**Scientific Journals**
**Maritime University of Szczecin**

**Zeszyty Naukowe**
**Akademia Morska w Szczecinie**

**2013, 36(108) z. 2 pp. 5–12**
**ISSN 1733-8670**

**2013, 36(108) z. 2 s. 5–12**

# Application of risk analysis in maintenance of ship power system elements

**Andrzej Adamkiewicz[1], Janusz Fydrych[2]**

[1] Maritime University of Szczecin, Faculty of Mechanical Engineering
Diagnostics and Machine Repairs Department
70-205 Szczecin, ul. Podgórna 51/53, e-mail: a.adamkiewicz@am.szczecin.pl
[2] EUROAFRICA Services Limited, Dept. in Poland
70-952 Szczecin, ul. Energetyków 3/4, e-mail: fydjan@plusnet.pl

**Key words:** technical risk, sea-going vessel, power system, maintenance strategy

**Abstract**
Searching for a safe ship, this paper presents operational strategies which are used for ship power system maintenance, conditions for their realization have been shown. The procedure of risk analysis has been decomposed and its stages have been discussed. Methods of risk evaluation and methods of ship power system threat identification have been analyzed. The choice of risk evaluation method has been made for the management of maintenance of elements of the system taking into account good maritime practice, ICM code, regulations of classification societies and international maritime organizations. Studies on possibilities of extending operational time of the engine from the main power system using risk analysis with the Expert Method have been presented. On the basis of the results of studies, applicability of the Expert Method for risk analysis on ships has been shown.

## Introduction

Risk analysis used for the needs of maintenance of technical condition of a monitored object (condition monitoring, diagnostics and servicing) integrates technical, economic and safety issues [1, 2, 3]. The notion of an absolutely safe ship so far has been an open issue and is a subject of scheduled work of Classification Societies and International Maritime Organization IMO [4]. This is due to the lack of possibilities of univocal defining of determined operational risks of a sea-going vessel, as well as to the lack of definition of a safe and effective operation of a certain type of ship (multi-purpose carriers, container ships, tankers etc). It is dependent on design construction assumptions which are burdened with some indetermination of construction solutions accepted in the designing and ship building process and on random interaction of hydro meteorological conditions in the sailing area, ship maintenance procedure, crew experience and their habits [5, 6]. However, a full risk analysis requires, apart from design data and operational conditions, data bases comprising additional information referring to [7]:

– operational history;
– failure analysis;
– costs of servicing and repairs;
– operational efficiency.

In reference to a ship as a safe maritime facility, different operational strategies and maintenance methods can be applied [2]. At present development of designing and manufacturing technologies, rational management of operational process is a necessary condition for maintaining a ship in the state of seaworthiness and thus also its power system. For the safe performance of a transportation task to be realized by ship, it is necessary to ensure flows of mechanical and electrical energy, as well as heat for the sea voyage (ship movement), loading functions, steering, communication and social conditions for the crew.

Realization of ship movement depends on the kind of ship main power system. At present, the main power system, in the case of most cargo ships, uses Diesel engines of high and medium output power which together with engines and equipment to realize all ship functions comprise its power system. Considering the safety of a ship in its real operational conditions, also its technical and design properties, logistics, ship management and the safety of the power system should be considered.

In the general structure of ship operation only technical issues directly influence the required state of safety, whereas organizational and management issues can lead to a state of its unseaworthiness and the remaining issues appear as consequences of previous non-required events (insufficient equipment, lack of revitalization and other negligence).

## Operational strategies in maintaining elements of the sea-going ship power system

Ship power system management is realized throughout such activities as: planning and decision making, organizing, managing and control. Together, they form the operational strategy which defines the methods of maintaining the technical condition at an assumed level and in the required time of their operation, often estimated with key indicators of effectiveness [1, 2]. In ship technology, maintenance of technical condition on the basis of risk analysis, so far has not been practically implemented to a satisfying degree. On contemporary ships in reference to certain machines and equipment, none out of the possible operational strategies based on the analysis of the current technical conditions have been univocally implemented: not the Control Based Maintenance (CBM) method using contemporary methods and control tools nor the less advanced ones like the Planned Maintenance (PM) strategy, where maintenance is carried out in a planned way in which preventive methods (Preventive Maintenance – PM) to a different extent are introduced, or the Reliability Centered Maintenance (RCM), service life strategy (according to the operational potential), authorized strategy of machine existence, or a mixed strategy [1, 5, 8, 9]. Most frequently maintenance within the Planned Preventive Maintenance is scheduled on the basis of operation time. This approach is called "according to time" or "basing on time" – TBM (Time Based Maintenance). Thus, on contemporary ships in reference to certain machines and equipment, in practice only a few out of the possible maintenance strategies are applied.

Operational maintenance of a ship power system is carried out in compliance with regulations of the ISM Code, classification societies and the applied operational strategy guaranteeing that the power system will perform the task facing it. It is realized using different maintenance strategies adjusted to the requirements of the ship owners. Because of this, the accepted strategy, relying on the results of current analyses, should be corrected. Introduction of modifications should be based on the trends shown by monitored diagnostic parameters. Therefore, more and more frequently there is a need for implementing TBM (Time Based Maintenance) with a modification option allowing, for example, the extension of periods between repairs and reductions of service ranges. Such an approach is justified by:

1. Diagnostics, which is a real part of maintenance (thermal-flow diagnostics, vibro-acoustics, thermo-visual), as well as a part of servicing and repairs (stand-by diagnostics, endoscopic inspections, oil properties analysis, non-destructive studies);
2. Underestimating, in the so-far period of ship operation, the economic factor both in the area of ship/system power efficiency and costs of servicing and repairs;
3. Personalizing maintenance – individual knowledge and experience of randomly exchanging engine room crews was replaced by documented operational history, carried out procedures and stored statistics.

The presented conditions limited, not stimulated, the creation of maintenance strategies of technical conditions of ship equipment based on optimizing economic resources on technology and safety [10]. Control systems with failure analysis (AMOS, EMOS, NORCONTROL, NORIS, MRS, TASCK, ASSYSTENT) have been implemented to a limited extent. Information systems documenting operation, register huge amounts of data, which for various reasons cannot be rationally used (they do not have an operation block for data transformation for the needs operational decision making). This, among others, is due to the fact that data bases are created from not entirely well-defined needs and requirements. Therefore, the maintenance strategy lacks reliable basing on technical risk for which it is necessary to possess data including information on [6, 7]:

– constructional characteristics of machines and equipment;
– operational history with operation conditions,
– failures and reliability;
– occurring failures and other undesirable events;
– effectiveness, as well as energy end economic (maintenance and repairs costs) effectiveness of

decisions made to improve safety and reliability of the power system,

which should fulfill the criterion of completeness, proper choice, reliability (quality) and the form enabling their transformation.

## Procedure of risk analysis

The concept of risk is connected with the uncertainty with a possible result with a loss [8, 11]. The condition of ability of a technical object allows the realization of operational tasks connected with usage. On the other hand, the condition of inability may lead to different situations. It mainly depends on which stage it was detected – before start-up, during the start-up, at operation or after switching the machine off [3, 12].

The consequences in each of these situations can be different. Risk in reliability considerations refers both to the technical object and to the power system as a whole, as well as to the operational system. The power system comprises other technical objects connected through power, whereas the operational system comprises also the people and relations between crew members.

Technical risk is defined as a multiplication of probability of undesirable event occurrence and its consequences [6, 12, 13, 14].

$$R = \sum P_i C_i \qquad (1)$$

where:

- $R$ – risk;
- $P_i$ – probability of undesirable event occurrence;
- $C_i$ – consequences of the undesirable event occurrence.

Probability of failure occurrence is the value which is sought in a formalized way regardless of the particular event. Estimation of unserviceability consequences is connected with the technical object it refers to. Risk analysis of a ship power system comprises: identification of dangerous scenarios (risks), quantitative and qualitative evaluation of scenario probability and the probability of a failure, risk estimation and risk evaluation in the view of accepted criteria and requirements, as well as actions resulting from the carried out risk analysis. An example of an algorithm of a technical risk analysis is shown in figure 1 [13].

**Procedure of risk analysis** requires the system and its structure to be defined. Complicated and complex systems at this stage are divided into subsystems (machines, equipment, installations). Defining the system and its decomposition takes into account constructional, technological and operational aspects, as well as data bases comprising operational history, failure of elements, design and constructional information.

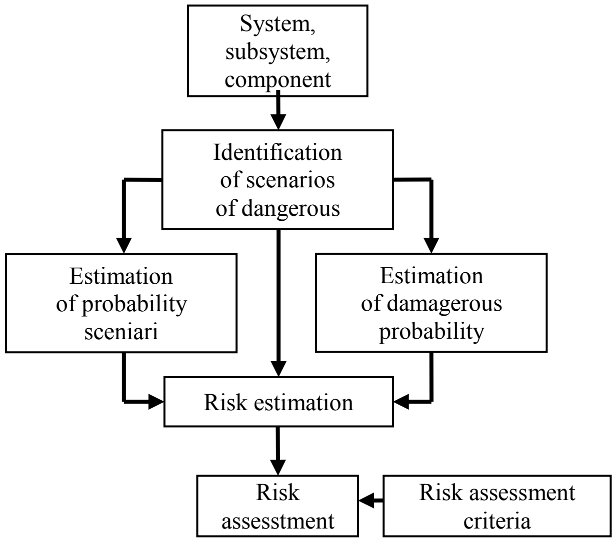


Fig. 1. Risk analysis algorithm for a technical object

**Identification of dangerous scenarios** is the answer to the question "what that is undesirable can occur?", what situations and processes can lead to faulty and dangerous operation of elements of the system. Identification of dangerous scenarios requires excellent and thorough knowledge of the system (in this case ship engine room) from the constructional and operational point of view, as well as the knowledge of technology and material engineering of the elements of the system. Records of failures during the so-far operation, data on conditions and occurring operational problems of the system on similar ships and expertise of the experienced crew are a source of precious information on possible scenarios and faults.

**Risk estimation** in relation to the specifics of the studied system, accessibility and type of data, as well as the required accuracy of estimation can be performed using *quantitative* or *qualitative* methods, proceeded by initial analyses. They are equally rich in the number and versatility of their methods [6].

*Qualitative methods* comprise the following: matrix method, indicator methods (profession risk analysis methods – Risk Score), experimental methods analysing adverse effects of different risk factors and a separate group of tree methods. Tree methods enable a more detailed consideration of causes of a primary undesirable occurrence and the scenario of events after they occur, applied in the cases of more accurate qualitative methods of risk analysis, useful in such technologies as nuclear power, ship industry, and means of air transport. As qualitative methods are used for qualitative comparisons of risk levels and for searching for ways to lower them, they are not useful for estimating risks or detailed analyses.

*Quantitative methods* comprise mainly probabilistic and statistical methods. Probabilistic models are based on models of failures and risks and they are especially useful for prognostic analyses. Statistical methods are used for evaluation of risks on the basis of statistical data on losses which were noted in the past in the population of studied systems. The choice of a risk analysis method in the case of a particular power system is influenced by a number of factors: the aim of the carried out analysis, the foreseen level of risks, tradition and also insufficient knowledge of other methods of risk analysis.

## Methods of identification of risks (scenarios) of ship power systems

The operation of a ship power system is a multi-aspect issue requiring comprising constructional matters, working media influencing system construction and conditions in which the facing tasks are realized. Their mutual functional connections can and often cause a serious risk for their functioning, from minor faults (like disturbances at fuel spraying throughout Diesel engine injection valves) to serious ones in fact to the destruction of their basic constructional elements (like destruction of the piston or cylinder of the Diesel engine).

Developments in computerization, and as a result introduction of digital calculation methods into the processes of manufacturing new constructional materials and designing new constructions of power systems enabled the construction of engines of substantial powers at the same time maintaining their relatively small dimensions. In spite of the fact that these engines are becoming safer and safer, they require a more precise identification of possible risks which directly results from the relation of the obtained power to the engine mass unit (increase of unitary power). This fact enforced development of methods for risk identification of power system elements like PHA (Preliminary Hazard Analysis), which comprises the "What – If" method and various audits and identification methods such as:

- **FMEA** – Failure Modes and Effects Analysis;
- **ET** – Event Tree Method;
- **FTA** – Failure Tree Analysis.

Taking into account contemporary development tendencies in the processes of power generation, it is obvious that there is a need for development and better adjustment of diagnostic methods, and as a consequence obtaining results being a basis for creating data storage and histories of events, and thus making adequate and justifiable operational decisions [6, 10]. A complete description of risk analysis methods is a task which exceeds the scope of a single paper.

## Maintenance management based on risk analysis – choice of a risk evaluation method

Dynamic development of ship technology, application of digital calculation tools in designing and construction of ship power equipment brought about the possibility of reaching higher and higher output power generated by engines maintaining unchanged geometry and mass. However, the excessive stress on the engine enforced the need to apply more precise tools, and methods diagnosing their current technical condition. These methods involve among others application of computer systems in operational processes and controlling parameters indicating the current technical condition of the monitored engine/equipment which as a result, throughout identification of ability states according to a devised algorithm of events and values, supports the operator in the decision making process of operation control.

At present, methods used for the evaluation of the technical condition of equipment mainly base on the so-far acquired knowledge, i.e. theoretical knowledge supported by practical expertise. It shows the complexity of issues which have to be considered in the decision making process of controlling generation and operation of ship power equipment.

Probabilistic and statistical methods are only an interpolation of values characterizing events previously occurring and do not encompass currently existing state. Therefore, it is justified to incorporate into the methods diagnosing technical condition new technologies such as acoustics, thermovision, elastic wave propagation methods and similar ones which give the picture of current structure of working (surface layers) and constructional surfaces of the technical object.

According to the 75$^{th}$ article of the Maritime Code, a ship can be accepted for sailing at sea if it meets the requirements resulting from rules and regulations of good maritime practice. However, although the term "good maritime practice" comes from multi-year practice of sailing in different environmental conditions, the regulations have exact recorded meaning and they are obligatory for ship owners and crews working on such ships. These documents confirm ship technical condition based on the classification requirements of the controlled unit. They realize general and particular requirements resulting from IMO resolutions and directives and SOLAS 1974 convention (with later amendments). They are issued by the classifier after having the ship inspected and presentation of particular equipment in operation. They state the condition of the ship on the day of inspection, and as the assumption and aim of IMO is safety of sailing and of natural environment in the whole period of the ship active lifetime (also during repairs and operational switch-offs), crews are obliged to periodically control the efficiency of specified elements guaranteeing the safety of the whole sailing unit. According to SOLAS convention these elements were determined and classified to the group of the so called Critical Equipment (CE) and defined as "equipment and technical systems whose sudden failures may cause situations of emergency" – it results from the ISM Circular 01/2008 – Critical Equipment Code § 10.3. They comprise such equipment as: engines of the main power system, steering equipment, pumps, filters, air compressors, safety systems of the main power engines and boilers, as well as many other. According to the SOLAS, Chapt. III 20.6.1. the total number of all specified elements is equal to 47, yet it is different for particular ships. Operational ability of the specified equipment, and thus the ship too, depends on its technical condition. The obtained parameter values of the controlled equipment are the basis for obtaining confirmation of the state of ability from the classifier. In spite of the fact that each piece of equipment is liable to technical control resulting from its Technical Operational Documents (DTR) classification control is carried out basing on the time according to the inspection schedule. There are inspections which take place yearly, once in five years or after failures. In response to ship owner's request they can be performed sooner or later in relation to those that were scheduled, i.e. after a certain amount of operation time which results from the accepted maintenance strategy. In ship operational practice there are cases of exceeding the required period of operational time until the subsequent control without negative operational consequences.

As Convention requirements (including those of Critical Equipment, Ship Oil Policy Emergency Plan) refer to operational efficiency, therefore, it is possible to extend the periods between servicing times for some equipment maintaining their operational ability [6, 7]. It may refer to inspection dates of, for example: systems of electrically driven pumps mounted on the main power system engines, scheduled inspections of the conn-rod piston systems of the engines form the main power, inspections of main bearings, timing gear of engines etc. in the absence of accelerated wear.

The classifier evaluates and accepts the controlled equipment for further operation on the basis of positive evaluation of its actual technical condition. As a result the accepted and realized strategy of ship power system elements maintenance is a compilation of the strategy based on the technical condition (CBM), planned-preventive (PPM), directed towards reliability (RCM), technical service life and time (TBM), which should be oriented towards safety applying the method of risk analysis [6, 8].

The presented earlier difficulties and limitations connected with implementation of the strategy based on the risk, Risk Based Maintenance, led to the necessity of basing risk analysis on the knowledge and practical expertise of sea-going ship crews. This fact leads to the application of the expert method of technical risk evaluation [15].

## Studies on the possibilities of extension of operational time based on the risk analysis

The need to extend the time period between repairs is rationally justified not only in the case of the planned-preventive strategy (PPM) but also in most of the other strategies. The operational practice of ship power system elements enforces the necessity of such a procedure for obtaining the highest priority aims i.e. performing the transportation tasks. Then, it is indispensable for the considered object (engine, equipment) to estimate and analyse its reliability or its being prone to failures including for example probability $P_i(t)$ of a certain occurrence $A_i$. Then the main reliability models are used. For direct evaluation of probability $P_i(t)$, and also for other events – accounted for in the models using the tree methods, statistical methods based on experimental and expert methods. Statistical methods can be used only in the cases when data on considered occurrences are recorded and stored. Expert methods do not require such data. They are based on the expertise opinions of professionals on the probability of certain event occurring in a defined time period. Expert opinions can be expressed in different forms and they can be obtained using for example specially prepared surveys. Estimations will be better, the bigger the number of experts take part in the survey [15].

For the sake of this paper, a study using the expert method was carried out on the subject of the possibility of extending periods between preventive servicing, representative for energy conversion, for the elements of the ship main power system. As the object of studies elements of the RO-RO type ship, operated on the Baltic Sea, main power systems were chosen. Within the study operational procedures of Diesel engines of the main power system were considered. Nineteen chief engineer and thirty-four engineer, dealing with this engine in the period of time not shorter than 3 years, took part in the survey. They were the source of information as the respondents in a specially prepared expert survey. Shared operational reports and the data base of the system of control of the operation of the ship power plant were the additional sources [16, 17]. The survey comprised three groups of questions:

1. The first one defined the term "expert". It contained questions on education, professional experience, qualifications documented with certificates and diplomas. Its aim was to confirm the competences of the surveyed as experts. Most (79%) of the respondents had university degrees, and 55% of them had additional professional qualifications. The average professional experience amounted to 17 years, which gave the respondents the right to be considered as experts on ship power system operation.
2. The second group of questions referred to technical data concerning the ships and their power system, kind of fuel, degree of engine room automation, type of main engine kind of propeller, method, way of reporting, creating data storage etc. This group of questions aimed at identifying the ship which allowed a subsequent comparison of previous occurrences (on other ships) with events on the studied vessel regarding mechanism of the same type.
3. The third set of issues comprised questions referring to the time and ranges of servicing resulting from the accepted strategy of technical control and ship power plant operation. On the basis of service report analyses and periodical controls carried out by engine room crews, the experimental results were averaged and the possible new times of servicing were presented.

The analysis of the survey report indicated in reference to the main power engines, among others that:

1. It is possible to extend the time of operation of injectors, on average by 500 hours, – according to 75.47% of the respondents. The extension of operation time may, according to the respondents, influence the quality of the sprayed fuel and worsen the process of its combustion, maintaining the limiting acceptable values of operational parameters.
2. It is possible to extend the period of time between servicing to check for valve clearance, at the inlet and outlet and also on rotocaps – that was accepted by almost 80% of respondents.
3. Experts suggested extending the period of time between engine servicing by about 500 hours of operation, which in total gives about 125% of the time stated in the manufacturer's documentation.
4. Almost all of the experts (96% of the respondents) admitted, that it is possible to extend the time between servicing the connrod-piston system and all the other servicing connected with from the so-far 8000 hours of operation time to about 10500 hrs.

Table 1. Presents a listing of the expert study on the ship main engine

| Service type | Time between servicing according to Maintenance documentation [h] [9, 17] | Average time between servicing suggested by expert [h] |
|---|---|---|
| Fuel injector replacement | 4000 | 4500 |
| Clearance checking of inlet and exhaust valve | 2000 | 2500 |
| Rotocap checking | 2000 | 2500 |
| Combustion pressure control | every 30 days | every 30 days |
| Measurement of clearance in the grooves of piston rings | 8000 | 10500 |
| Measurement of piston rings | 8000 | 10500 |
| Measurement of ovalization of cylinder liner | 8000 | 10500 |
| Crank case inspection | every 30 days | every 30 days |
| Flow ducts of compressor rinsing | 120 | 120 |
| Flow ducts of turbine rinsing | 480 | 600 |
| Replacement of air filters in the charging system | every 10 days | as needed |
| Turbocharger oil replacement | 1500 | 1500 |
| Charging air cooler rinsing | 120 | 150 |
| Chemical analysis of engine cooling water and its treatment | every 7 days | every 3 days |

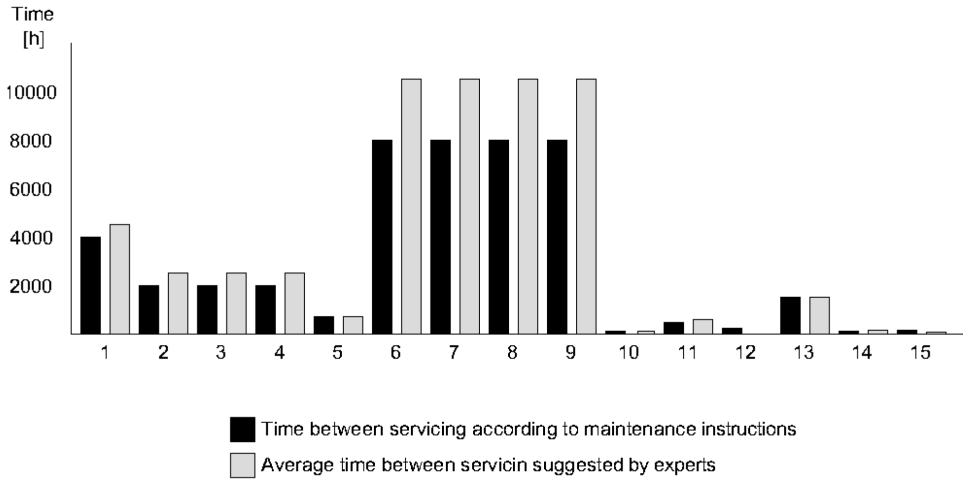


Fig. 2. The results of expert studies on a ship main power engine; 1 – injector replacement; 2 – control of clearance at the inlet valves; 3 – control of looses at the outlet valves; 4 – rotocap control; 5 – combustion pressure control; 6 – control of clearance in the grooves in piston rings; 7 – control of piston rings; 8 – control of ovalization of the cylinder; 9 – carter control; 10 – compressor flow ducts washing; 11 – turbine flow ducts washing; 12 – replacement of air filters in the charging system; 13 – replacement of oil in the turbocharger; 14 – charging air cooler washing; 15 – chemical analysis of engine cooling water and its treatment

Table 1 presents listed results obtained via the expert method, whereas figure 1 illustrates them graphically.

The experts also presented a set of preventive services where the time periods between servicing should not be extended. According to the respondents if that was done in the cases of some particular pieces of equipment, it could lead to lowering the reliability of the main power engine and increase the risk of its failure and as a result lower the ship safety.

One of such devices is a turbocharger of the main power engine, where extension of the period of oil replacement and bearings increases the probability of failure occurrence in this piece of equipment. The oil is very demanding as far as the properties are concerned, and its replacements should be performed after periods of time not exceeding those given by the manufacturer.

Washing and cleaning of inter-blades of the turbocharger of both rotor machines: the generator and the gas turbine, were qualified by the experts to the group of those that could not be extended in time. It was accepted almost univocally (by more than 98% of the experts) all the servicing connected with the control of technical condition (appropriate tension of press bolts of the engine head, correct operation of rotocaps, lubricating oil analyses) or inspections (e.g. combustion pressure measurements or inspections of the engine drip pan) confirming the current technical state should be performed according to the recommendations of the manufacturer, classification society or ship owner.

Validation of the results obtained via the expert method was carried out on a chosen ship of the RO-RO type with the 6764 DTW and contract speed of 19 knots, constructed in 1993 in a Dutch shipyard Van der Giessen-de Noord. The ship operating on the Baltic Sea under the supervision of Germanischer Lloyd underwent a major overhaul connected with class servicing. Operation of the main power system of this ship confirmed the possibility of implementing the suggestions on the extension of the between-service period derived from the expert method study.

## Conclusions

In the so-far applied strategies of maintenance of elements of sea-going ship power systems risk analysis did not support the decision making process. It was due to the actual level of technology in the monitoring systems and storage of data from the operational process.

However, the contemporary operation of ship power systems is becoming a more accurately monitored process. It is possible thanks to the contemporary systems of control, monitoring, recording, data storage, faster miniaturized computers and universal open software. The stored data become a precious source of information and their identification and analysis make rationalization of the operational process possible [1, 2, 10]. Efficiency of ship operation can be understood in a different way depending on the field and conditions in which it is estimated. In operational systems it is meeting the requirements in different context: reliability, economy, quality [1, 2, 7]. On the basis of the carried out measurements of operational properties of machines and equipment installed on ships, organizational and economic conditions significant groups of information for realization of risk analysis can be determined. Out of the presented in this paper methods of risk evaluation of ship power system elements, the expert method was applied to study the possibilities to extend operational time. A synthesis of the obtained results shows the agreement of experts in respect to the possibility of extending the period between servicing of particular elements of the main power engine, such as: connrod-piston system, valve clearance, rotocaps, injectors which will not result in deterioration of technical condition of the engine and lowering the economic efficiency of its operation. The experts did not approve of the extension time periods between preventive servicing of turbochargers.

Having access to advanced monitoring systems and operational process recordings it will be possible to increase the estimated reliability of ship power system elements using Event Tree (ET) or the Failure Tree Analysis (FTA). Then the optimization of time periods between preventive servicing may become an element of maintenance strategy based on an analysis of the technical condition CBM (Condition Based Maintenance) where risk analysis is applied

## References


1. ADAMKIEWICZ A., BURNOS A.: Influence of maintenance strategies on the reliability of gas turbines in power systems of floating production, storage and offloading units (FPSO). 28th International Scientific Conference DIAGO® 2009. Technical diagnostics of machines and Manufacturing equipment. Vysoká Škola Báňská – Technická Univerzita Ostrava. Asociace Technických Diagnostiků České Republiky, o.s., CD, Ostrava, Rožnov pod Radhoštěm, 27–28. January 2009.
2. ADAMKIEWICZ A., BURNOS A.: Utrzymanie turbinowych silników spalinowych na jednostkach typu FPSO. Zeszyty Naukowe Akademii Marynarki Wojennej 178 A, 2009, 9–20.
3. PN-ICE 60 300-3-9:1999: Analiza ryzyka w obiektach technicznych.
4. RAMĘDA H.: Zarządzanie bezpieczeństwem statku. Zachodniopomorski Uniwersytet Technologiczny, Wydział Techniki Morskiej, Szczecin 2009.
5. Raport techniczny Nr RT – 95/T – 01 Niezawodność okrętowych siłowni spalinowych – sformułowanie problemu i propozycja jego rozwiązania. Centrum Techniki Okrętowej, Gdańsk 1995.
6. SZOPA T.: Niezawodność i bezpieczeństwo. Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2009.
7. TRZESZCZYŃSKI J. i inni: Analiza ryzyka jako wsparcie utrzymania stanu technicznego urządzeń cieplno-mechanicznych elektrowni. Energetyka, czerwiec 2012, www.energetyka.eu, 23–29.
8. MODARRES M. i inni: Reliability engineering and risk analysis. Marcel Dekker. New York 1999.
9. ŻÓŁTOWSKI B.: Diagnostyka maszyn. Wydawnictwo Uczelniane Akademii-Techniczno-Rolniczej w Bydgoszczy, Bydgoszcz 1996.
10. GIRLTER J.: Diagnostyka jako warunek sterowania eksploatacją okrętowych silników spalinowych. Wyższa Szkoła Morska, Szczecin 1997.
11. LEWITOWICZ J.: Podstawy eksploatacji statków powietrznych – Systemy eksploatacji statków powietrznych. Wydawnictwo Instytutu Technicznego Wojsk Lotniczych, Warszawa 2006.
12. MOBLEY R. i inni: Maintenance Engineering Handbook. Seventh Edition, The McGraw-Hill Companies, 2008.
13. RUSIN A.: Awaryjność, niezawodność i ryzyko techniczne w energetyce cieplnej. Wydawnictwo Politechniki Śląskiej, Gliwice 2008.
14. New Sulzer Diesel Operation Manual – Diesel Engines ZAL40S.
15. CIEŚLAK M.: Prognozowanie gospodarcze: metody i zastosowania. Państwowe Wydawnictwo Naukowe PWN, Warszawa 2001.
16. Maintenance Reminder System. Program monitorujący eksploatację jednostki badanej. Program autorski EURO-AFRICA Shipping Lines Ltd.
17. NAZARKO P.: Ocena stanu konstrukcji. Oficyna Wydawnicza Politechniki Rzeszowskiej. Rzeszów 2009.


### Other


18. http://www.mandieselturbo.com, dostęp z dnia 12.02.2013.