2

A COMPARATIVE COMPONENTS IMPORTANCE ANALYSIS OF A COMPLEX TECHNICAL SYSTEM WITH THE USE OF DIFFERENT IMPORTANCE MEASURES

2.1 INTRODUCTION

Reliability theory concentrates on the operation of systems, both in terms of statistics and physics of failure, and is effective when it comes to determining measures for reliability, availability and indices for states of emergency of the operated system.

As for the system as a whole, basic reliability measures such as reliability, availability, MTTF, failure frequency and so on, have great information value in terms of the intact system operation. However, when it comes to system components, these measures give mainly general information on their vulnerability and availability. Thereby, except for a series reliability structure, they do not describe the influence of components being down on the system being down.

The system tolerance for its components failure depends on their reliability and the structure of the system where a particular component is located. So far a series of measures has been proposed to describe the components importance in the system reliability structure considering a particular importance criterion e.g. Vesely–Fussell's, Birnbaum's, Lambert's known as a criticality measure, and many others [9, 13].

It needs to be underlined that different reliability measures lead to different importance rankings, what results from different definitions of measure. That is why the character of a given measure must be taken into account while interpreting the results obtained during the analysis. Apart from differences between given measures in the rankings there are significant differences in the obtained measure values, often of a few orders of magnitude. This complicates the visualization and comparison of components importance results obtained by means of various criteria. Using measures presented in this paper might be helpful to visualize the values of different measures on common charts.

2.2 SELECTED IMPORTANCE MEASURES

The Birnbaum's reliability importance measure IB is the most useful to indicate system components whose reliability parameters should be improved in order to increase the system reliability. IB for a given component does not depend on the reliability of the component in question but on the system reliability structure and reliability of other components. If $\vec{r}(t)=[r_1(t),r_2(t),\dots,r_n(t)]$ is a system component reliability vector in moment t and $R[\vec{r}(t)]$ is the system reliability which is dependent on the reliability of given components and the system reliability structure then the Birnbaum's reliability importance measure for an *i*-th system component is defined as:

$$I_i^B(t)=\frac{\partial R[\vec{r}(t)]}{\partial r_i(t)}=R[1_i,\vec{r}(t)]-R[0_i,\vec{r}(t)] \tag{2.1}$$

To identify the component whose failure will most probably cause the system failure, the Vesely-Fussell's measure IVF is helpful. If $\Phi[\overline{X}(t)]$ is the system structure function, equal to 0 when the system is down and to 1 when it is up, and it is determined by a binary vector $\overline{X}(t)$ whose elements are equal to 0 when a given component is down and 1 when it is up, then IVF is described as the relation:

$$I_i^{VF}(t)=P\{D_i(t)\,|\,\Phi[\overline{X}(t)]=0\} \tag{2.2}$$

where:

m_i – the number of minimal cut sets containing an i-th component;

$C_{ij}(t)$ – a j-th minimal cut set containing an i-th component and failing in time t;

$D_i(t)=C_{i1}(t)\cup C_{i2}(t)\cup\ldots\cup C_{im_i}(t)$

– a set containing at least one cut set $C_{ij}(t)$ which is down in time *t*.

Another measure helpful to determine the components criticality [11] is ICR proposed by Lambert. Component *ei* is critical if: the system is intact when component *ei* is up, and the system is down when component *ei* is down as well. In a system with a series structure, all components are critical. In other types of structure, the component becomes critical when all other components belonging to a given cut set fail. The criticality measure is described as a conditional probability of event:

$$Cr[\overline{X}(t),X_i=1]\cap[X_i(t)=0]$$

if the system is down in time t what can be shown as:

$$I_i^{CR}=P\{Cr[\overline{X}(t),X_i=1]\cap[X_i(t)=0]\,|\,\Phi[\overline{X}(t)]=0\} \tag{2.3}$$

where:

$Cr[\overline{X}(t),X_i=1]$ – an event when the system is in a state of an i-th component being critical and it is independent of this component's state.

The reliability improvement potential IIP is a similar criticality measure and it can be interpreted as a probability that an *i*-th component is critical and fails in time t what can be expressed by the formula:

$$I_i^{IP}(t)=P\{Cr[\overline{X}(t),X_i=1]\cap[X_i(t)=0]\} \tag{2.4}$$

A component's criticality for a system is well described by the Birnbaum's structural importance measure IBs. It a qualitative measure i.e. its value is independent of time and system components reliability but depends on the system reliability structure. The Birnbaum's structural importance measure for an *i*-th component is defined as a relative number of system states for which an *i*-th component is critical for the system. Hence, this measure can be described as the relation:

$$I^{Bs}(t) = \frac{\eta_{\phi}(i)}{2^{n-1}} \tag{2.5}$$

where:

$\eta\varphi(i)$ – the total number of critical path set vectors for component *i*

Beside the afore-mentioned importance measures, used to illustrate their application character in this paper, there are others - Bergman's, Natvig's, Barlowa-Proshan's, minimal cut set order and many others which have been left out in this paper because of the extent of the topic [1, 2, 3].

2.3 THE OBJECT OF ANALYSIS

The analysis has been performed on a stern tube lubricating and sealing system installed on a container ship [10, 18]. Fig. 2.1 shows the installation layout.

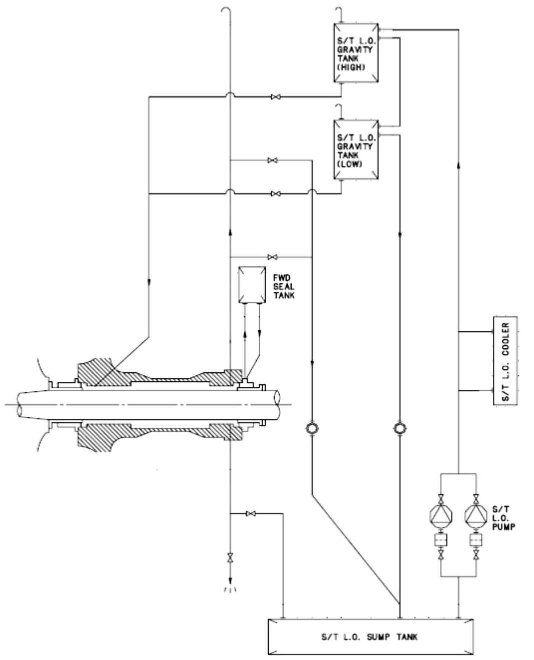

Fig. 2.1 The stern tube sealing system

Source: [18]

The stern tube lubricating and sealing system is responsible for sealing the propeller shaft and providing an appropriately low coefficient of friction in the shaft line. The incorrect operation of the analyzed system might result in:

- flooding the engine room with sea water and sinking the ship;
- the escape of lubricating oil and the sea environment contamination with petroleum products;
- increasing the friction between the cooperating components causing an increase of the tribological pair intensity and decrease of the propulsion efficiency of the vessel (increase of the fuel consumption by the propulsion system).

So, a reliable operation of the analyzed technical system affects the engine room reliability of a single sailing ship and a transportation chain. The analyzed system is one of the critical components of every sea ship. To analyze the influence of the stern tube sealing system components being down, performed an importance analysis [6, 12].

2.4 A DEPENDABILITY SYSTEM MODEL

Table 2.1 shows descriptions of particular system components and their reliability characteristics. It has been assumed in the analysis that the system is renewable and the components have an exponential distribution of time to failure with Lambda [failure/h] parameter and exponential distribution of time to repair with parameter MTTR (mean time to repair) [h]. In the case of E1, the most beneficial repair scenario (immediate docking of the ship) has been assumed. The failure intensity and mean repair time have been assumed based on [14]. The filter-pump system has been duplicated in the model, the analysis has been performed for mean values of parameters of the failure and repair process considering the periodical change of the working and stand-by component. It has been assumed that both branches of the pumping system fail with same failure intensity [4, 5, 7].

Table 2.1 Data on vulnerability and maintenability of given system components

Description	Type	Parameter	Value	Remarks
E1	Repairable component	Lambda MTTR	0,0000292 168	Stern tube seal with bearings
E2	Repairable component	Lambda MTTR	0,0000111 24	Higher gravity tank
E3	Repairable component	Lambda MTTR	0,0000111 24	Lower gravity tank
E4	Repairable component	Lambda MTTR	0,0000058 24	Lube oil cooler
E5	Repairable component	Lambda MTTR	0,0000121 24	Lube oil sump tank
E6	Repairable component	Lambda MTTR	0,0000821 4	Pipelines with equipment
E7	Repairable component	Lambda MTTR	0,0001750 12	Circulation pump no 1
E8	Repairable component	Lambda MTTR	0,0001750 12	Circulation pump no 2
E9	Repairable component	Lambda MTTR	0,0000307 2	Filter no 1
E10	Repairable component	Lambda MTTR	0,0000307 2	Filter no 2

The reliability structure of the system was modeled by means of the fault tree. Fig. 2.2 presents a dependability model. While constructing the tree, a composition level was assumed where system components are responsible for certain process functions so the components match particular machines and devices.

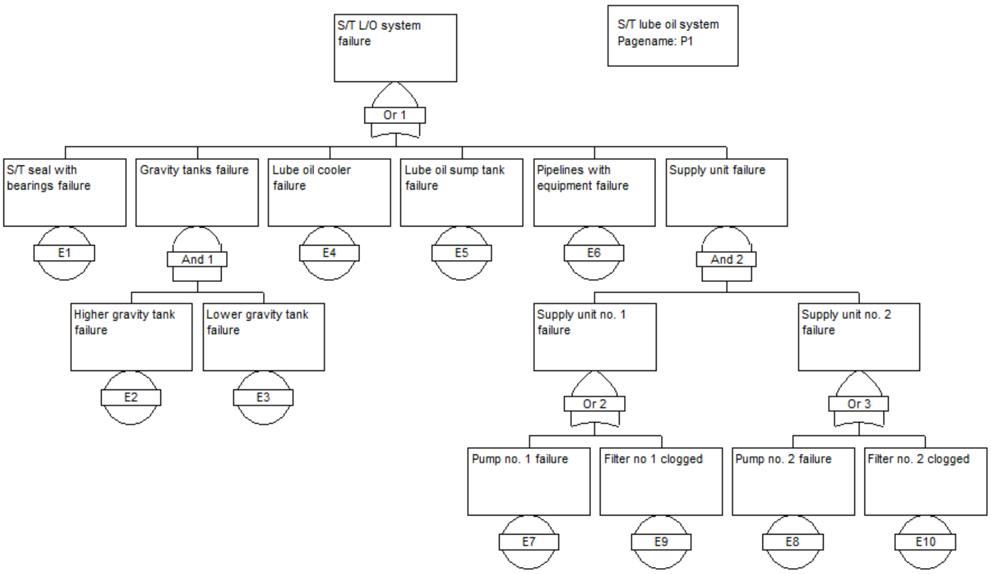

Fig. 2.2 The reliability structure of the analysed system

2.5 SYSTEM COMPONENTS IMPORTANCE ANALYSIS

The importance analysis has been carried out with the use of software CARA Fault Tree ver. 4.1. Academic by Sydvest Software. The following assumptions and entry parameters have been taken for calculation:

- analysis done for top event OR1,
- mission time a year (8760h),
- the level of fault tree modularization equal to 0,
- the maximum, possible size of the analysed minimal cut sets.

Table 2.2 Determined measure values of the analysed technical system

Component	IVF	IBs	IB	ICR	IIP
E1	0,8655800	0,0410160	0,9992400	0,8649300	0,0048730
E2	0,0000127	0,0136720	0,0002658	0,0000126	0,0000001
E3	0,0000127	0,0136720	0,0002658	0,0000126	0,0000001
E4	0,0246610	0,0410160	0,9945000	0,0245260	0,0001382
E5	0,0513170	0,0410160	0,9946500	0,0510420	0,0002876
E6	0,0582920	0,0410160	0,9946900	0,0579820	0,0003267
E7	0,0008019	0,0175780	0,0021440	0,0007973	0,0000045
E8	0,0008019	0,0175780	0,0021440	0,0007973	0,0000045
E9	0,0000235	0,0175780	0,0021396	0,0000233	0,0000001
E10	0,0000235	0,0175780	0,0021396	0,0000233	0,0000001

Table 2.2 shows certain importance measure values (primary measures) calculated by means of Aven's algorithm of exact reliability and availability calculation (ERAC) [17]. Because the values of some measures are very low, it was necessary to show them accurately to the seventh digit after the decimal point.

Due to big differences between the values of certain measures, it is very complicated to compare them on the same plane as observed in the visualization of the obtained measure values by means of bar charts (Fig. 2.3).

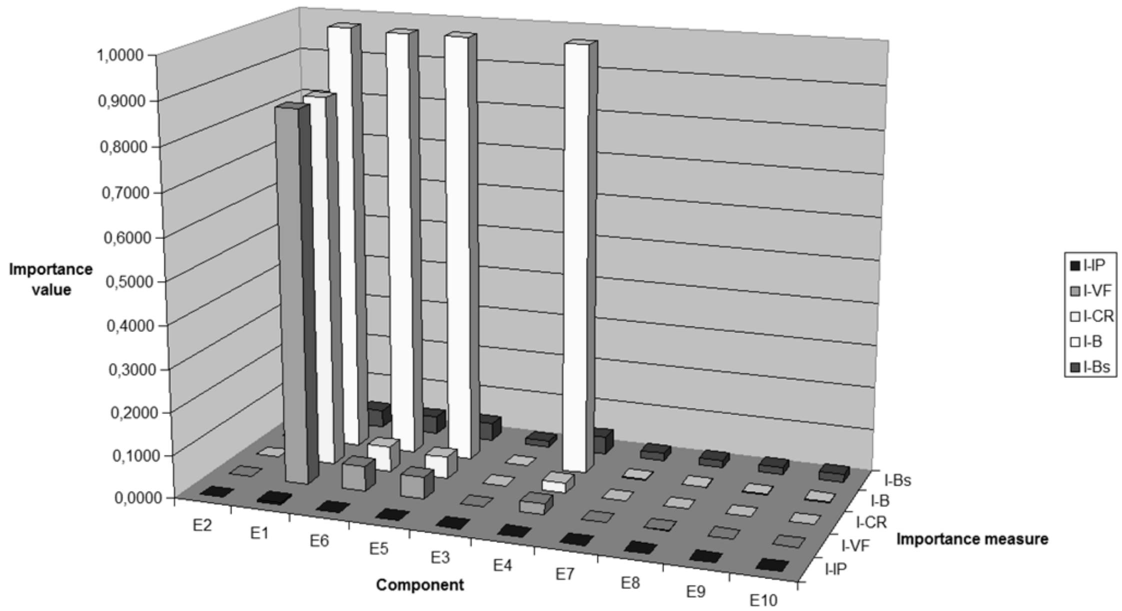

Fig. 2.3 Primary measures of system components importance

2.6 SCALING IMPORTANCE MEASURES

To make the comparison of given importance measure values easier and to use more tools in the multi-criteria analysis of components importance such as radar charts, it is indispensable to process the scaling of measures. Based on the maximum value ϑ of importance measures for all components in time t described as:

$$\vartheta = \max_{i=1,2..n} \{ \bigcup_{I_j = I_1, I_2 ... I_m} [I_j(i \mid t)] \} \tag{2.6}$$

where:

i – the component number in the system;

j – the next mark for a considered components importance measure;

n – the number of system components;

m – the number of used importance measures;

the authors proposes to introduce a scaled coefficient for all measures determined for a *j*-th measure in time t as:

$$\zeta_{j,t} = \frac{\max_{i=1,2..n} I_j(i \mid t)}{\vartheta} \tag{2.7}$$

For the analyzed example:

$$\vartheta = \max_{i=1,2..10} \{ \bigcup_{I_j = \{I^B, I^{VF}, I^{CR}, I^{IP}, I^{Bs}\}} [I_j(i \mid t)] \} = 0{,}99924 \tag{2.8}$$

Particular coefficients ζ for every measure is shown in Table 2.3.

Table 2.3 Scaled coefficients for given measures

Measure	IVF	IBs	IB	ICR	IIP
ζ	1,15	24,36	1,00	1,16	205,06

Multiplying the values of given measures by given scaled coefficients, corrected importance measures have been obtained (marked by an asterisk next to the superscript) what has been presented in Table 2.4.

Table 2.4 Corrected importance measures of the analysed technical system

Name	IVF*	IBs*	IB*	ICR*	IIP*
E1	0,9992400	0,9992400	0,9992400	0,9992400	0,9992400
E2	0,0000146	0,3330800	0,0002658	0,0000146	0,0000146
E3	0,0000146	0,3330800	0,0002658	0,0000146	0,0000146
E4	0,0284691	0,9992400	0,9945000	0,0283345	0,0283347
E5	0,0592412	0,9992400	0,9946500	0,0589680	0,0589681
E6	0,0672933	0,9992400	0,9946900	0,0669857	0,0669858
E7	0,0009257	0,4282388	0,0021440	0,0009211	0,0009211
E8	0,0009257	0,4282388	0,0021440	0,0009211	0,0009211
E9	0,0000271	0,4282388	0,0021396	0,0000269	0,0000269
E10	0,0000271	0,4282388	0,0021396	0,0000269	0,0000269

2.7 RESULTS OF THE IMPORTANCE ANALYSIS

Owing to the proposed transformation, there appear new opportunities in terms of importance presentation and comparative analysis using different importance measures. Fig. 2.4 shows a visualization of scaled importance measures. The measure values which were very small at first were proportionally increased.

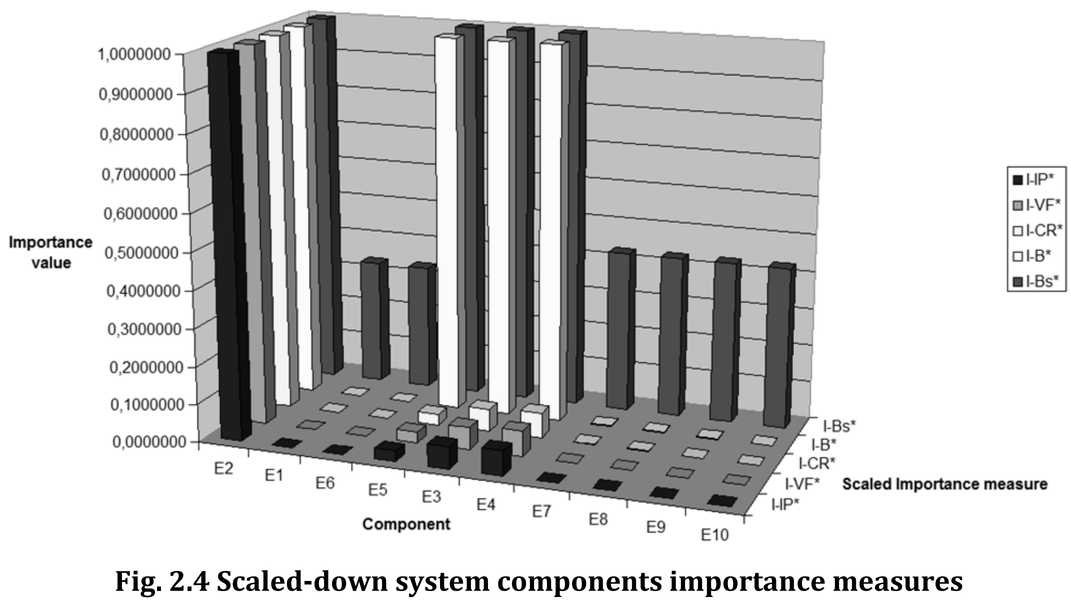

Fig. 2.4 Scaled-down system components importance measures

The applied transformation allows to use radar charts in the importance analysis relying on different relevance criteria of system components. For the analyzed example shown in Fig. 2.5, the visualizations of selected scaled-down importance measures for given system components have been presented. For the presented measures, components E2, E3, E4 and E5 affect the system most strongly.

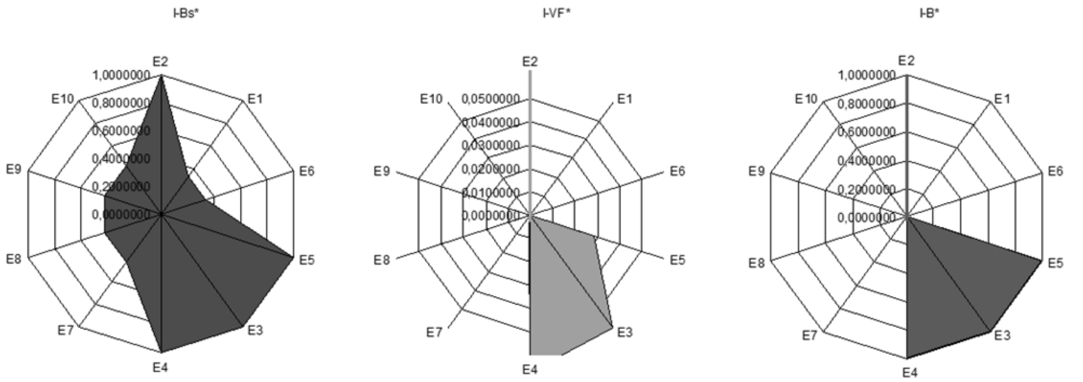

Fig. 2.5 Radar charts of scaled-down importance measures for given system components

While segregating the data series according to the components, it is possible to obtain radar charts showing the values of given measures for every component on the same data plane. Fig. 2.6 presents an example of using this kind of data. Component E2 influences the system operation the most – all of the analyzed measures equal nearly 1 for it when scaled-down.

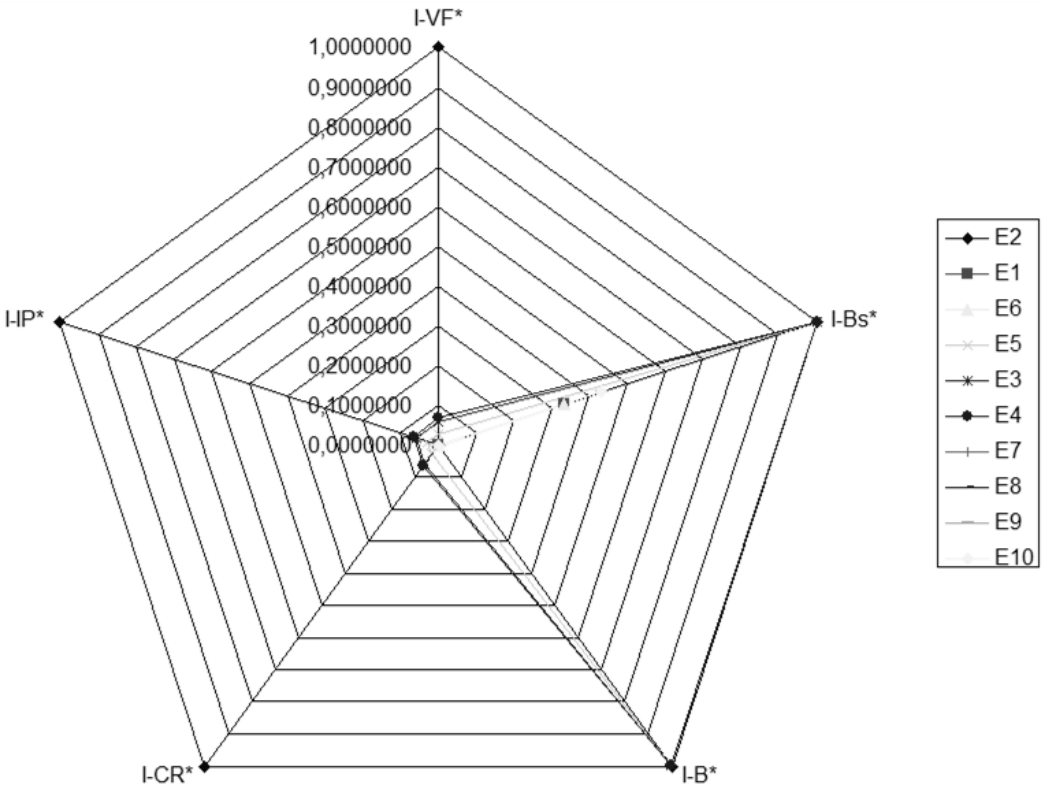

Fig. 2.6 Results of components importance analysis with the use of many criteria after being scaled-down

CONCLUSIONS

The application of scaled-down importance measures allows for a much better (than in the case of primary measures) comparison of different measures leaving an appropriate proportion of a given measure for different system components (all values of a given measure are scaled-down with the use of the same scaled coefficient).

Being scaled-down, the differences between the values of a given measure for different system components are greatly emphasized. It is particularly significant for primary measures of very low values. The scaled-down measures will certainly not be consistent with the basic definition relevant for given measures before scaling e.g. conditional probability of a given event.

The presented methodology of a comparative presentation of importance measure values for complex technical systems might be used in the multi-criteria analysis of components importance. Especially when other than reliability components importance criteria are assumed for the system reliability structure such as structural and parametric criteria [6, 8, 9, 15, 16, 19]. The criteria in question might be the following: safety threat connected with a component failure, repair and system operation interruption costs, maintainability (spare parts availability, repair ergonomics, manpower) etc.

ACKNOWLEDGMENTS

The research presented in this article was carried out under the Grant NCN 2011/01/D/ST8/07827: Importance analysis of components in reliability structure of complex technical systems illustrated by a marine power plant.

REFERENCES

1 Andrews J. D.: Birnbaum and criticality measures of component contribution to the failure of phased missions.REaSS, 93 (2008), pp. 1861-1966.

2 Borgonovo E.: Apostolakis G.E., A New importance measure for risk-informed decision making. RAaSS, 72 (2001), 193-212.

3 Borgonovo E.: Apostolakis G.E. et al., Comparison of global sensitivity analysis techniques and importance measures in PSA. REaSS 79 (2003), pp. 175–185.

4 Chybowski L.: Assessment of Reliability and Availability of Fishing Vessels Power, Propulsion and Technological Plants Based on Fault Tree Analysis, Polish Journal of Environmental Studies, Vol. 18, No. 2A, 39-44, 2009.

5 Chybowski L.: Application of External Events Vectors for Defining Reliability Structure of Fishing Vessels Power, Propulsion and Technological Plants, Polish Journal of Environmental Studies, Vol. 18, No. 2A, 45-50, 2009.

6 Chybowski L.: Safety criterion in assessing the importance of an element in the complex technological system reliability structure. Management Systems in Production Engineering Vol. 1(5), 2012, pp. 10-13.

7 Chybowski L.: The problems of modeling the reliability structure of the complex technical system on the basis of a steam-water system of the engine room. Management Systems in Production Engineering Vol. 2(6), 2012, pp. 12-17.

8 Chybowski L.: A Note On Modifications To The Methodology For Components In The Complex Technical Systems Reliability Structure Importance Evaluation. Journal of Polish CIMAC Vol. 6 No. 2, Diagnosis, Reliability and Safety, Gdańsk 2011, pp. 59-64.

9 Chybowski L.: A New Aproach To Reliability Importance Analysis of Complex Technical Systems. Journal of Polish CIMAC Vol. 6 No. 2, Diagnosis, Reliability and Safety, Gdańsk 2011, pp. 65-72.

10 Chybowski L.: Qualitative and quantitative multi-criteria models of the importance of the components in reliability structure of a complex technical system. Journal of KONBIN No 4(24) 2012, pp. 33-48.

11 Espiritu J.F., Coit d.W., Prakash U.: Component criticality importance measures for the power industry. Electric Power Systems Research 77 (2007) pp. 407–420.

12 Liberacki R.: Risk criteria for sea-going ships arising from the operation of the main engines' crankshaft - connecting rod - piston systems. Journal of Polish CIMAC Vol. 7, No 2, 2012, pp. 115-121.

13 Uuo W., Zhu X.: Importance Measures in Reliability, Risk, and Optimization: Principles and Applications. Wiley 2012.

14 Niezawodność okrętowych siłowni spalinowych. Sformułowanie problemu i propozycja jego rozwiązania, Raport techniczny Nr RT-95/T-01, Centrum techniki Okrętowej, Gdańsk 1995.

15 Smalko Z., Jaźwiński J.: Domyślne nadmiary systemu działaniowego statku powietrznego. Materiały XXXII Zimowej Szkoły Niezawodności, KBM PAN, Szczyrk 2004, pp. 319-330.

15 Twadochleb M.R., Rychcicki R.: Efficiency of hybrid optimization method in solving tasks of verified characteristics. Metody Informatyki Stosowanej No 4, 135-145, 2009.

16 Vatn J.: Finding minimal cut sets in a fault tree. Reliability Engineering and System Safety, Vol. 36, 1992, s. 59-62.

17 Vessel specification. Engine room systems. 6,500 TEU Class Container Carrier.

18 Zolkiewski S.: Numerical Application for Dynamical Analysis of Rod and Beam Systems in Transportation. Solid State Phenomena Vol. 164 2010 pp. 343-348 2010 Trans Tech Publications, Switzerland doi:10.4028/www.scientific.net/ SSP.164.343.

A COMPARATIVE COMPONENTS IMPORTANCE ANALYSIS OF A COMPLEX TECHNICAL SYSTEM WITH THE USE OF DIFFERENT IMPORTANCE MEASURES

Abstract: *This paper presents a components importance analysis of a complex technical system with the use of selected reliability components importance measures. The analysis was carried out on a propeller shaft stern tube seal of a ship propulsion system. The reliability structure of the analyzed system was modeled by means of the fault tree. For given system components the following were determined: the Birnbaum's reliability and structural importance measure, reliability improvement potential, criticality measure and Vesely-Fussell's measure. A transformation of measures based on rescaling their values has been proposed to simplify the comparative analysis using different measures with reference to the same system components. A transformation process for the analyzed system has been presented together with a results visualization of comparative components importance analysis by means of 3D bar charts and radar charts for a data series determined as system components and importance measures. Comments on the proposed methodology have been presented and other ways of its application have been indicated.*

Key words: *Importance measures, comparative analysis, ship propulsion system*

ANALIZA PORÓWNAWCZA WAŻNOŚCI ELEMENTÓW SYSTEMU TECHNICZNEGO Z JEDNOCZESNYM WYKORZYSTANIEM RÓŻNYCH MIAR WAŻNOŚCI

Streszczenie: *W artykule przedstawiono analizę ważności elementów złożonego systemu technicznego z wykorzystaniem wybranych niezawodnościowych miar ważności elementów. Analizę przeprowadzono na przykładzie systemu smarowania i uszczelnienia pochwy wału śrubowego układu napędowego statku. Strukturę niezawodnościową analizowanego systemu zamodelowano z wykorzystaniem drzewa niezdatności. Dla poszczególnych elementów systemu wyznaczono niezawodnościową miarę ważności Birnbauma, miarę strukturalną Birnbauma, Potencjał przyrostu niezawodności, miarę krytyczności oraz miarę Veseley-Fussell'a, Zaproponowano transformację miar polegająca na przeskalowaniu ich wartości w celu ułatwienia analizy porównawczej wykorzystującej różne miary w odniesieniu do tych samych elementów systemu. Przedstawiono dla analizowanego systemu proces transformacji oraz zaprezentowano wizualizację wyników analizy porównawczej ważności elementów z wykorzystaniem wykresów słupkowych 3D oraz wykresów radarowych dla serii danych ustalonych jako elementy systemu oraz jako miary ważności. Przedstawiono uwagi dotyczące zaproponowanej metodyki i wskazano inne możliwe jej zastosowania.*

Słowa kluczowe: *Miary ważności, analiza porównawcza, okrętowy układ napędowy*

Leszek CHYBOWSKI, PhD
Maritime University of Szczecin
Faculty of Marine Engineering
1-2 Wały Chrobrego St., 70-500 Szczecin, Poland
e-mail: L.Chybowski@am.szczecin.pl

Dorota IDZIASZCZYK, MA
Maritime University of Szczecin
Centre for Maritime Technology Transfer
1-2 Wały Chrobrego St., 70-500 Szczecin
e-mail: D.Idziaszczyk@am.szczecin.pl

Bogusz WIŚNICKI, PhD
Maritime University of Szczecin
Faculty of Economics and Transport Engineering
11 Henryka Pobożnego St., 70-506 Szczecin, Poland
e-mail: B.Wisnicki@am.szczecin.pl