ISSN 1509-5878
Nr 6
6/2010
AUTOBUSY
Technika, Eksploatacja, Systemy Transportowe

Leszek CHYBOWSKI, Zbigniew MATUSZAK

RELIABILITY IMPORTANCE ANALYSIS OF MARINE TECHNICAL SYSTEMS ELEMENTS

Abstract

Measures, which can be applicable for reliability importance analysis of components and groups of components in technical systems, have been shown. Selected qualitative measures (order of minimal cut set, numbers of occurrences i-th events in the fault tree, stream measure and Birnbaum's structural importance measure), and quantitative measures (Birnbaum's reliability importance, Vesely-Fussel's measure, The improvement potential reliability measure and Lambert's measure) have been described. Some of mathematical formulas (also approximations) have been pointed out. Estimation of selected importance values of system components (on the basis of complex technical system with multi-state reliability and functional structure) has been done. As example system marine power plant system (main power plant sea water cooling system) installed on board offshore multi support vessel has been chosen. Analysis for two different operation i.e. operation during offshore project (operation with dynamic positioning of the vessel) and during sea passage, states has been performed. System for these two states has been modeled with fault tree structures. Particular importance rankings of system components have been shown in bar charts. Some conclusions of applied importance measures have been presented.

INTRODUCTION

Very often as one of steps in reliability analysis, it is necessary to determine which elements or cut sets are the most important for system [1], on account of optimal value of selected dependability measure assurance.

These issues are connected to problem of searching for *weak links* in the system, and it is called *importance analysis*. From dependability point of view, importance of given component in the system is depending on two factors:

1. Reliability characteristics of the component.
2. Reliability structure in which the component is located.

Influence of first factor is obvious. In relation to component location in reliability structure, the component is the more important, the component is more similar to single item inserted in serial reliability structure of system. Influence of component on system reliability is decreasing with component redundancy level increasing. There are qualitative and quantitative importance measures used in dependability analysis of technical systems. In the material selected importance measures are compared based on example system of marine power plant.

1. PRESENTATION OF ANALYZED SYSTEM

Analysis of component importance has been done for sea water cooling system fitted on-board offshore multi support vessel for assisting in exploration of the seabed, mainly for executing constructional works on mining and processing subsea installations. During operations unit is positioned by automatic dynamic positioning system. This ship is made and operated according the third consequence class, it means that level of redundancy of the vessel's equipment in terms of offshore standards is the highest, what is very important in offshore industry marine operation, where fatal operating accidents or severe pollution and damage with large economic consequences are probable results of loss of ships position.

Vessel has three engine rooms: original auxiliary engine room on the aft and two main new forward engine rooms (port and starboard). Once set up for class 3 operations, the new engine room and old engine room systems can operate without any mutual support. The port and starboard engine rooms (main power plant) are similar and totally separate from each other with respect to fuel, lube oil, cooling water, air and power supplies. Each forward engine room contains two Detroit Diesel 149 engines driving ABB alternators HSG 500 MDE type; each rated at 1370 kVA at 1800 rpm. A third set in each forward engine room is Detroit Diesel 149 engine driving an ABB alternator HSG 500 type, rated 1620 kVA at 1800 rpm.

Each of the forward engine rooms has its own sea water cooling system. Functional structure of this installation is presented in figures 1 (port and starboard sides).Importance of components has been calculated for two operation states of vessel:

- engine rooms split (crossover valves for all main engine rooms systems are in closed positions), this state is normal operation state during third consequence class operations;
- engine rooms connected (crossover valves for all main engine rooms systems are in opened positions), this state can be normal operation state if ship is not making third consequence class operations.

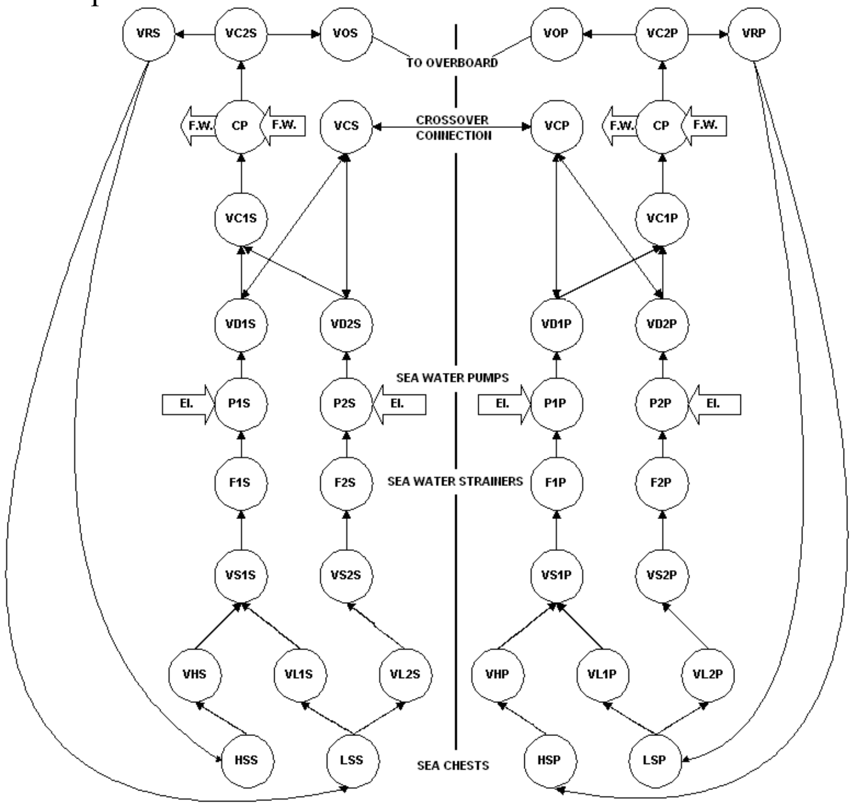

Fig. 1. Functional structure of energetic fluids flow in sea water cooling system

All elements and events associated with them are given in table 1. Values of parameters have been taken from literature [2, 3, 4]. In figures 2, 3 fault tree models for analyzed system has been presented.

Table 1. Description of system components and analyzed events in the system

Symbol	Component name	Type	Event description	Parameter	Value
VL1P	Bottom sea chest valve no 1 Port	On demand	Valve failed in closed position	q [-]	3,0000e-005
VL1S	Bottom sea chest valve no 1 Stbd	On demand	Valve failed in closed position	q [-]	3,0000e-005
VL2P	Bottom sea chest valve no 2 Port	On demand	Valve failed in closed position	q [-]	3,0000e-005
VL2S	Bottom sea chest valve no 2 Stbd	On demand	Valve failed in closed position	q [-]	3,0000e-005
VHP	High sea chest valve Port	On demand	Valve failed in closed position	q [-]	3,0000e-005
VHS	High sea chest valve Stbd	On demand	Valve failed in closed position	q [-]	3,0000e-005
VOP	Outlet valve Port	On demand	Valve failed in closed position	q [-]	3,0000e-005
VOS	Outlet valve Stbd	On demand	Valve failed in closed position	q [-]	3,0000e-005
VS1P	Suction valve of pump no 1 Port	On demand	Valve failed in closed position	q [-]	3,0000e-005
VS1S	Suction valve of pump no 1 Stbd	On demand	Valve failed in closed position	q [-]	3,0000e-005
VS2P	Suction valve of pump no 2 Port	On demand	Valve failed in closed position	q [-]	3,0000e-005
VS2S	Suction valve of pump no 2 Stbd	On demand	Valve failed in closed position	q [-]	3,0000e-005
VD1P	Delivery valve of pump no 1 Port	On demand	Valve failed in closed position	q [-]	3,0000e-005
VD1S	Delivery valve of pump no 1 Stbd	On demand	Valve failed in closed position	q [-]	3,0000e-005
VD2P	Delivery valve of pump no 2 Port	On demand	Valve failed in closed position	q [-]	3,0000e-005
VD2S	Delivery valve of pump no 2 Stbd	On demand	Valve failed in closed position	q [-]	3,0000e-005
VC1P	Cooler inlet valve Port	On demand	Valve failed in closed position	q [-]	3,0000e-005
VC1S	Cooler inlet valve Stbd	On demand	Valve failed in closed position	q [-]	3,0000e-005
VC2P	Cooler outlet valve Port	On demand	Valve failed in closed position	q [-]	3,0000e-005
VC2S	Cooler outlet valve Stbd	On demand	Valve failed in closed position	q [-]	3,0000e-005
P1P	Sea water pump no 1 Port (active pump)	Non repairable	Failure during starting / running	λ [failure/h]	3,0000e-005
P1S	Sea water pump no 1 Stbd (active pump)	Non repairable	Failure during starting / running	λ [failure/h]	3,0000e-005
P2P	Sea water pump no 2 Port (standby pump)	On demand	Start on demand failed	q[-]	3,0000e-004
P2S	Sea water pump no 2 Stbd (standby pump)	On demand	Start on demand failed	q[-]	3,0000e-004
F1P	Suction filter no 1 Port	Non repairable	Filter clogged	λ [failure/h]	6,9400e-004
F1S	Suction filter no 1 Stbd	Non repairable	Filter clogged	λ [failure/h]	6,9400e-004
F2P	Suction filter no 2 Port	Non repairable	Filter clogged	λ [failure/h]	6,9400e-004
F2S	Suction filter no 2 Stbd	Non repairable	Filter clogged	λ [failure/h]	6,9400e-004
CP	Central cooler Port	Non repairable	Cooler clogged / seals damaged	λ [failure/h]	1,0000e-006
CS	Central cooler Stbd	Non repairable	Cooler clogged / seals damaged	λ [failure/h]	1,0000e-006

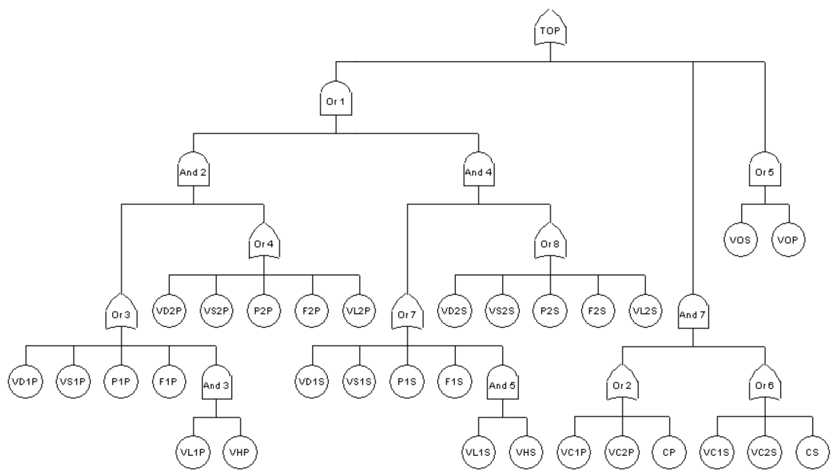

Fig. 2. Fault tree model for sea water cooling system when engine rooms are split

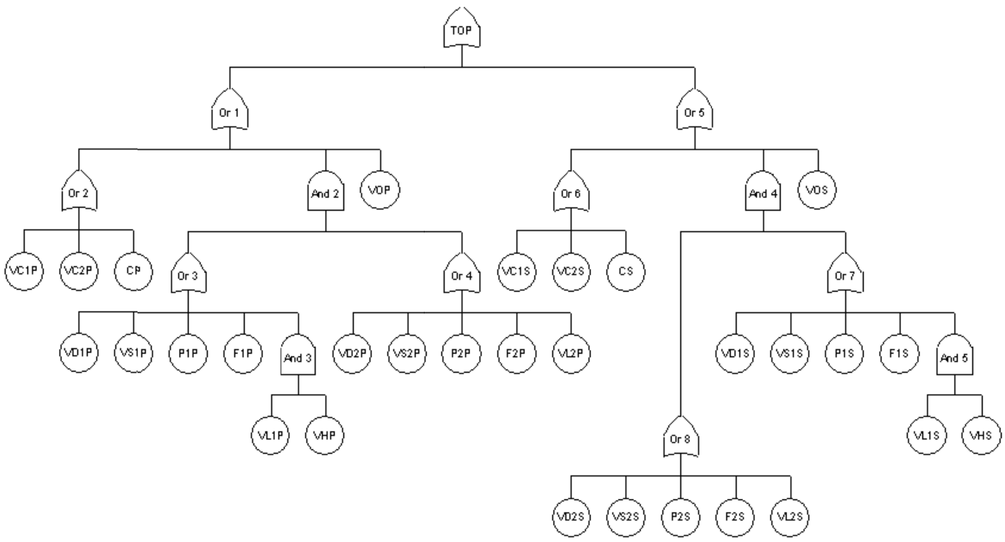

Fig. 3. Fault tree model for sea water cooling system when engine rooms are connected

2. SELECTED QUALITATIVE IMPORTANCE MEASURES

In qualitative analyses, importance of minimal cut set usually depends on number of elements in this set. This number is called *order of minimal cutest*. Very often cut set of first order is more important (critical) then cut sets of higher orders. If system has cut set with one component only, then fault of this component is bringing on down state of the system. This case is related to elements in serial reliability structures.

Order of smallest cutest with *i*-th elements is given by qualitative measure $I^O(i)$. Let C_{1i}, C_{2i}, ..., C_{ni} are describing all cut sets with event E_i, then:

$$I^O(i) = \min_{k=1i,2i,\dots ni} [card(C_k)] \tag{1}$$

Value of $I^O(i)$ does not depend on the component reliabilities. For analysis systems modelled by means of fault tree, can be useful similar coefficient with is giving numbers of occurrences *i*-th events in the fault tree [5]. Usually component is the more important, the component exist in more number of cut sets. Values of order of minimal cutest for presented system components are shown in fig. 4. Two operation states (engine rooms split or connected) are corresponded with models presented in fig. 2 and 3 respectively.

Other important factor in qualitative analysis of component important is ranking of primary events in given cut set [6]. For instance, it can be depending on assumption that, human faults are more frequent then failures of active elements, and failures of active elements are more frequent then failures of passive elements. Based on ranks of elements, it is possible to build rankings of two or more events minimal cut sets consisted of different kind of events [7]. Qualitative methods are useful for systems modelled with binary function of system structure [8].

Matuszak and *Kolodziejski* proposed other qualitative measure [9]. According to them importance of component is characterised by sum of energetic fluids streams $I^{KM}(i)$ (*stream measure*) which are on input s_i and on output s_o from *i*-th component of technical system. It can be presented by formula:

$$I^{KM}(i) = s_i(i) + s_o(i) \tag{2}$$

Values of stream measure for presented system components are shown in fig. 5. Two operation states (engine rooms split or connected) are corresponded with models presented in fig. 2 and 3 respectively. Due to lack of connection changes in this operation states values for given component in both operation states are same according to structure shown in fig. 1. *Chybowski* and *Matuszak* proposed this measure represented by value from range <0,1>:

$$I^M(i) = k_{KM} I^{KM}(i) = k_{KM}[s_i(i) + s_o(i)] \tag{3}$$

Where: $k_{KM} = [\sum_{i=1}^{n} I^{KM}(i)]^{-1}$ - coefficient which is providing summing to the one, n – number of elements in the system.

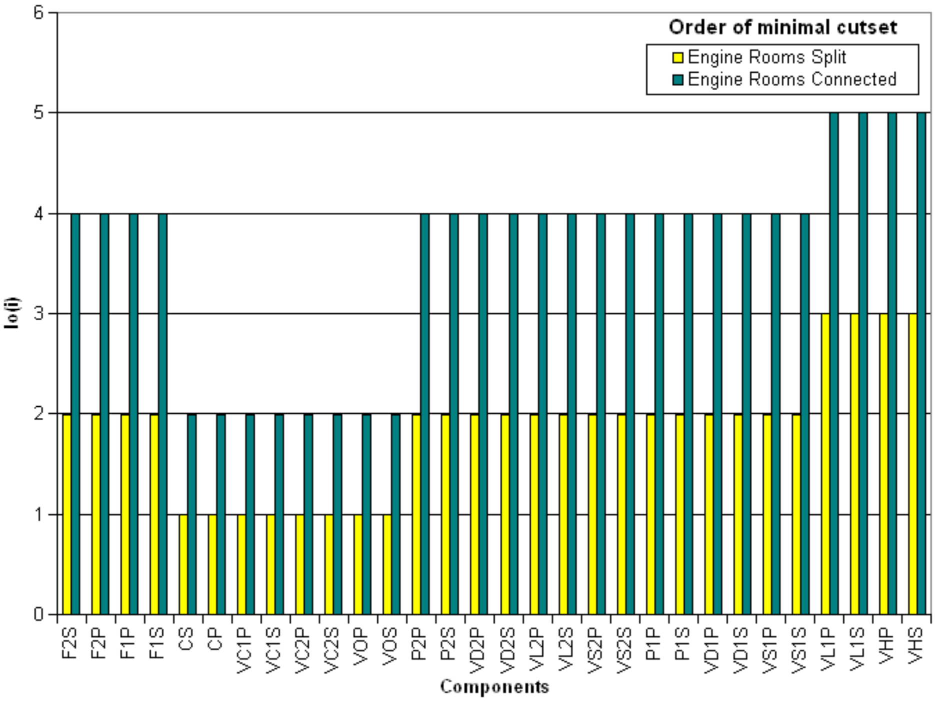

Fig. 4. Order of minimal cutest for analyzed system components in two different operation states

Birnbaum's measure of structural importance for *i*-th component is defined as the relative number of system states for which component *i* is critical for the system. Measure this can be presented by formula:

$$B_\phi(i) = \frac{\eta_\phi(i)}{2^{n-1}} \tag{4}$$

Where: $\eta_\varphi(i)$ is the total number of critical path vectors for *i*-th component.

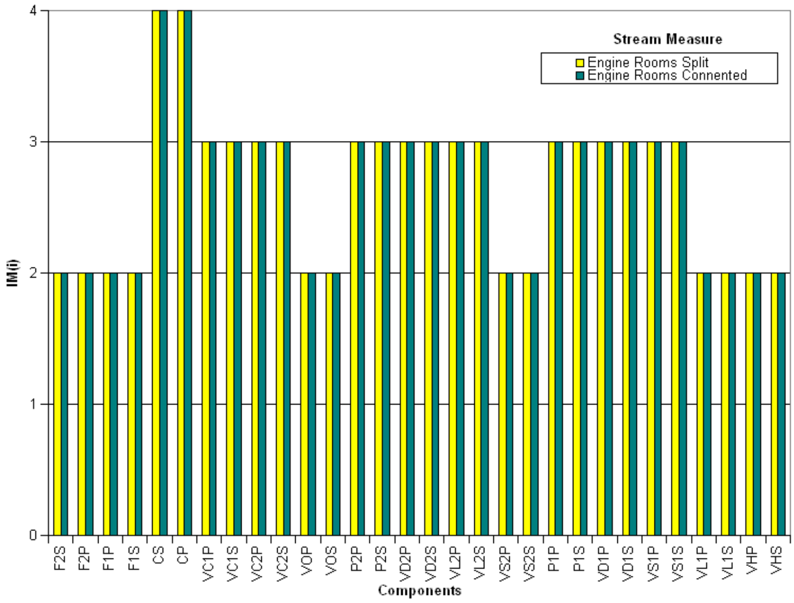

Fig. 5. Stream measure for analyzed system components in two different operation states

A critical path vector for component i is a state vector of the other components in the system such that the system functions if and only if the i-th component functions. This measure is helpful for count the relative number of different states of the system (all other elements than i) which cause i-th component to be critical for the system. If all elements of system have unavailability $q_i = 0{,}5$, then $B_\varphi(i) = I^B(i|t_0)$. Values of Birnbaum's structural importance measure for presented system components are shown in fig. 6. Two operation states (engine rooms split or connected) are corresponded with models presented in fig. 2 and 3 respectively. For quantitative analysis of importance, there are introduced *measures of* importance. It is number of these measures, which application is depend on importance aspect, which is developed. Different measures have different definitions, so these are providing different importance rankings.

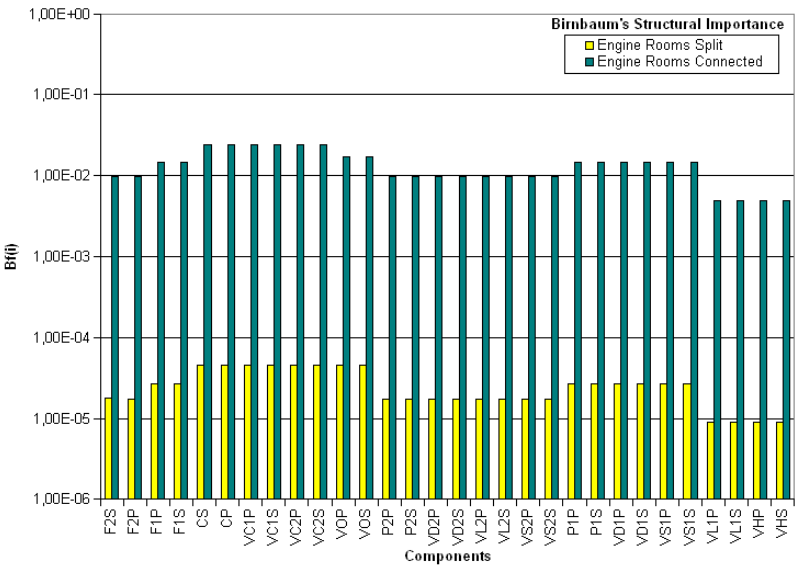

Fig. 6. Birnbaum's structural importance measure for analyzed system components in two different operation states

Usually it is necessary to find elements (importance measures of elements) which dependability measures should be improved for increase reliability increase of whole system. Analogically it is possible to analyse importance of cut sets (locally importance measures).

Qualitative ranking of minimal cut sets is based on measure called cut set importance. Unavailability of cut sets quantifies the probability that k-th cut set is in failed state at a time t:

$$Q_k(t) = q_{1,k}(t) \cdot q_{2,k}(t) \cdot \ldots \cdot q_{j,k}(t) = \prod_{i=1}^{j} q_{i,k}(t) \tag{5}$$

The cut set importance can be interpreted as the conditional probability that minimal k-th cut set is failed at time t, given that the system is failed at time t. The cut set importance is calculated as:

$$I^{CI}(k,t) = \frac{\breve{Q}_k(t)}{Q_0(t)} \tag{6}$$

Where: $Q_0(t)$ – unavailability of system.

3. SELECTED SYSTEM COMPONENTS QUANTITATIVE IMPORTANCE MEASURES

Some of importance measures for elements have been presented below. Measures can be applicable for repairable and non-repairable systems. Authors selected measures: Birnbaum's measure of reliability importance, Vesely-Fussell's measure of reliability importance, improvement potential, Lambert's criticality importance, Birnbaum's measure of structural importance.

Historically first measure has been proposed by Birnbaum [10]. Let $\bar{r}(t) = [r_1(t), r_2(t), \ldots, r_n(t)]$ is system elements reliability vector in moment t, and $R[\bar{r}(t)]$ is system reliability, which is depend on reliability of all elements and reliability structure of system. *Birnbaum's measure* for i-th component is given as:

$$I^B(i \mid t) = \frac{\partial R[\bar{r}(t)]}{\partial r_i(t)} = \frac{\partial F[\bar{r}(t)]}{\partial f_i(t)} \tag{7}$$

Where: $F[\bar{r}(t)] = 1 - R[\bar{r}(t)]$ is unreliability function of system in moment t, and $f_i(t)$ is probability density function of time to i-th component.

Measure of Birnbaum for i-th component in moment t, can be represented analogically by unavailability functions:

$$I^B(i \mid t) = \frac{\partial Q_0(t)}{\partial q_i(t)} = \frac{\partial Q[\bar{q}(t)]}{\partial q_i(t)} \tag{8}$$

Where: $\bar{q}(t) = [q_1(t), q_2(t), \ldots, q_n(t)]$ – vector of unavailability of system elements in moment t, $Q_0(t) = Q[\bar{q}(t)]$ – unavailability of system.

For preliminary analysis can be use formula given in [11]:

$$I^B(i \mid t) \approx \frac{\sum_{j=1}^{m_i} \breve{Q}_j(t)}{q_i(t)} \tag{9}$$

Where: $\breve{Q}_j(t)$ – unavailability of j-th cut set, which contains of i-th component, $m_i(t)$ – number of cut sets, which consist of i-th component, $q_i(t)$ – unavailability of i-th component.

Birnbaum's measure can be calculated as the difference between the probabilities of system failure event calculated under the assumptions that *i*-th component is known to occur and is known to not occur, respectively. This difference may be interpreted as the probability that input event no. i is critical at time *t*:

$$I^B(i \mid t) = \frac{\partial Q_0(t)}{\partial q_i(t)} = Q[q_i(t) = 1, \overline{q}(t)] - Q[q_i(t) = 0, \overline{q}(t)] \tag{10)}$$

Values of Birnbaum's reliability importance measure for presented system components are shown in fig. 7. Two operation states (engine rooms split or connected) are corresponded with models presented in fig. 2 and 3 respectively.

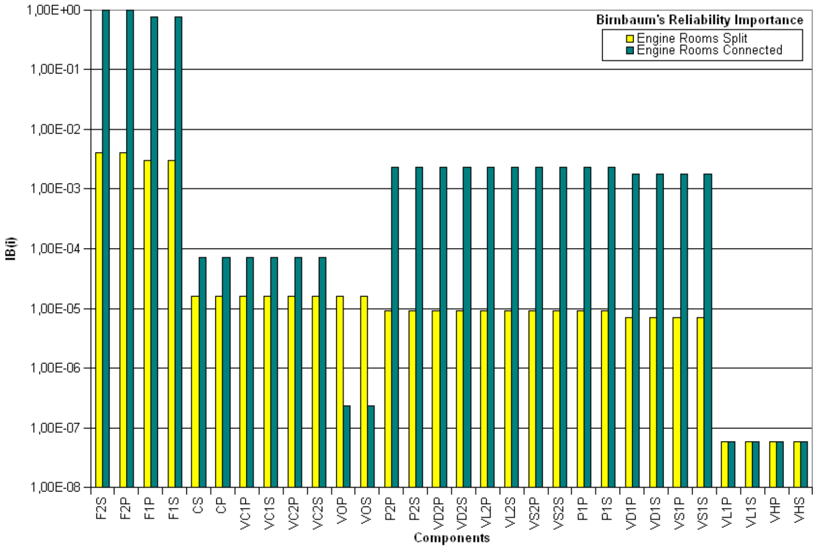

Fig. 7. Birnbaum's reliability importance measure for analyzed system components in two different operation states

Vesely-Fussell's measure of reliability importance $I^{VF}(i|t)$ for component *i* is defined as the conditional probability that at least one minimal cut set containing *i*-th component is failed at time *t*, given that the system fails at time *t*.

Let m_i is describing number of minimal cut sets with *i*-th component; $C_{ij}(t)$ – *j*-th minimal cut set, which consist of *i*-th component and being down in time *t*; $D_i(t) = C_{i1}(t) \cup C_{i2}(t) \cup \ldots \cup C_{im_i}(t)$ - set consist of at least one cut set $C_{ij}(t)$, which is down in time *t*, then Vesely-Fussell's measure is defined:

$$I^{VF}(i \mid t) = P\{D_i(t) \mid \Phi[\overline{X}(t)] = 0\} \tag{11}$$

Vesely-Fussell's measure of importance can be interpreted as the probability that system failure state is caused by *i*-th component fail, when it is given that the system failure has occurred. For preliminary analysis can be use formula:

$$I^{VF}(i \mid t) \approx \frac{\sum_{j=1}^{m_i} \breve{Q}_j(t)}{Q_0(t)} \tag{12}$$

Where: $\breve{Q}_j(t)$ – unavailability of j-th cut set, which contains of *i*-th component, $Q_0(t)$ – unavailability of system.

Values of Vessely-Fussell's reliability importance measure for presented system components are shown in fig. 8. Two operation states (engine rooms split or connected) are corresponded with models presented in fig. 2 and 3 respectively.

The improvement potential reliability measure $I^{IP}(i|t)$ for *i*-th component is defined as the increase in system reliability if component *i* is replaced with a perfect component at time *t*. Improvement potential is interpreted as probability that *i*-th component is critically *Cr* for system and it fails in time *t*.

$$I^{IP}(i \mid t) = P\{Cr[\overline{X}(t), X_i = 1] \cap [X_i(t) = 0]\} \tag{13}$$

Critically measure of Lambert $I^{CR}(i|t)$ is given as probability that component *i* is critical for the system and is failed at time t, given that the system is failed at time t [12], what can be presented:

$$I^{CR} = P\{Cr[\overline{X}(t), X_i = 1] \cap [X_i(t) = 0] \mid \Phi[\overline{X}(t)] = 0\} \tag{14}$$

$$I^{CR} = \frac{P\{Cr[\overline{X}(t), X_i = 1] \cap [X_i(t) = 0]\}}{P\{\Phi[\overline{X}(t)] = 0\}} \tag{15}$$

Lambert's measure can be connected with Birnbaum's importance measure by means of formula:

$$I^{CR}(i \mid t) = \frac{I^B(i \mid t) \cdot q_i(t)}{Q_0(t)} \tag{16}$$

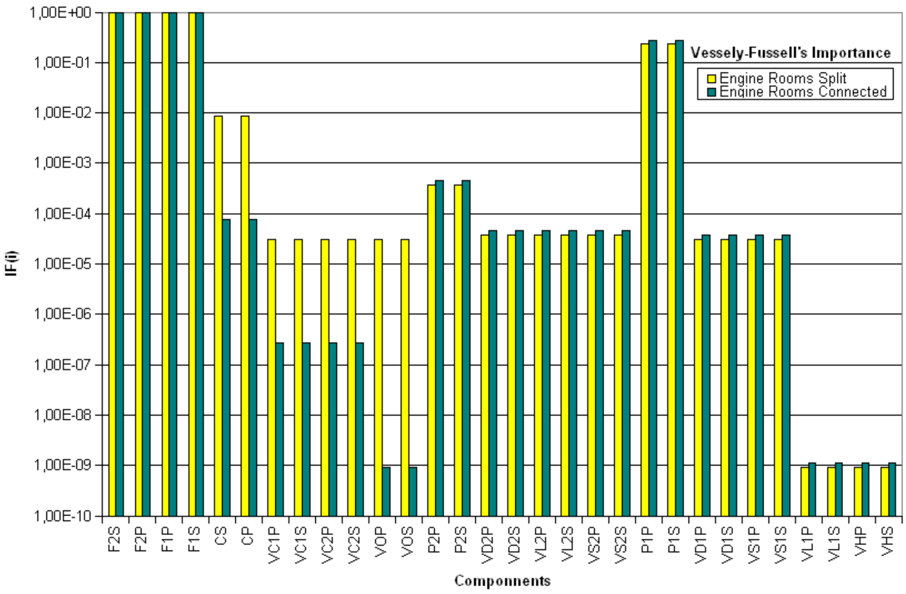

Fig. 8. Vessely-Fussell's reliability importance measure for analyzed system components in two different operation states

Values of Lambert's critically importance measure for presented system components are shown in fig. 9. Two operation states (engine rooms split or connected) are corresponded with models presented in fig. 2 and 3 respectively.

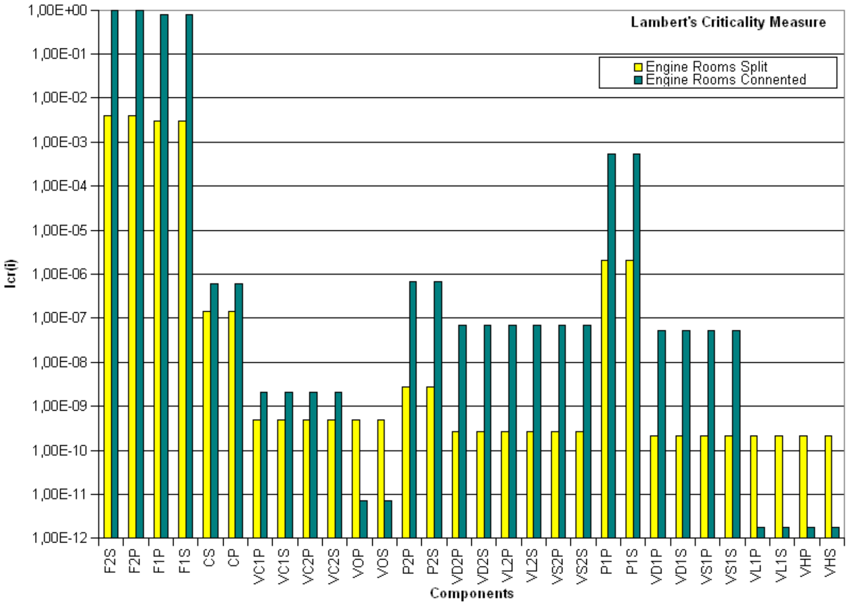

Fig. 9. Lambert's critically importance measure for analyzed system components in two different operation states

FINAL CONCLUSION

For finding elements, which dependability measures should be improved for increase of system reliability, the most useful are Birnbaum's reliability importance measure and improvement potential.

For finding elements, which faults with highest probability will lead to system down, the most useful are Vesely-Fussell's and Lambert's measures of importance. These two measures are useful for building of priority check lists and planed maintenance schedules. For rankings of elements which can be critical for system very useful is Birnbaum's measure of structural importance, which is time independent measure (depends only on system structure).

Based on comparison of different measures, conclude that all measures can be used for technical systems analysis. Proper measure should be selected accordingly to requirements of analysis and information about system. All importance measures can be supported by application of qualitative measures, for instance stream measure can be useful for finding elements, which are working more intensively then others in serial reliability structure of system.

Apart from measures shown in the paper, there are also many other measures (e.g. Natvig's, Bergman's, Barlow-Proshan's), which have not shown here. Some of measures are evaluated based on function of system reliability, what can make them difficult for practically application [1, 13, 14].

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Reviewer: prof. dr hab. inż. Andrzej Niewczas

Authors:
dr inż. Leszek CHYBOWSKI - Akademia Morska w Szczecinie
dr hab. inż. Zbigniew MATUSZAK, prof. AM - Akademia Morska w Szczecinie