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SELECTION OF SHIP MAINTENANCE STRATEGY APPLYING THE COMPUTER

RAČUNARSKI ODABIR STRATEGIJE ODRŽAVANJA BRODOVA

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Review
Pregledni članak

Summary

The traditional strategy to the maintenance of shipboard equipment and system, except for its aim, has gone through radical changes. The greatest influence upon the changes has been that of anticipating the failures, applying the computer, and possibility of obtaining information on the condition and on the performances of the equipment. The rapid development of electronics and computer applications offers an increasing number of new possibilities. Computer application in the selection maintenance strategy based on risk analysis by taking into consideration the risk index and the frequency index is a contribution to the problem of ship maintenance.

Sažetak

Tradicionalna strategija održavanja brodske opreme i sustava, prolazi kroz mnoge značajne promjene, zadržavajući svoj osnovni cilj. Najveći utjecaj na promjene je predviđanje pogrešaka, upotreba računala i mogućnost dobivanja informacija o uvjetu i karakteristikama opreme. Brzi razvitak elektronskih i računarskih aplikacija nudi sve veći broj mogućnosti. Primjena računala u odabiru strategije održavanja utemeljenoj na analizi rizika, uzimajući u obzir indeks rizika i indeks učestalosti, je doprinos rješavanju problema održavanja broda.

1. Introduction
Uvod

The maintenance of a system includes all the activities necessary to retain the system in, or to return it to its operative condition. The necessity of maintaining the shipboard system and equipment results from the necessity to increase the availability of the ship for its function to transport cargoes and passengers. Here the degree of safety prescribed by legal regulations and the increasingly stricter ecological standards of environmental protection has to be satisfied. The strategy and manner of maintenance, with the diversities resulting from the organizational and personnel equipment of the shipping companies and other participants, are determined by economic, technical and legal imperatives.

With regard that the maintenance as a component of the ship's exploitation is a very old discipline, valorization of its achievements, but also constant reexamination and improvement of its methods adapting them to the development and possibilities of new, especially information technologies, is a necessity.

The scientific bases of this discipline, founded on statistical methods and the theory of reliability for the determination of time between the appearance of failures and the necessary intervals of time between two successive maintenance operations, have been established at a relatively early period.

As for a ship in exploitation its availability is decisive, constant efforts are being made to shorten the time necessary to remove the failures, or the time of preventive operations, through the increased reliability and redundancy of the equipment and system.

The development of modern computers has in a very short time found application on shipboard through the organization of preventive maintenance and supply of spare parts. The failures of preventive maintenance disregarding the valorization of the "Quality" of equipment, have initiated the constant need for recognizing the condition of the equipment.

A contribution to the recognition of the condition of the equipment was the development of electronics. Microprocessors are becoming a component part of the equipment, and with the implementation of artificial intelligence intelligent equipment are realized. By connecting microprocessors with superimposed compu-

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ters and the realization of a network of computers, the possibility of detecting a failure in time is realized, as well as the possibility of controlling and diagnosing the equipment from any of the computer in the network of computers.

By making use of the mentioned possibilities, the ship maintenance will, step by step, move in that development direction, and in this form become indispensable for the future generations of ships.

2. Maintenance strategy
Strategija održavanja

In order to make maintenance more efficient and economical, the maintenance operations are planned in advance, and without a good plan it is not possible to carry out a good maintenance organization. As the proportion of accident failures is very large, maintenance is planned in the basis of same statistical methods and empirical data used also in the theory of reliability. Through statistical methods it is possible with a certain probability to anticipate failures, meaning that also unplanned failures will appear, i. e. that unplanned maintenance will be necessary. Unplanned maintenance is the maintenance carried out if the failure has to be eliminated at once (affects the safety of ship, or causes a hold-up so that the ship is not a position to carry out its function normally). On board unplanned maintenance is most unwelcome.

The maintenance strategy classifies maintenance actions according to their contents, and moment of execution. If the maintenance action is meant to retain the operational conditions (failure didn't occur yet) it is preventive. On the other hand, if the maintenance action is requested to restore a system back to its operational state, it is corrective.

When defining the maintenance strategy, the ship operator does not strictly observe either of these two, but uses a combination of them. By the strict application of corrective maintenance the frequency of failures is increased, and hence also the costs in consequences due to greater number of ship's stoppages. Strict observance of the preventive maintenance would be in compliance with observance of the principle of maximum reliability, but also with the maximum maintenance costs. Corrective maintenance in this context would refer only to the cases of failures the consequence of which would be avoided through the reserve of shipboard systems.

An important factor when defining the strategy to the maintenance is the personnel that carry it out. The ship has a crew that can carry out the maintenance actions also during the ship's exploitation. With sufficient supplies in the systems and good provision with spare parts it is possible to eliminate the failures without any hold-up and stoppage of operations. It can be said that the reliability of the shipboard systems is reliability with interventions. This determines and brings into equilibrium the various strategies to maintenance. The major maintenance strategies are pictured in Figure 1.

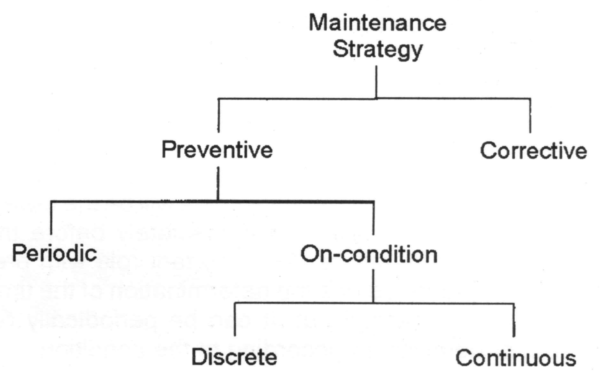

Figure 1. Maintenance strategies
Slika 1. Strategije održavanja

2.1 Corrective strategies to maintenance
Korektivne strategije pri održavanju

The corrective strategy to maintenance is the strategy where waiting for the failure to occur is necessary in order to start the maintenance actions. This means that no preventive action before failure is performed.

Corrective maintenance is suitable for systems which have no spare parts, or with which failures take place by chance (accidental failures). With accidental failures the cause in most cases cannot be established with certainly. It can be presumed that they have been caused by unexpected stresses (e.g. mechanical, termical, electrical,...) to which parts of the system are explored, and which are not foreseen in the design. Hence the period of time in which any particular part of the system ought to be replaced cannot be determined in advance. The replacement of a particular part will not at the same time eliminate the cause of the failure either. This group embraces electrical units and particular electrical devices.

When, however, corrective maintenance is applied to failures caused by wear, and tear (temporal failure), this results in an increased number of failures, and thereby also in higher maintenance costs. Temporal failures occur as a result of wear and tear, corrosion, dirt, erosion and the like.

Advantages of corrective maintenance strategy:
- The system or part of system is used in the entirety.
- No maintenance costs until occurrence of failure.

Disadvantages of corrective maintenance strategy:
- Greater number of stoppages because there is not preventive maintenance actions.
- Major failures may occur which the ship's crew cannot eliminate on their own.
- Increased time of ship's hold-up.

Corrective maintenance strategy is acceptable there is redundancy in components, devices or systems. The characteristic shipborne equipment with which this kind of maintenance is applied is an electronic device.

2.2 Preventive strategies to maintenance
Preventivne strategija pri održavanju

The preventive strategy to maintenance is intended to prevent the occurrence of failure, which is achieved by replacing the system or part of the system before the failure occurs. Maintenance costs will be the lowest if part of system is replaced immediately before the occurrence of the failure. An important role with preventive maintenance has the determination of the time when it will be carried out. It can be periodically repeated, or determined according to the condition.

In the case of periodical maintenance actions are performed, the interval between two maintenance actions can be calendar time based, or exposure based, depending on nature of components operation. If the operation is continuous, time should be used, but if operation is intermittent, other maintenance relevant units (e.g. number of process cycles) may be more suitable. Condition of the component, which is maintenance, after maintenance execution, is assumed to be as good as new. Periodic preventive strategy is effective and efficient only in case failure predictability is high.

If the condition of the system is checked up, the results of check-up determine the time of maintenance.

Preventive maintenance strategy consists of two steps. The first step is condition assessment, which includes inspecting the component for impending failures. The inspection should detect deterioration called potential failure that could lead to a real functional failure. If condition verification is done at discrete moments in time this is called discrete on-condition preventive maintenance. When condition verification is continuous it is called continuous on-condition preventive maintenance. Discrete inspection is usually carried out manually by means of a number of instruments, while for continued inspection a system for continued monitoring of the condition has to be built in. The second step includes maintenance action. This happens if component's condition, as assessed during step one, falls below the condition according potential failure. This strategy is effective only when potential failure can be detected by either monitoring operational parameters, or by dedicated deterioration monitoring equipment, or by inspections.

By preventive maintenance strategy the number of failures can be reduced, but they cannot be entirely prevented.

Advantages of preventive maintenance strategy:
- A great number of systems will have a reduced number of failures in relation to corrective maintenance.
- Reduced number of hold-up due to failure.
- More uniform burdening of the crew with maintenance actions.
- Maintenance plans can be coordinated to the exploitation actions on the ship.

Disadvantages of preventive maintenance strategy:
- Possibility of "over" maintenance, resulting in unnecessary increase in maintenance costs.
- Occurrence of a number of failures proved by upsetting the prearranged work characteristics of the system.

For the greater part of shipborne machinery systems preventive maintenance strategy yields better results than the corrective one. Maintenance actions can be planned, so that also the crew is more evenly burdened with maintenance actions. The ship's business is more economical as the number of failure is reduced, as well as the number of ship's stoppages and averages.

Today the number of built-in shipborne diagnostic devices and systems is on the increase, so that the periodical preventive maintenance is more and more being replaced by preventive maintenance according to the condition.

3. Determination of priority maintenance actions
Utvrđivanje prioritetnih radnji pri održavanju

The ship of today consists of great number of different kinds of equipment, which have to be obtained. The costs of maintenance present a considerable item of business operations, and so the shipowners are striving to reduce them.

The aims of the ship's maintenance are reduction of the costs and the extension of the life span, at the same time satisfying the requirements of safety. The satisfaction of the aims of ship's maintenance more and more shipowners sees in computerized maintenance. Besides traditional keeping of spare parts and planning of preventive maintenance, the possibility of computer applications is also in the selection of the maintenance strategy. With the appearance of the failure, and on the basis of the information on failures stored in computer (such as the risk of failure, incidence of its occurrence), the program of determination the strategy to the maintenance is set in motion, as a variety of strategies yield as their result a different failure incident, consumption of spare parts, hold-up the ship, or different total maintenance costs.

3.1 Risk analysis
Analiza rizika

Risk is the assessment of the occurrence of loss or damage. Risk is also connected with the uncertainty of the occurrence of the unwelcome event (condition, state,...), as well as the resulting consequences. Risk can be defined as expected loss associated with the occurrence of unwanted event.

The risk analysis describes the influence of the failure upon the failure devices, as well as upon the environment (system in which the device is contained, ship, ship's environment). This influence is in the first place manifested in reduced safety, deteriorated functionality, and ecological influence. In the analysis the failure has to be classified and quantified according to

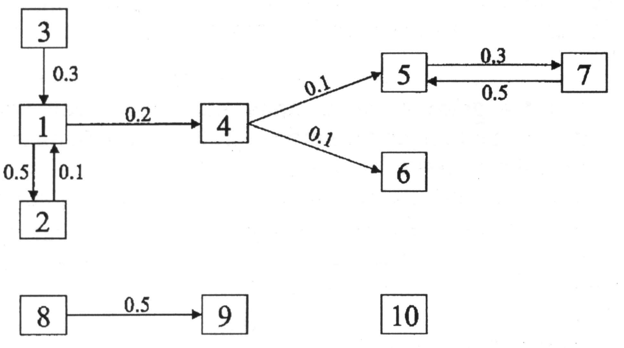

Figure 2. Graph of failure spread
Slika 2. Graf širenja pogreške

its consequences. The critical character of the consequences is represented with the *risk index* (i_r).

When determining the risk index the spread of the failure has also to be considered, i.e. the failure on the component can also cause the occurrence of failure on the other components. The spread of the failure can be shown in graph, as represented in Figure 2.

The graph consists of components and connections between them. The connections show direction of the failure spread. On each connection between the components is the numerical sign representing the probability that the failure on one component will cause failure on the other one.

For example with the relay the heating on the switches is transferred to the spring and weakens the pressure of the switches. The opposite is also true; the weakening of the pressure of the spring increases the electric resistance, which will result in the heating of the switches.

If the failure spread on the particular system is known, when determining the risk index, the greater index has to be ascribed to the, in appearance, small failure, if there is a great possibility that it is going to cause another failure with much more serious consequences.

When determining the risk index attention is to be given to the consequences of the failure and their influence upon the safety and functionality of the ship, environment, and on the frequency of the failures. The seriousness of the consequences of the failure and their influence are quantified by the *danger index* (i_d), while the frequency of the failure occurrence on the component maintained is shown by the *frequency index* (i_f). It depends on the ship and on its built in equipment.

Frequency index can be expressed as:

$$i_f = f(r \cdot \lambda \cdot m)$$

where:

r - redundancy of the equipment,

λ-index of failure,

m - characteristic of the material.

The index of failure presents the reciprocal value of the average time between the failure *(MTBF)* and it is the indicator of reliability.

$$\lambda = \frac{1}{MTBF}$$

The failure analysis adds to each failure the danger index. The number of possible danger index indicates varies.

$$i_d = f(p \cdot s \cdot e \cdot c)$$

where:

p - influence of failure upon functionality,

s - influence of failure upon safety,

e - influence of failure upon ecology (pollution of air/sea),

c - influence of failure upon the price of repair.

The index of danger can be presented as a number in value from 0 to 1, where:

- danger index 0 - is the smallest danger from the consequence of the failure (the failure does not affect the safety, functionality and ecology),
- danger index 1 - is the greatest danger from the consequence of the failure (possibility of loss of ship, catastrophic consequence for environment, and the like).

An example of possible determination of danger index is shown in Table 1.

The risk index is the product of multiplication of danger index and the frequency index.

$$i_r = i_d \cdot i_f$$

The risk index ought to present the seriousness (importance) of the danger that the consequences of the failure present. The definition of the risk for particular failures depends on the legal regulations, as well as on the policy of the ship operator. The operator determines which consequences of the failure are

Table 1. Danger index
Tablica 1. Indeks opasnosti

Index of danger	*Degree of danger*	*safety*	*functionality*
1	catastrophic	loss of ship	
1 - 0,1	critical	critical damage, great damage	without functionality (duration in days)
0,1 - 0,01	acceptable	minor damage	without functionality (duration in hours)
0,01 - 0,001	marginal	possible damage	decrease performances
0,001 - 0,0000	desirable	without damages	full functionality

acceptable, and which still call for the elimination of the failure. The risk index has an important role in the determination of maintenance plan in case of failure (selection maintenance strategy, methods and operations).

According to the consequence of the failure, the components are divided into those, which are significant, and those, which are not significant. The significant components are those which the occurrence of failure has significant failure effects upon the functionality of the ship, safety, ecology, or price of the repairs. The rest of the components from the viewpoint of maintenance, can be classed as non-significant. For them preventive maintenance does not pay, it is cheaper to carry out the repairs when the failure has happened.

The classification of the components is done on the basis of questions such as:

- Do the laws, or the regulations of classification societies require maintenance?
- Is the consequence of the failure caused by lack of maintenance a make possible of hold-up the ship?
- Is the lack of maintenance the cause of an unacceptable fall of the performances?
- Does the failure caused by the lack of maintenance results in the high costs of its elimination? (E.g. high cost of spare parts, consumption of material, of time etc.).
- Does the failure caused by the lack of maintenance results in a considerable reduction of safety?
- Can the failure cause ecological consequence?

By asking questions in connection with the influence of the consequence of the failure upon safety, functionality, ecology, or price of repairs, the component is determined as significant or non-significant. If the answer to any questions is the affirmative, the component should be classed among the significant components.

4. Selection of strategy to maintenance
Odabir strategije pri održavanju

For each component part the strategy to its maintenance has to be determined, which may be either corrective or preventive. If by maintenance the component ought to remain functional (the failure has not occurred), the strategy to the maintenance is preventive. The corrective strategy to the maintenance is imperative when the maintenance has to be done to return the component into its functional state.

With the components of non-significant the strategy is corrective, because if they are damaged, their functional character, safety, ecology or price of maintenance are not affected. Hence with these components it is less expensive to effect corrective maintenance after the failure has occurred, than to perform preventive maintenance.

With significant components the strategy to maintenance is determined in accordance with the consequence of the failure. The selection of the maintenance strategy with these components is done on the basis of the risk index. The risk index from the viewpoint of maintenance strategy can be divided into three groups:

1.small - in this case the risk index together with the selected maintenance strategy has been well selected; small danger for safety, ecology, functionality, and price of repairs.

2.acceptable - considerable influence upon safety, ecology, functionality or price of repairs; it should be reconsidered whether also some other strategy to maintenance can be applied.

3.critical - great danger for safety and/or functionality of ship; efforts should be made to reduce it within the acceptable limits by means of number of modifications (e.g. by means of redundancy, modification or replacement with new part made from more resistant material).

In the logical diagram on Figure 3., an algorithm of maintenance strategy selection for significant components is presented on the basis of the risk index. This algorithm is started on computer in case of failure, or in case of an observed symptom of failure. The failure presents the moment when the system is no longer in a position to perform its function in a satisfactory way. The moment of the onset of the failure is preceded by the time of declining performances of the system. The symptom of failure is the indicator that the system is being failure, or that its performances are declining. The failure or the symptom of failure can be detected in a number of ways. If detected visually or through instruments, the information about the failure is entered in the maintenance computer by way of the console. In case that the device has an implemented microprocessor system of monitoring its performances, and if the shipboard computer network has been implemented, then the information about the occurrence of the failure can be directly forwarded from the device on which the failure has occurred, to the maintenance computer.

The first step in selecting the strategy is the checking of the seriousness of the index risk, which includes the selection of the corrective maintenance. In other words, the question arises whether the failure component can work. If in this point the corrective strategy to the maintenance has been selected, any further checking is not necessary. Otherwise, for the acceptable risk index corrective maintenance is added to the list of strategies and further checking is continued, so that the list might be expanded by preventive strategies to the maintenance. For the observed symptom of failure corrective strategy means that it is possible to wait till the occurrence of failure in order to start maintenance action.

With critical risk index indices maintenance actions have to be undertaken. If the failure has already occurred, this means to undertake corrective maintenance. In order to prevent the recurrence of the failure, modification on the component ought to be considered, or the selection of a different strategy (e.g. implement on this component a device for monitoring the condition). Attempts should be made to prevent the occurrence of the failure for the symptom of the failure observed, or to perform preventive maintenance. If it is in some way possible to determinate the moment of the appearance of the failure, a list of possible preven-

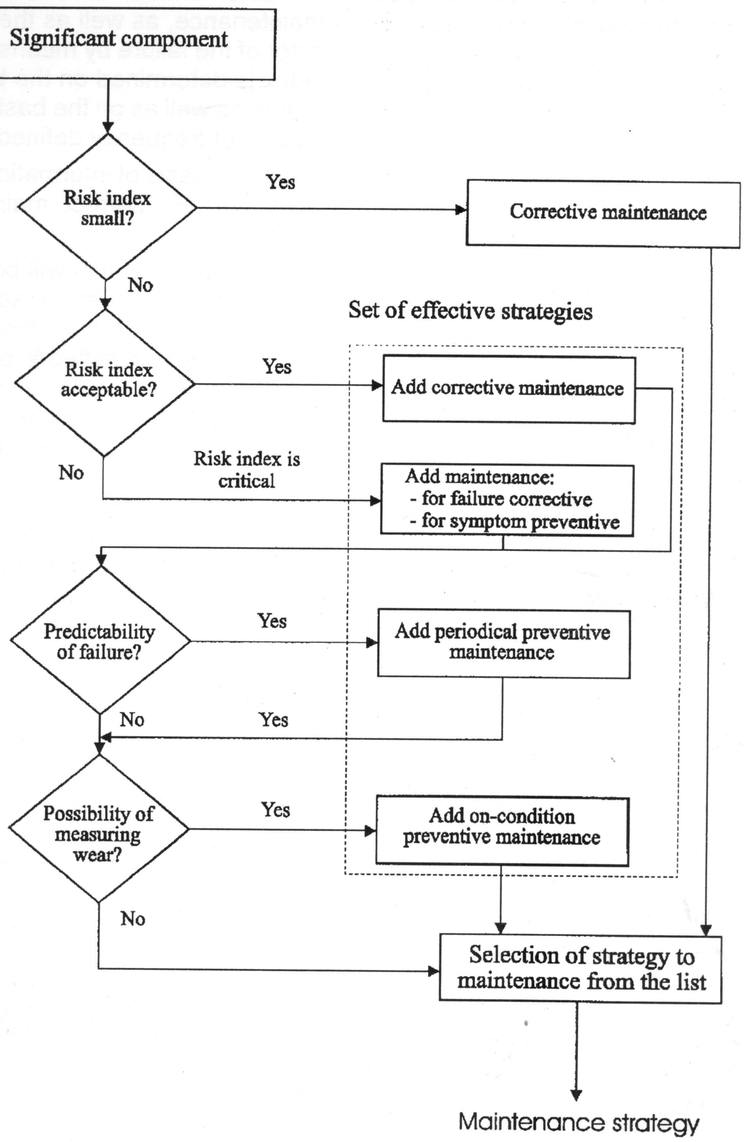

Figure 3. Maintenance strategy selection
Slika 3. Odabir strategije održavanja

tive strategies is formed. The possibility of anticipating the failure is checked, or whether it is possible to measure the wear of the component.

Predictability shows whether the incidence of the occurrence of the failure is on the increase, on the decrease, or whether it is constant (it is shown by means of failure index and the mean time between the occurrence of the failure). In case of the increasing incidence of the failure only the predictability is satisfactory, and the preventive periodical maintenance will be added to the list of the possible strategies to the maintenance.

If it is possible to monitor or to measure the wear of the component, the maintenance according to the condition is added to the list.

The makers of the major shipboard systems and equipment supply their recommendations on the planned maintenance actions, as a rule determined by the hours of work of the main motor, or have to be done after a certain period of time has elapsed. It can be said that for the components built in these systems it is possible to anticipate when the maintenance is to be performed. The periodical preventive strategy to the maintenance is therefore added to the list for these components.

The interval of maintenance suggested by the makers are a recommendation and can be modified because of specific work conditions, quality of the fuel used, oils, and other factors influencing the condition of the component. As distinguished from these fixed terms by means of applying predictability, based on statistical methods of dealing with previous failure, will be obtained also the time periods of maintenance. This preventive strategy will also be added to the list of possible strategies. Later on, while selecting the maintenance strategies from the list, depending on the ship operator's maintenance policy, the decision is made on the selection of one of the possible strategies.

From the above-mentioned it can be seen that for one failure symptom, or for one failure occurrence, a number of possible strategies can be taken into consideration. In case of failure, it will depend on the risk index whether to start the corrective maintenance action at once or if is possible to wait with this procedure. With the failure symptom a list of possible maintenance strategies has be created. From the list most favorable strategy is selected, taking into consideration:

- the possibility of application (availability of people, equipment, spare parts),
- the price of the maintenance operation,
- the ship operator's policy.

After the selected maintenance strategy the next step is definition of maintenance action. The maintenance action contains a detailed description of all work to be done, as well as the resources required to do the work (people, tools, material, time).

the determination of the components significant for maintenance, as well as the definition of critical character of the failure by means of the risk index. The risk index is determined on the basis of the failure spread graph, as well as on the basis of indices of danger and indices of frequency defined for that failure.

On the basis of information deposited on the critical character the correct maintenance strategy is selected.

The given solution will become fully prominent if it is implemented in entire solution of keeping maintenance business through the computer, and if the shipboard computer network permitting the inclusion of maintenance computer in the integrated information system of the ship has been realized. This will make the failure symptom detected on any part of equipment, the process control console of which is part of the computer network, available for the maintenance computer, where the maintenance strategy selection process is automatically set in motion, and then also the defining of maintenance action plan.

5. Conclusion
Zaključak

The maintenance of shipboard systems and equipment, expressed as an economic category through the maintenance and technical costs through the manner of maintenance, has a considerable influence upon the shipowner's business efficacy. More frequent preventive maintenance actions will increase the availability and extend the service life of the ship, but also increase the maintenance costs. The corrective strategy to maintenance will cause a larger number of the hold-ups, and therewith also greater indirect maintenance costs (the ship does not perform its intended function). It is necessary to implement such solutions which would satisfy all safety requirements, and at the same time active optimum maintenance, which means that attempts are being made to select the correct strategy to maintenance with which the total costs will be the lowest. For these reasons on particular systems a combination of both strategies is used, where for particular components the preventive strategy is used and for other the corrective strategy to maintenance.

In order to apply computers in the selection of maintenance strategy with the occurrence of failure, a risk analysis has to be done. The risk analysis implies

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References
Literatura

[1] Kelly A., *Maintenance Planning and Control*, Butterworths, London, 1984.

[2]Lovrić J., *Osnove brodske terotehnologije*, Sveučilište u Splitu, Pomorski fakultet Dubrovnik, Dubrovnik, 1989.

[3]Nieuwhof G. W. E., *Risk: A Probabilistic Concept*, Reliability Engineeering vol. 10, pp. 183-188, Elsevier Applied Science Publishers, London 1985.

[4]Rysst J., Hoen H., Melhus O., *RCM-designed maintenance program for ship main engines,* CIMAC 95, pp. 117-125, The Institute of Marine Engineers, 1996.

[5]Shields S., Sparshott K. J., Cameron E. A., *Ship Maintenance: a quantitative approach*, Marine Media Management Ltd, London, 1975.

[6]Šegulja I., Tomas V., *Improvement of ship maintenance by applying the RCM method*, Proceedings of ICTS´97, pp 189-195, Fakulteta za pomorstvo i promet in Slovensko društvo za znanost v prometu, Portorož, 1997.

[7]Tudor M., *Računalni model održavanja broda*, Magistarski rad, Pomorski fakultet u Rijeci, Rijeka, 1997.

[8]Tudor M., Martinović D., *Primjena računala u održavanju broda*, Zbornik radova Pomorskog fakulteta, pp. 49-59, Pomorski fakultet u Rijeci, Rijeka, 1997.

[9]Vučinić B., *MA - CAD, Maintenance Concept Adjustment and Design*, Delf University of Technology, Faculty of Mechanical Engineering and Marine Technology, Delf, 1994.