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Economic aspects of component importance analysis for complex marine systems

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Abstract
The paper presents the application of cost-based, component-importance measures for complex technical systems. A stern tube sealing system installed on a sea vessel was used as an example of a complex technical system. Selected statistics of a ship's operation losses were calculated. Selected, known-importance measures were presented and the authors' own approach to cost-based, component-importance analysis was shown. The following measures were discussed: the operation-interruption cost index, the maintenance potential, the simulation-based maintenance index, and maintenance and operational costs. A description of factors influencing the importance of the technical system components was provided.

Introduction

While analysing the activity of complex technical systems (CTS), it is often necessary to determine not only which components require an upgrade of reliability to improve overall system stability, but also which components, if damaged, trigger the most significant losses in terms of recovery costs and downtime, the latter being highly important for an operator.

The analysis of component importance in a reliability structure may be considered in economic terms. Several such economic measures have been described in the literature (Hilber & Bertling, 2004). These measures differ from indicators presented in (Chybowski, 2014; Chybowski & Gawdzińska, 2016) by being more multi-factorial. One of the primary differences is that interruptions in the operation of the system may incur contractual penalties which are not necessarily linearly dependent on the duration of the interruption (Hilber, 2005; Paska, 2013). Financial losses are different in terms of their assumptions and points of reference; for example, losses due to electrical power outage will be different for given end recipients, and different for the power-plant. It is also necessary to specify the components of total operational interruption costs, which comprise losses incurred by the operator due to interruption of the system's operation, as well as costs of carrying out repairs (purchase and transport of replacement parts, worker costs, etc.) (Woropay, 1983; Karanta, 2011; Kuo & Zhu, 2012; Chybowski, 2014; Chybowski & Gawdzińska, 2016).

The operation interruption cost index I^H uses the total costs associated with a disabled and non-functional system as a measure of reliability instead of using the probability of failure. These costs are, however, a result of the value of the system component reliability function. This index is based on the failure intensity of components, instead of the reliability of components, and is defined as follows (Hilber, 2005):

$$I_i^H = \frac{\partial C_s}{\partial \lambda_i} \text{ [EUR/failure]} \tag{1}$$

where: C_s is the total yearly cost of system operation interruption [EUR/year]; and λ_i is the failure frequency of the i-th component of the system [failures/year].

The interruption cost index of the system's i-th component is dependent on the failure frequency of the system's other components, restoration time of the i-th component, and location of the component within the system's reliability structure (Chybowski & Gawdzińska, 2016; Derlukiewicz, Ptak & Koziołek, 2016; Chybowski & Żółkiewski, 2016).

The maintenance potential I^{MP} is the measure which describes the total predicted annual system repair cost reduction, when the i-th component is replaced with an ideal one (not subject to failure). This index describes the total predicted annual interruption cost caused by failure of the i-th component. The maintenance potential is defined as follows (Hilber, 2005):

$$I_i^{MP} = I_i^H \lambda_i \text{ [EUR/year]} \tag{2}$$

The simulation-based maintenance index is a measure which uses the indicators in Equations (1) and (2). This index specifies the total cost of system operation interruption caused by the down state of the i-th component as determined through stochastic simulation, and is defined mathematically as follows (Hilber, 2005):

$$I_i^M = \frac{C_{(a)i}}{\tau} \text{ [EUR/year]} \tag{3}$$

where: $C_{(a)i}$ is the total accumulated cost of the system's operation interruptions during time τ due to failure of the i-th component [EUR]; and τ is the simulation time (time horizon) [years].

The I_i^M index makes it possible to determine the components whose failure will comprise the largest share of the total costs associated with an interruption of the system's operation. The interruption cost index and maintenance potential are analytically determined measures, while I_i^M is determined by means of a stochastic simulation. Due to the contribution of various types of costs incurred by the operator and/or user of the system, in practice it is more useful to divide the total costs into fractions, and conduct the analysis in phases corresponding to the parts that are significant from the perspective of the overall system operation assessment (Bajkowski & Zalewski, 2014; Zalewski & Szmidt, 2014).

System operation cost measures

When conducting an important economic evaluation, it is extremely important to describe the boundary conditions and assumptions due to the fact that many factors contribute to the final result. The total costs C associated with a system's reliability, called *reliability costs* according to (Chybowski, 2014), are divided into the following components: C_P, the system purchase and installation costs associated with production costs, [EUR]; and C_{SK}, the costs associated with interruptions of operation (Ptak & Konarzewski, 2015) due to corrective and preventive maintenance [EUR]. The sum of costs is also important in the evaluation of the influence of component failures on the system's operation, as shown in the following equation:

$$C = C_{SE} + C_{SK} + C_{SP} = C_{SE} + C_{SO} \text{ [EUR]} \tag{4}$$

where: C_{SE} is the operational loss associated with operation interruptions [EUR]; C_{SK} is the cost of corrective maintenance (repairs, renovations) [EUR]; C_{SP} is the cost of preventive maintenance (planned preventive works) [EUR]; and C_{SO} is operating work costs [EUR].

When analysing the influence of a given component's failure, it should be noted that operational losses associated with disabling the system because of the failure of the i-th component during operating time t can be dependent on the critical operation interruption time coefficient:

$$C_{SEi} = I_i^{DTCI} d_{SEH} t_d \text{ [EUR]} \tag{5}$$

where: I_i^{DTCI} is the critical operation interruption time coefficient of the i-th component [%]; d_{SEH} is the hourly cost of system operation interruption [EUR/h]; and t_d is the time of system operation interruption [h].

The lost profits associated with total operational losses for a system comprised of n components can be expressed by the following formula:

$$C_{SE} = \sum_{i=1}^{n} C_{SEi} \text{ [EUR]} \tag{6}$$

The mean total costs associated with carrying out restoration of the i-th component for failures causing interruption of the system's operation may be determined by the critical failure number index, a parameter which is described by the following formula:

$$C_{SKi} = I_i^{FCI} d_{SKi} m_f t \text{ [EUR]} \tag{7}$$

where: I_i^{FCI} is the critical failure number index of the i-th component [%]; d_{SKi} is the average repair cost of the i-th component, including purchase and delivery of replacement parts, energy and personnel [EUR/failure]; m_f is the total number of system failures recorded during the time t [failures/h]; and t is the operating time [h].

The costs associated with restoring all components, including those which are unrelated to the interruption of the system's operation, will be higher than the ones described by Equation (7). For a given component, restoration costs are as follows:

$$C_{SKi\,\text{total}} = d_{SKi} m_i t \ \ \text{[EUR]} \tag{8}$$

where: d_{SKi} is the average repair cost of the i-th component, including purchase and delivery of replacement parts, energy and personnel [EUR/failure]; m_i is the total number of failures of the system's i-th component within time t [failures/h]; and t is operation time [h].

The total restoration cost for a system consisting of n components within time t can be estimated by the following equation:

$$C_{SK} = \sum_{i=1}^{n} C_{SK\,\text{total}_i} \ \ \text{[EUR]} \tag{9}$$

Similarly, the average total cost associated with carrying out corrective and preventive maintenance for the i-th component in situations related to interruption of the system's operation can be determined by the critical number of operation interruptions index:

$$C_{SOi} = I_i^{DECI} d_{SOi} m_d t \ \ \text{[EUR]} \tag{10}$$

where: I_i^{DECI} is the critical number of interruptions index of the i-th component [%]; d_{SOi} is the average cost of maintenance of the i-th component [EUR/maintenance]; m_d is the total number of system operation interruptions recorded in time t [operation/h]; and t is operation time [h].

The costs associated with the maintenance of all components, including those which are not associated with the system's operation interruption, will be higher than the costs described by Equation (10), and will be given by the following expression:

$$C_{SO\,\text{total}_i} = d_{SKi} m_o t \ \ \text{[EUR]} \tag{11}$$

where: d_{SKi} is the average maintenance cost of the i-th component [EUR/maintenance]; m_o is the total number of maintenance events for the i-th component within time t [maintenance/h]; and t is operation time [h].

The total maintenance cost of a system consisting of n components within a duration of t can be expressed by the formula:

$$C_{SO} = \sum_{i=1}^{n} C_{SO\,\text{total}_i} \ \ \text{[EUR]} \tag{12}$$

Object of analysis

An illustration of selected monetary 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 (Hyundai Heavy Industries, 2003). This system is designed to minimise friction during normal operation of the ship propulsion system, and to provide a sealing of the propeller shaft at the stern such that seawater is excluded from the machine room. The reliability structure of the system was modelled using the reliability block diagram shown in Figure 1. The structure assumes a decomposition level consisting of main system components, taking their function in the system into account and considered as separate machines or devices.

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 delivers the oil through the cooler C into one of gravity tanks T1, 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 from tank T2 again to the circulation tank T3.

Basic characteristics of reliability system components are summarised 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. Assuming failure intensity λ [damage each 10^6 hours], the average renewal time T_D [h] is taken from publications (Duda-Gwiazda, 1995; Chybowski, 2014). 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

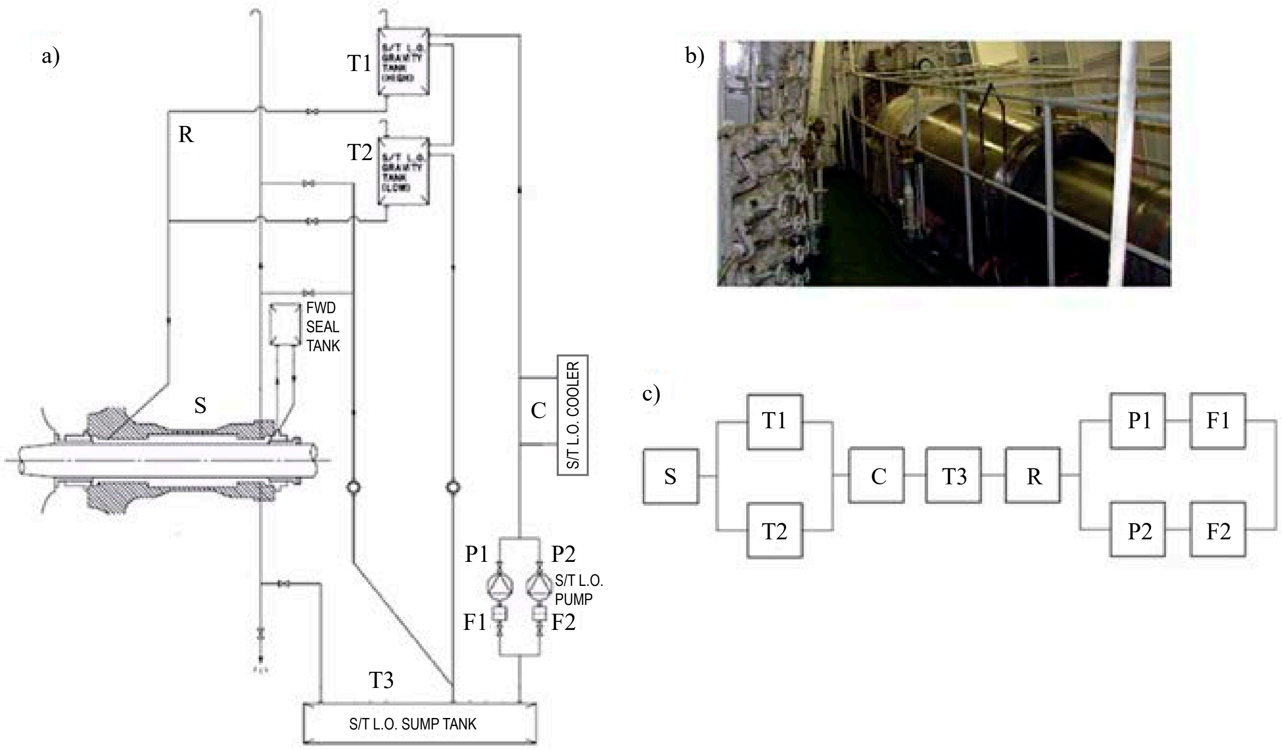

Figure 1. Ship's lubrication system of stern tube shaft sealing: a) system diagram; b) fore sealing view; c) reliability structure of the system (Hyundai Heavy Industries, 2003; Chybowski, 2014)

Table 1. Reliability system component characteristics of ship's lubrication system of stern tube shaft sealing (Duda-Gwiazda, 1995; Chybowski, 2014)

Component marking	Component description	Failure intensity λ [damage/106 h]	Average renewal time TD [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

Table 2. Summary of planned maintenance works to the stern tube sealing lubrication system of the container ship (Duda-Gwiazda, 1995; Chybowski, 2014)

Component marking	Component description, type of service	Average time between maintenance procedure [h]	Average duration 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

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.

Due to the confidentiality of information regarding costs incurred by freighters, as well as many factors which affect the results, general information regarding system repair costs was used to show the viability of the aforementioned indices. It is assumed that the cost of a ship's operation interruption is 15,000 EUR/day, while the individual average costs associated with system component restoration are presented in Table 3.

Table 3. Average restoration cost of the propeller shaft tube seal lubrication system components of a container ship (generic data) (Chybowski, 2014)

Component designation	Component description	Restoration cost d_{SKi} [EUR]
S	Propeller shaft tube seal with bearings and sealing container	30 000
T1, T2, T3	Oil gravity tank (upper)	500
C	Lubricating oil cooler	250
R	Pipelines, valves and other equipment	125
P1, P2	Lubricating oil pump No. 1	1250
F1, F2	Lubricating oil filter No. 1	125

Calculation of monetary measures

The 20,000 h operation time simulation was carried out using the *Synthesis 9* calculating platform by *ReliaSoft*. Parameters for the simulation are: simulation start time: 1 h; point results at every: 100 h; number of simulations: 100,000; seed value: 1; report sub-diagram: OFF; run throughput simulation: OFF; report throughput point results: OFF; use system downtime threshold: OFF.

A detailed report from the analysis is presented in (Chybowski, 2014). In the simulation result, which encompassed a year of system operation, the total time of ship operation interruption was 69 h. Taking into consideration that the hourly cost of ship operation interruption is 625 EUR, the estimated operating losses associated with system operation interruption caused by failure of the *i*-th component during operation time *t* were estimated [EUR].

The effect of failures on the system operation interruption costs calculated with use of (5) is presented in Figure 2.

Average costs associated with restoration of system components which caused interruptions of system operation calculated with the use of (7) are presented in Figure 3.

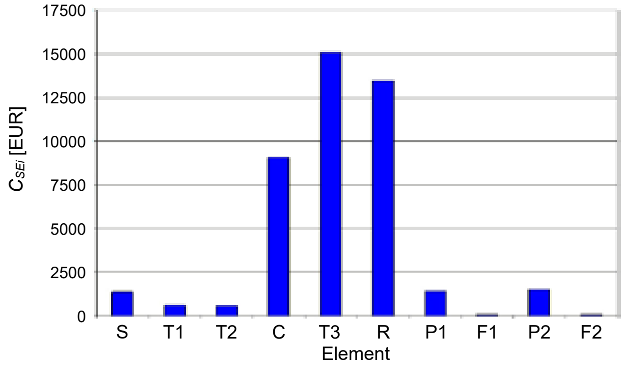

Figure 2. Operating losses associated with system operation interruption caused by failure of the *i*-th component of the propeller shaft tube seal lubricating oil system during operation (Chybowski, 2014)

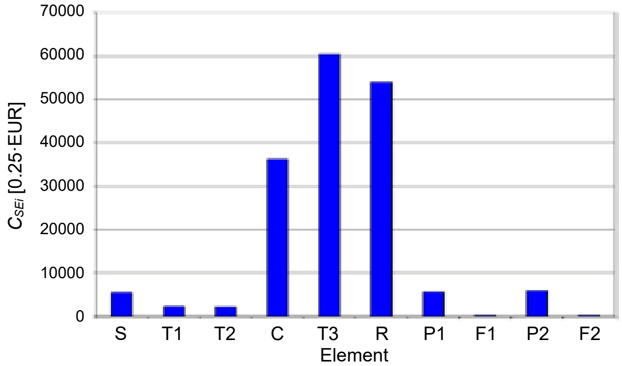

Figure 3. Average yearly restoration costs of the *i*-th component of the propeller shaft tube seal lubricating oil system (critical failures) (Chybowski, 2014)

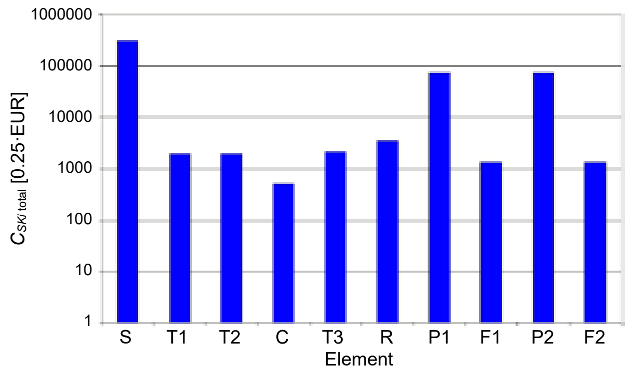

Figure 4. Average yearly renovation costs of the *i*-th component of the propeller shaft tube seal lubricating oil installation (all failures) (Chybowski, 2014)

The highest costs associated with system operation interruption caused by failure of a given component correspond to failures of the T3 circulation tank, the C cooler, and the R pipelines and their equipment. These are components for which the critical operation interruption time index reached the highest value.

The I_i^{DECI} index can, therefore, constitute a measure which describes the influence of component failure on the degree of losses associated with interruption of the system's operation. The highest C_{SKi} costs are associated with repairs to the S propeller shaft tube seal, due to the necessity of docking the ship or hiring divers for underwater work. Due to the large difference in repair costs of the *S* component, compared to other components, the results are presented on a logarithmic scale.

In relation to the yearly operation time of the analysed system, the average total restoration costs of individual system components calculated with the use of (8) are presented in Figure 4.

The highest $C_{SKi\ \mathrm{total}}$ repair cost of the propeller shaft lubrication and tube seal installation are associated with the S sealing (over 25,000 EUR), followed by circulation pumps P1 and P2 (over 17,500 EUR) and other system components (below 875 EUR).

Conclusions

These estimates of importance measures, encompassing the economic aspect of operation (Figures 2, 3 and 4), basically correspond to results achieved in stochastic simulations (ReliaSoft, 2007; Chybowski, 2014). Weak links in the system which significantly influence operating costs include pipelines and their equipment, the oil cooler and the circulation tank (Figures 2 and 3). Due to the consequences of failures (high restoration costs and system operation interruption), the most important component of the system is the shaft tube seal, for which the importance measures reached very high values (Figures 2 and 3). Considering that the maintenance costs of the shaft tube seal are several times higher than for any of the other components, it is classified in terms of failure consequences as the most critical component in the system despite the fact it is a very reliable component.

Full assessment of a component's importance requires knowledge of the consequences of its failure (Chybowski, 2014; Chybowski, Laskowski & Gawdzińska, 2015; Chybowski & Gawdzińska, 2016). For example, although the crankshaft of an internal combustion engine is very reliable, the engine will be out of commission for a relatively long time whenever the crankshaft is damaged. Thus, the component could be considered very important. Therefore, the importance of complex technical system components depends on:

- the reliability characteristics of the system components;
- the system reliability structure; and
- the consequences of damage to system components.

A crucial issue related to the topic is the need to determine the uncertainty of obtained results. Analysing this concept is highly complicated due to the non-linear relationship among costs and instances of downtime and the necessity of including various additional costs such as duty, taxes, transportation costs, contractual penalties, etc. All the above items create a basis for conducting long-term research aimed at establishing detailed methodologies for cost analyses of system sensitivity. Due to the complexity of measurement uncertainty and the fact that the main objective of the paper is to suggest a methodology useful in the initial analysis of component importance in minimising system exploitation costs, the presented methodology may find its application in various CTSs used daily.

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