value (considerably smaller than in case of the sea voyage) results from a big number of components participating in the system operation process for the system configuration defined by the vector (18). In this case the set of the system minimal cut sets contains 33 cut sets and this can be presented as follows:

$$\Omega = \{\{1\},\{2\},\{3\},\{4\},\{5\},\{6\},\{7\},\{8\},\{9\},\{11\},\{12\},\{13\},\{14\},\{15\},\{16\},\{17\},\{18\},\{13a\},\{14a\},\{15a\},\{16a\},\{17a\},\{18a\},\{19\},\{SAC\},\{SH1\},\{SH2\},\{SP1\},\{SP2\},\{SW1\},\{SW2\},\{x\},\{y\}\} \quad (24)$$

Detailed reports of the reliability analyses for the assumed data and presented *SENiT* configurations have been enclosed in [6].

Conclusions

The method of modeling structure change for systems with many operational states is relatively simple and useful in building a computer system of reliability assessment for multi-state systems of the same destiny as the presented *SENiT* systems.

Estimation of the system selected reliability measures has been carried out for the selected fishing vessel operational *SENiT* states and selected system configurations presented in the paper. The systems have been modeled by means of the logical models (9-14). The analyses have been carried out with the use of *CARA Fault-Tree 4.1 Academic Version* computer code. The full report of the analyses enclosed in [6].

In order to obtain accurate results defining events (faults of an components) assessed on the basis of data from the reliability operational research of the outlined systems.

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