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A STOCHASTIC SIMULATION-BASED COMPONENT IMPORTANCE ANALYSIS FOR COMPLEX TECHNICAL SYSTEMS

Key words: importance analysis, complex system, marine system, machinery, Monte Carlo simulation, computer simulation.

Abstract: The paper presents the application of simulation-based component importance measures for complex technical systems. A stern tube sealing system was installed on a sea vessel as an example of a complex technical system (CTS). Selected statistics of ship operation losses were generated as well as the following measures: the failure criticality index, the downing event criticality index, and the downtime criticality index. A need for further development of the importance analysis methods for machinery operation is exposed and the factors influencing the importance of the technical system components are presented.

Analiza ważności elementów złożonych systemów technicznych oparta na symulacji stochastycznej

Słowa kluczowe: analiza ważności, system złożony, system morski, maszyny i urządzenia, symulacja Monte Carlo, symulacja komputerowa.

Streszczenie: Artykuł przedstawia zastosowanie analizy ważności elementów opartej na symulacji w odniesieniu do złożonych systemów technicznych. Jako przykład złożonego systemu technicznego wykorzystano uszczelnienie pochwy wału śrubowego statku morskiego. Wyznaczono wybrane miary statystyczne związane z wyłączeniem statku z użytkowania oraz następujące miary: wskaźnik krytyczności liczby uszkodzeń, wskaźnik krytyczności liczby wyłączeń z użytkowania oraz wskaźnik krytyczności czasu wyłączenia z użytkowania. Przedstawiono potrzeby dalszego rozwoju metod analizy ważności w zastosowaniu dla maszyn i urządzeń. Wskazano czynniki oddziałujące na ważność elementów systemu technicznego.

Introduction

From a general point of view, an important element is one that has the appropriate set of characteristics relative to properties, with values adopted *a priori* within an acceptable range of variability [11]. Woropay [15] defined importance as the ability to reach the "vertical impact" (in terms of subsystem-super system relations) of damage to the subsystem with the concerned level of decomposition to reduce the possibility of the task accomplishment by parent systems. Therefore, the importance to the system is a function of fulfilling requirements defined by k_q criteria as follows [10, 15]:

$$I = f(k_1, k_2, k_q, k_{nk},),\ q = 1, 2...n_k \qquad (1)$$

The importance of system components may be determined by a set of criteria [8]. The greater the number of criteria, the more detailed is the analysis of the component's importance (subsystem) to system functioning. The concept of "weight of evaluation criteria" (hereinafter referred to as *relevance criteria*) is to be found in the literature [9, 11], and it must be distinguished from the *importance criteria*.

If the functional state of the system assigns a defined number to each *f* function of function space, then a criterion for the analysis of importance consists of determining whether the assigned value is within the specified range of acceptable variation as follows [15]:

$$a \leq \Phi(f) \leq b \tag{2}$$

Importance in terms of reliability is intended to determine the key component for the functioning of the system to ensure an optimal value of a dependability measure under consideration, for example, determining which component has the biggest impact on changing the value of system readiness, preparing for damage to occur, or increasing the relative likelihood of causing system failure. The concept of component importance is closely linked to the concept of sensitivity, and these terms are sometimes used interchangeably in the literature. In the publication [9], *sensitivity* is defined as the partial derivative of the system reliability function with respect to reliability of the *i*-th component of the system. This definition is synonymous to the Birnbaum's Reliability importance measure:

$$P_i^D = \frac{\partial R}{\partial r_i} \tag{3}$$

According to Equation (3), the component importance depends on two basic factors:

- The reliability characteristics of the system components, and
- The system reliability structure.

To perform a quantitative assessment of the reliability state of a component's impact on the reliability of a system, quantitative measures of the component's importance to the system have been developed. Currently, a wide range of measures have been developed that assess the importance of a component to a system's reliability. Each of these indicators reflects a different approach to the problem, reflecting different definitions. Figure 1 shows the process of a quantitative assessment of a component's importance. Identification and modelling can be used to represent the reliability structure (structure model) of a system [1, 16, 17, 18]. Together with reliability models of system components, these models can evaluate the reliability of the system.

The next step involves choosing quantitative importance measures and applying them to the model of the system to estimate selected importance measures, followed by the ranking of system components in terms of importance for each measure. The results of these measures allow for an evaluation of the design of the system and the effectiveness of procedures called for during prescribed service times.

The most practical way of obtaining estimates of quality comparable to empirical observations for systems with a considerable number of faults is to use simulation methods for specific reliability measures. This also applies to creating the component importance rankings in the CTS reliability structure. One way to solve mathematical problems is by "statistical modelling," such as matching the problem to be solved with a random process with defined statistical parameters. This allows the calculation of approximate results obtained by stochastic simulation (*"Monte Carlo" simulation*).

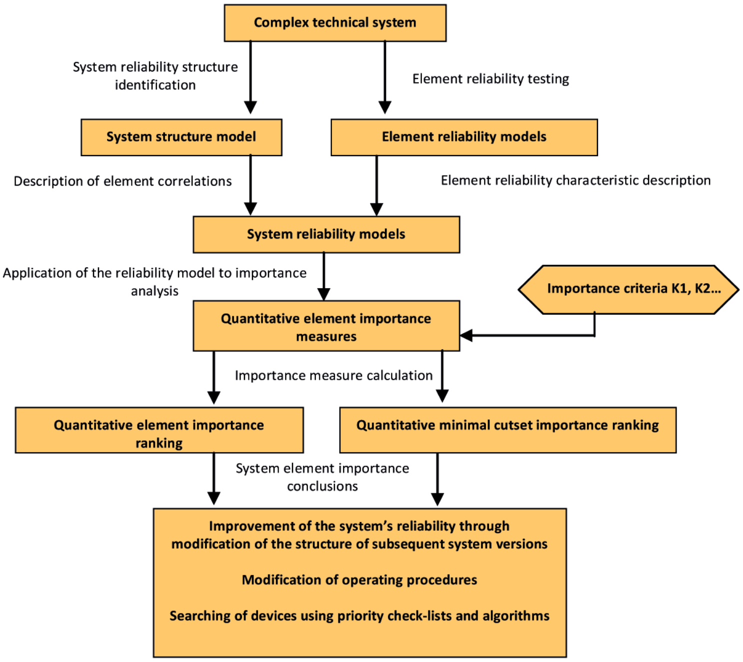

Fig. 1. Process of quantitative analysis of component importance measures in complex technical systems
Source: [2].

Component importance measures determined by simulation are used in reliability analysis of renewable systems. They are based on the number of faults of a specific component, on system down time, and on the count of all system faults registered at a particular time [6].

The *failure criticality index*, sometimes called the *weak link index*, is defined as the percentage of the total downtime count of the *i*-th component causing downtime of the system at time t, to the total count of all system downtime at time *t* [2, 14]:

$$I_i^{FCI}(t) = \frac{m_{nsdf(i)}(t) + m_{zd(i)}(t)}{m_f(t)} \cdot 100\ [\%] \tag{4}$$

where

$m_{nsdf(i)}(t)$ – the total number of system downtime caused by the fault of the *i*-th component;
$m_{zd(i)}(t)$ – the fault counter of the *i*-th component with zero renewal time;
$m_f(t)$ – the total counter of all system downtime at time *t*.

The *downing event criticality index* is defined as a percentage of the number of downtime (or downing) events (damage, waiting for repair, repair, inspection, etc.) of the *i*-th system component causing the system downtime at time *t* to the total number of downtime events at time *t* [2, 14]:

$$I_i^{DECI}(t) = \frac{m_{nsde(i)}(t)}{m_d(t)} \cdot 100\ [\%] \tag{5}$$

where

$m_{nsde(i)}(t)$ – downtime events caused by the *i*-th component;
$m_d(t)$ – the total system downtime events at time *t*.

The *downtime criticality index* is defined as a percentage of the all downtime events (damage, waiting for repair, repair, inspection etc.) of the *i*-th system component causing system downtime at time *t* to the total downtime of the system in the period (0, t), as expressed by the following equation [2, 14]:

$$I_i^{DTCI}(t) = \frac{\sum\limits_{k=1}^{m_{ndse(i)}(t)} T_{D(k)}}{\sum\limits_{j=1}^{m_d(t)} T_{D(j)}} \cdot 100\ [\%] \tag{6}$$

where

$m_{nsde(i)}(t)$ – the total system downtime events caused by the *i*-th component;
$m_{d(i)}(t)$ – the total of all system downtime events at time *t*; and
$T_{D(j)}$ – the duration of the *j*-th system downtime
$T_{D(k)}$ – the duration of the *k*-th system downtime.

1. Object of analysis

An illustration of the most important simulation-based quantitative importance measures of components was performed for the lubrication system of the stern tube shaft sealing of a container ship with 6500 TEU capacity [13]. This system is designed to minimize friction during normal operation of the ship propulsion system [3] and to provide a sealing of the propeller shaft at the stern such that seawater is excluded from the machine room.

A diagram of the lubrication system of the stern tube seal is shown in Fig. 2. Oil circulation in the system is carried out by one of the circulation pumps (P1, P2), which takes oil from the circulation tank T3 through a filter (F1, F2) and it delivers the oil through the cooler C into one of gravity tanks T1 and T2. Selection of the active gravity tank is dependent on the draught of the vessel; when the vessel is sufficiently drafted, the upper gravity tank T1 is selected as the active one, while tank T2 is used during low draught conditions. The oil from the gravity tank flows freely into the stern tube seals to provide sealing, lubrication and cooling of the shafts, thus ensuring proper operating conditions. From the seals, oil outflows into the circulating tank T3. Because the circulating pump works continuously, excess oil in the gravity tank T1 is drained back to tank T2 using a pipeline system, and then from tank T2 again to the circulation tank T3.

The reliability structure of the system was modelled using a reliability block diagram as shown in Figure 3. The structure assumes a decomposition level that consists of the main system components. The structure takes the function of the main system components into account and considers them as separate machines or devices.

Basic reliability system component characteristics are summarized in Table 1. This table reflects the assumption that all components are repairable objects. The distribution of probability of time to damage and recovery time are exponential distributions. Assumed failure intensity, λ, is defined as damage at each 10^6 hour. The average renewal time, T_D [h], is taken from publications [2, 7]. The circuit of the pump-filter is reserved, so the analysis uses an average value of damage and renewal process parameters because of the periodic replacement of these devices between operating and backup system. It was also assumed that both subsystems (pump systems) are damaged in the same way. A similar assumption is made for gravity oil tanks.

The characteristics of planned maintenance works of the system described are presented in Table 2. It is assumed that the operational time is equal to 20,000 hours.

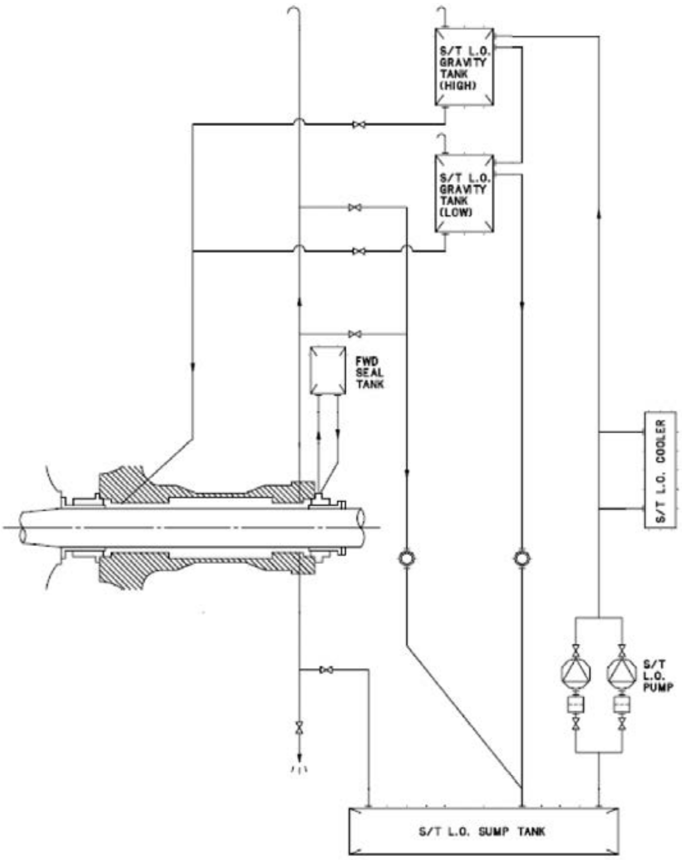

Fig. 2. Lubrication system of stern tube shaft sealing of a container ship with 6500 TEU capacity
Source: [13].

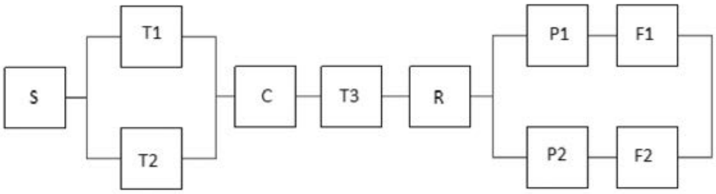

Fig. 3. Reliability structure of ship's lubrication system of stern tube shaft sealing
Source: Authors, based on [13].

Table 1. Reliability system components characteristics of ship's lubrication system of stern tube shaft sealing

Component marking	Component description	Failure intensity λ [damage each 10^6 h]	average renewal time T_D [h]
S	Stern tube shaft sealing with bearings and sealing tank	291.70	168.00
T1	Gravity oil tank (top)	111.40	24.00
T2	Gravity oil tank (bottom)	111.40	24.00
C	Lubrication oil cooler	57.90	24.00
T3	Circulation oil tank	120.50	24.00
R	Pipes. valves and fittings	821.30	4.00
P1	Lubrication oil pump no 1	1749.50	12.00
P2	Lubrication oil pump no 2	1749.50	12.00
F1	Lubrication oil filter no 1	307.00	2.00
F2	Lubrication oil filter no 2	307.00	2.00

Source: [2, 7].

Table 2. Summary of planned maintenance works of the stern tube sealing lubrication system of the container ship

Component marking	Component description, type of service	Average time between maintenance procedure [h]	Average time of system downtime [h]
S	Stern tube shaft sealing with bearings and sealing tank – annual inspection	8760	12
	Stern tube shaft sealing with bearings and sealing tank – inspection every 5 years (in dry dock)	43800	48
T1, T2, T3	Lubrication oil tanks – annual inspection	8760	24
P1, P2	Lubrication oil pumps – annual inspection	8760	24
C	Lubrication oil cooler – cleaning	8760	24

Source: Authors, based on [2, 7].

2. Monte Carlo simulation

The simulation was performed using the *Synthesis 9* platform produced by *ReliaSoft*. The software provides *BlockSim*, *ALTA*, *Lambda Predict*, *Weibull++* and *Xfmea* programs. A detailed report of the analysis is presented in [2]. Parameters for the simulation are the following: simulation start time: 1 h; simulation end time: 175 200 h; point results at every: 100 h; the number of simulations: 100 000; seed value: 1; report sub diagram: OFF; run throughput simulation: OFF; report throughput point results: OFF; and use system downtime threshold: OFF.

Figure 4 shows the values of the failure criticality index. Simulation results demonstrated that the most critical components are pipes with fittings R (59.90%), followed by stern sealings with bearings S (21.08%). Other system components collectively give a common value of I^{CF} lower than 20%. This fact is a result of the relatively larger count of component R failures and the consequences of the component S failure being the most serious (because of the longest renewal time).

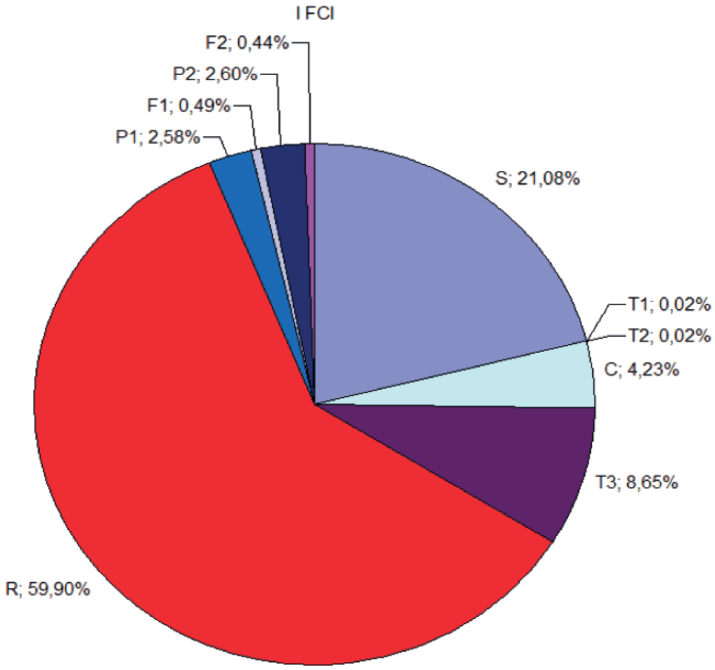

Fig. 4. Failure criticality index for components of the stern tube sealing lubrication system
Source: [2].

The value of the I^{DECI} index is shown in Figure 5. The greatest number of incidences of system downtime is caused by pipes with fittings R (69.47%), followed by circulation oil tanks (12.44%), and the oil cooler (7.24%). The impact of stern tube sealing S with equipment failures is much smaller than the failure criticality index, at 2.18%. This is caused by frequent maintenance work associated with this component, which is under special supervision because of classification boards that ensure the safety and reliability of vessels.

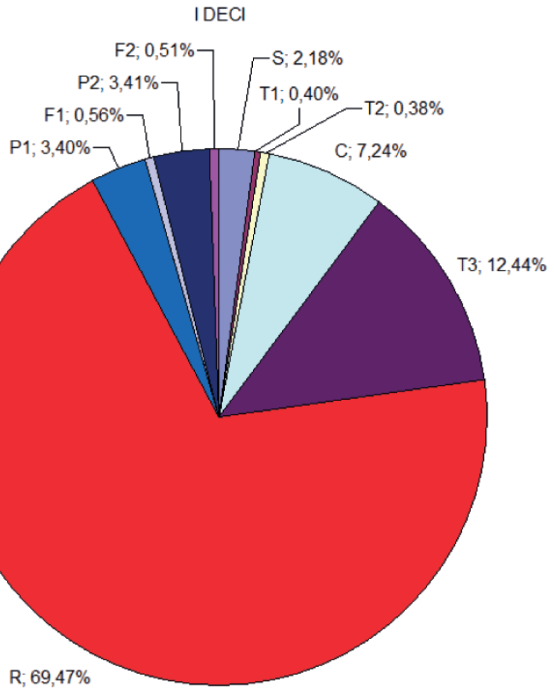

Fig. 5. Downing event criticality index for components of the stern tube sealing lubrication system
Source: [2].

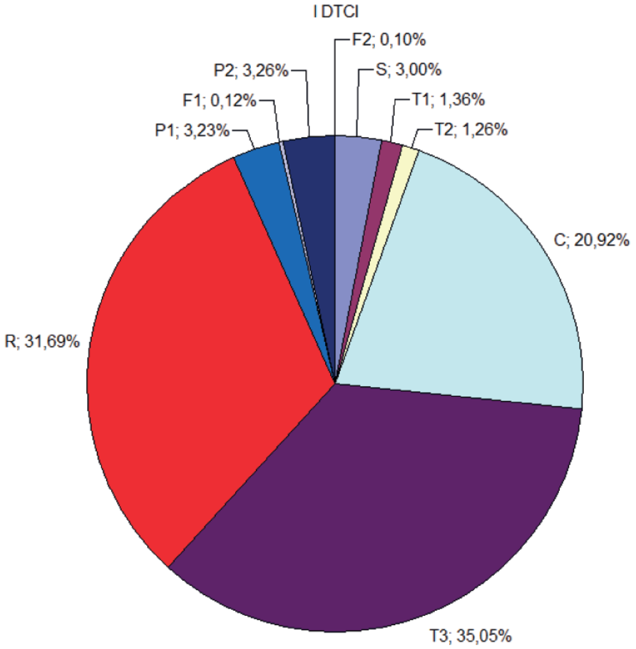

Fig. 6. Downtime criticality index for components of the stern tube sealing lubrication system
Source: [2].

The impact of key components on total system downtime is shown in Figure 6. The largest percentage of shutdown time is caused by circulation oil tanks T3 (35.05%), followed by pipes with fittings R (31.69%), and oil cooler (20.92%). I^{DTCI} values for the other system components are lower than 4%.

In the analyses presented above, approximately 90% of the index value is shared between the three most important components (Figures 4, 5, and 6). The estimates of simulation importance measures described above show clearly that the most important components are pipes with fittings, because of their high vulnerability. The estimates also have high indicator values for stern tube sealings, circulation tanks, and the oil cooler, because of their lack of reserve and the significant duration of maintenance time.

Conclusions

Definitions of component importance and importance criteria of component damage effects on systems were provided. This entailed a review of the most popular theories of exploitation of analytical and simulative reliability measures of components. Analytical indices were divided into qualitative and quantitative ones. The application of individual measures was supported by examples of calculations based on marine vessel's engine room subsystems [2, 4]. A stern tube lubricated seal system was analysed, along with oil circulation pumps and heaters in the fuel supply system of the main engine.

The presented measures were used to create a ranking of component importance. The rankings were based on the following:

- Component location in the system,
- Reliability and the location of the component in the system,
- Unpreparedness and the location of the component in the system,
- The number of system outages due to a component failure,
- The number of system outages due to a component servicing, and
- The time of system outage due to component servicing.

The analysed cases were related to the reliability of the system components. This work has extended the process of component importance evaluations in the CTS reliability structure by applying many more criteria, such as safety, reliability, and cost-effectiveness [2, 4, 5, 12]. The proposed approach provided for distinguishing certain components in the system, which, due to their damage consequences, were deemed important for the system.

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