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MAINTENANCE STRATEGIES SELECTION MODELING FOR NAVAL SYSTEMS

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ABSTRACT

This paper presents a qualitative Maintenance Strategies Selection Model for Naval Systems based on basic RCM (Reliability Centered Maintenance) principles taking into consideration particularities of a warship and maintenance in former Serbian and Montenegro Navy. Due to the lack of statistic data on maintenance and failures, we used expert knowledge of naval systems operators and maintainers. Creation of a specific model was also necessary due to the lack of engineering resources and time for all the required analysis of complex technical items. Additional problem was a need to extend the ship's life cycle. With a purpose to make rational use of the resources for the analysis of all complex systems of the ship, three different approaches have been modeled depending on whether some experience in the previous maintenance exists and on the amount of their maintenance costs. Pilot-analyses conducted against this model showed its applicability and potential to reduce maintenance costs of ship's systems.

INTRODUCTION

A constant need for budget reduction planned for maintenance and prevention of technological lagging behind the neighboring countries conditions advancement and improvement of maintenance in former Serbian and Montenegro Navy. On the basis of previous research results, it can be said that a maintenance strategy is the key factor influencing effectiveness and efficiency of a maintenance system (Stanojevic et al, 2000; Stanojevic et al, 2004) thus its (strategy) selection represents a basic

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problem, which should be solved in the maintenance system in its phase of creation, as well as in the phases of its later improvement. Strategy determines which maintenance activities will be performed, at what frequency i.e. when and in what scope, for the purpose of achieving maintenance system objectives. The strategy could be defined for parts of a technical device, individual technical devices and maintenance system on the whole. This created a request for making maintenance strategies auditing model for naval systems which are already in use for the purpose of reducing maintenance costs and preserving functional safety and combat readiness as a step in advancing the existing maintenance systems of naval systems (Aleksic, 2006).

Prior to modeling, particularities of the warship first had to be taken into consideration. Maintenance of warships is the most expensive in comparison to the maintenance costs of other military equipment. Former Serbian and Montenegro Navy has a developed preventive maintenance with characteristic overhauls that require a specific infrastructure and labor force specialties. Maritime strict regulations related to the safety of navigation, crew, cargo and natural surroundings also adhere to Navy. Regarding the number and complexity of implemented systems, a warship has the most complex equipment and devices. Every complex system on a warship has operators. Most of critical systems on a warship are redundant.

Distinctive features of maintenance in former Serbian and Montenegro Navy, which are relevant for the new model, are also identified. The Serbian and Montenegro Navy has very experienced personnel. The experience is large, both of the personnel that operates or has operated with the systems and skilled/scientific personnel in institutions envisaged for the development of maintenance systems or maintenance of systems themselves. Ships have been in use for a long time and what is expected is extension of their life cycle. Furthermore, there is a problem of deciding on and managing failures in conditions that lack adequate statistic data, so the basic attention has been paid to qualitative methodologies. Ships belonging to our former Serbian and Montenegro Navy have relatively shorter routine missions, due to the small territorial sea.

The following maintenance strategies have been selected: corrective maintenance, preventive maintenance, detective maintenance, predictive or condition based maintenance and proactive maintenance. Detective maintenance is a new strategy proposed for the purpose of adjusting to modern world trends. The content of this strategy has not got anything new in particular, except that it stresses the importance of managing hidden failures characteristic for protective systems. There is no evidence of a hidden failure occurring, because it in itself does not produce any consequences. Proactive maintenance is presented as a group of special techniques and methods for the improvement of maintenance systems in use (Deshpande and Modak, 2002).

RCM - Reliability Centered Maintenance has been selected as a model for the modeling methodology that has a holistic approach to the systems and treats all maintenance strategies equally in the sense that there is a tendency of creating their optimum mixture. When choosing a maintenance strategy, *RCM* predominantly starts from consequences of failure (Moubray, 1997). The basic idea of *RCM* methodology is presented in literature, but procedures are not appropriate for conditions and restrictions of the investigated systems in the form they were applied (Stanley and Heap, 1979; “NAVAIR 00-25-403, Guidelines for the Naval Aviation Reliability–centered Maintenance Process”, 2001; “Reliability Centered Maintenance Guide for Facilities and Collateral Equipment”, 2001; Conachey, 2005). Methodologies based on *RCM* are not too complicated, but are demanding regarding the engagement of the best specialists for a longer period of time, which is the biggest problem that has to be taken into consideration (“Study of existing RCM approaches used in different industries”, 2000). This is why an original model has been developed, which takes into account the stated particularities of the system and methodology limitations.

BASIC CHARACTERISTICS OF THE NEW MODEL

Selection of RCM methodology for the improvement of the Naval ship maintenance is too demanding for our present engineering capacities. Speaking objectively, the largest problem in the application of RCM methodology is consumption of enormous effort and time for the analysis. For many who have tried it, RCM stands for “Resource Consuming Monster” (Dunn. S). In order to save time and labor force resources, which have to be engaged during the analysis of maintenance strategy selection, we suggest some improvements in the methodology. This paper presents a more balanced approach where different ship’s systems have been dealt with in a different manner. For this reason, three branches of methodology have been modeled and they differ in depth of analysis, Figure 1.

The first step that needs to be made is breakdown the ship into the hardware sub-systems (systems). The next step is elimination of elements that will not be analyzed. Data needed for the analysis may be classified into three groups: construction data, operating data and reliability data.

The first separation is made against the principle of existence of defined maintenance programm in the previous period. If Naval Repair Facility is capable of performing system overhaul, which is the most complicated maintenance activity, it is considered that there is defined maintenance of the sub-system in the life cycle. It was decided that different approaches are used depending on the existence of significant maintenance experience.

In case there has been no defined maintenance programm in the previous period – the only source that could be relied on is operators’ experience. Thus, systems that do not have maintenance programm defined by overhaul documentation fall into the first branch and they are marked with number I on the Figure 1. The beginning

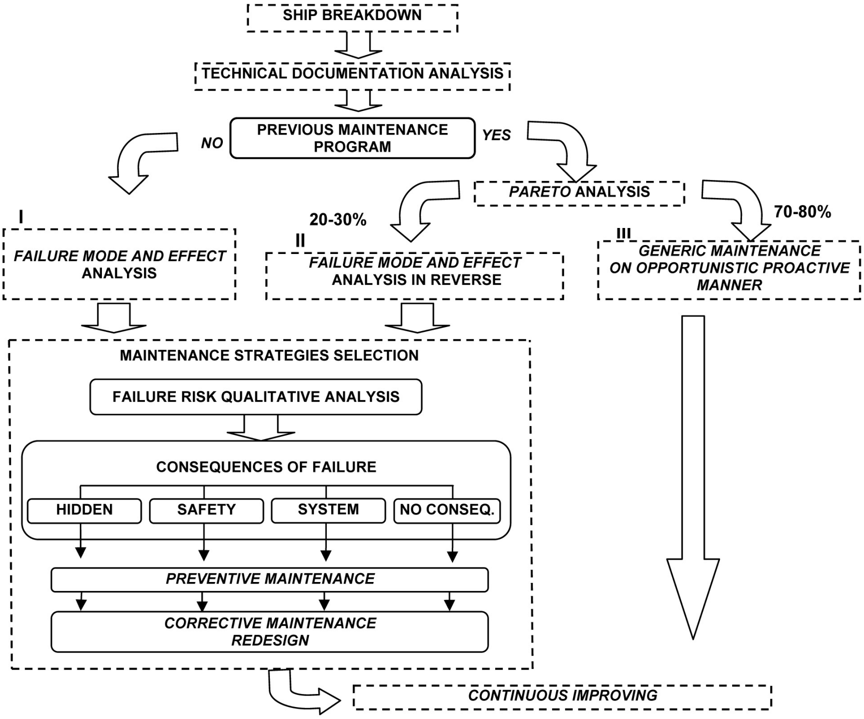

Figure 1. Model of Maintenance Strategy Selection

involves a very detailed analysis, which starts practically from null. This procedure enables systematic screening of systems. The important fact is that there are not many systems of such kind, so the problem of analysis duration is for the most part solved.

The second procedure is applied on the remaining group of systems for which previously defined maintenance programm exists. The beginning involves already performed and tested maintenance programm thus the analysis, apart from operator's experience, can rely on maintainers experience and technical documentation on systems maintenance. There have been some indications that there is a big problem of engaging human and material resources and time for analysis performance. To prevent the amount of the sub-systems being analyzed into more details, another selection has been made according to economic criteria – Pareto analysis of maintenance costs. In short, every element has a known or expected maintenance costs. Accordingly, 20-30% of the systems are classified into branch II whose maintenance costs are 70-80% of the total ship maintenance costs. The third branch (III) includes 70-80% of the systems whose maintenance costs make 20-30% of the total price paid for ship maintenance. The second branch is also systematic, but has a considerably smaller scope because it takes previous maintenance programm as its basis. The third is the simplest analysis that actually represents a systematization of familiar procedures. By this, greater attention will be directed to the systems whose analysis may bring the largest profit and relatively not so detailed analysis will be performed on most of the systems that have lower maintenance costs.

BRANCH I

Branch I represents a maintenance strategy selection methodology for complex ship systems that have not had defined maintenance programm. It has two basic stages: modified *FMEA* and maintenance strategies selection against the complete *FMEA* methodology.

Modified *FMEA* makes assumptions how to compensate the lack of statistic data on failures that are necessary for quanitative methodologies. This is achieved by a systematic analysis of failures that is directed on the function and system itself; hence it is performed from top to bottom. Other hardware parts of minor importance, which are not connected to the main function of the system, may fail without consequences and its repair should be done when most convenient. A special feature of the modified *FMEA* method is qualitative determining of a risk matrix consisting of failures consequences and failures frequency. Consequences and frequency of failures are determined on the basis of familiarity with the system that in this manner compensates the lack of statistic information on failures. Analysts perform functional systems failures modeling which makes the subject of analysis on the basis of technical documentation, expert knowledge of the system and engineer judgment. Modern views on analytic proactive techniques show that there is a need for the introduction of team techniques and methods for the purpose of increasing quality of subjective judgment (Durán, 2005; Tsang, 2002). An analytic team requires: operators, maintainers, members of command structure and, if possible, constructors.

The second stage in branch I is the selection of maintenance strategy. An original algorithm has been developed and it adheres to the basic principles of *RCM* methodology and is also adjusted to our conditions and limitations. The entire model is based on the principle of separation of the relevant from irrelevant (classical elimination method). The algorithm refers to all types of failures from the *FMEA*-list prepared. Rough separation is made using the failure risk matrix. If failures are categorized as small risk failures, then no prevention is performed, which means corrective maintenance will be performed according to the need, when a failure occurs. Failures that fall into high risks call for a redesign, that is, modification.

According to this model, the attention should be paid to consequences of failures and not to the failure itself. Four possible analysis directions have been defined based on consequneces of failures. Those are:

1. Failures with hidden consequences.

2. Failures with consequences dangerous for the safety of ship, people and environment.
3. Failures with consequences for system functioning.
4. Failures without consequences for system functioning.

Special attention and prevention need failures with consequences dangerous for the safety of ship, people and enviroment and failures with hidden consequences. Failures with hidden consequences mostly reffer to the environment protection and they are the first line of defense from multiple failures and accidents with more serious final effects. Failures with consequences for system funcioning require prevention if conditions exist, whereas failures without consequences for system functioning require corrective maintenance.

The next step involves consideration of technical characteristics of failures, that is, analysis of possibilities of preventive or corrective maintenance performance. In this model all maintenance strategies have an equal status meaning that any strategy may be selected if it is optimal against the given criteria. Preventive maintenance includes: technical diagnostics as a maintenance activity of condition based maintenance; then preventive repair and replacement as preventive maintenance tasks. Every strategy requires examination of specially defined technical feasibility and effectiveness. It is important that the economnic criteria is taken into consideration only after the safety criteria (consequences of failures). If there is no possibility for preventive maintenance then corrective maintenance is performed which includes: corrective repair, detective maintenance for hidden failures or redesign.

When considering application of preventive maintenance for maintenance strategy selection, the first places takes examination of condition based maintenance possibilities, because those techniques are not destructive or invasive. Most often system operation does not have to stop in order to perform technical diagnostics. Finally, it has been proved that it is the most cost-effective and technically the best choice. Condition based maintenance creates the possibility to utilize maximum lifetime of equipment and act preventively at the same time.

If there is no possibility to perform preventive maintenance, there is a possibility to perform corrective maintenance. When there is equipment that does not have a direct or significant effect on the safety or critical state of mission performance, it can be repaired after its failure. Possibility to accept equipment failure risks is a basic condition for proposing corrective maintenance. If it is about hidden failure, then, most often, detective maintenance is applied. Detective maintenance is characteristic for protective devices, which fail without giving a signal of their failure.

The last alternative is redesign. When there is no reliable data or indications of failures and when dangerous consequences can not be tolerated, the suggestion is to change design or process functioning. It is logical that such a maintenance activity is put on the last place, because it is performed very rarely and opted for less often due to its high costs.

BRANCH II

A smaller group of significant systems, according to the Pareto principle fall into the branch presented under the number II. If maintenance defined with documentation and standard overhaul statements exists, then revision of the previous maintenance is suggested for 20-30% of ship systems and equipment that make 70-80% of maintenance costs. In such a case experience obtained from the previous maintenance would not be used. This means that if this maintenance was used as the starting point, a lot of time would be saved because no redundant analysis would be performed. It starts from the assumption that the previous maintenance covered all critical failures. Our warships have been in use for a long time. On most failures that occurred during that time and had not been preventively maintained, corrective maintenance has been performed in the sense that afterwards those failures modes have been preventively maintained. Since the goal is to keep the sub-systems performance and low costs of the maintenance, this previous maintenance strategy needs to be revised.

This branch also consists of two basic steps. In order to provide a detailed analysis so called *reversed FMEA* is used (Girdhar, 2001). It starts with the inventory of maintenance operations from the last maintenance program on the basis of which identification of failure modes of the stated maintenance operations can be performed. This is followed by the review of failure modes whereupon the existing and additional failure modes are estimated for their effects and consequences. After failures modes are identified, with their effects and consequences, maintenance strategy selection is made in the same manner, as is in the branch I. It should enable introduction of new strategies and thus improve the previous maintenance.

BRANCH III

For most of other systems, modified methodology has been modeled on the basis of *RCM,* but with some important simplifications that enable an increase in the speed of analysis and costs reduction (Dozier, 1996). For the purposes of this paper it has been called *generic maintenance on opportunistic proactive manner* and it is presented under the number III in the algorithm (Figure 1). The title for this branch of methodology for maintenance strategy selection for complex ship systems says that generic maintenance is applied to that 70-80% of ship systems and equipment that take up 20-30% of maintenance costs. It represents maintenance strategies chosen for generic groups of equipment or systems that work and are maintained under the same or similar conditions. Opportunistic means that it is applied where it gives the best results and where no analysis is required. Proactive manner means that improvement of maintenance systems in use is done and that activities based on *RCM* and *RCFA* methodologies are performed for the purpose of preventing problems in equipment operation.

Generic group represents same systems or equipment, for example, pumps, engines, etc. This concept may be applied if it refers to the equipment that has a similar design, similar failure modes and failure frequency and also if such maintenance has proved to be proper during a longer period of time. The object of research in this paper are Naval ships for which it has been determined that they have similar or the same operative context in complex ship systems. In such conditions, generic principle leads to the use of standardized procedures. They reduce efforts and costs of maintenance strategy selection, ensure uniform and consistent maintenance activities, facilitate an analysis of a group of systems, as well as create conditions for a more simplified provision of documentation for this equipment and systems.

CONTINUOUS IMPROVING PROCESS

When analysis is performed on all three-algorithm branches, the defined programme has to be tested in real conditions. On the basis of information on its implementation, its constant improvement can and must be done with various proactive maintenance techniques. This means that maintenance strategies selection made in one of the three manners is not constant and it is subject to changes during time so the last stage called a process of continuous improving has been foreseen.

EXAMPLE OF SYSTEM MAINTENANCE STRATEGY SELECTION THAT DID NOT HAVE A DEFINED MAINTENANCE

This paper will show results of the first pilot-project of maintenance strategy selection for sonar ship system (underwater electric locator) on frigate type "Kotor", which has formerly been maintained in another Repair Facility. This means that certain operators experience in the system existed and they monitored maintenance and overhaul in the former period, which indicates that considerable experience in exploitation existed. Preventive maintenance of this type of sonar was one of conditions to docking the ship. This means that certain maintenance activities on this system had to be or could be performed only while the ship was in the dock. Since the extension of docking cycle is one of very important activities for cost reduction of ship maintenance, the analysis results represent the support for a possible decision of such a kind. Only analysis of antenna subsystem has been performed, whose maintenance previously required docking. Antenna part of the sonar has been placed below the keel line of the ship in the cupola made of a special rubber and enforced with a steel grid. Inside of the cupola are: high-frequency converter, low-frequency converter and cylindrical network of hydrophones of a broadband converter.

The analysis is performed according to *Branch I* that has two basic stages: modified *FMEA* and maintenance strategies selection against the complete *FMEA* methodology. Two primary functions of the analyzed part of the sonar system have been defined as well as four protective and safety functions. Upon functions definitions, it was relatively simple to define functional failures: five primary functional failures and six failures of protective and safety functions.

Defining failures modes and their effects require classic engineering knowledge since systematic analysis of failures is done and this is the phase which takes up most of the time of the analysis. In total, 41 failures modes have been defined. Every failure effect contains description of indications of an operator and a procedure of avoiding final negative effects. Then there are definitions what should be done to perform a repair, which should do it and what spare parts are required. It has been showed that several functional failures may have the same failure mode. Then all failure modes have been grouped and hardware parts-subsystems to which they refer identified.

After *FMEA* followed maintenance strategies selection against a developed algorithm in first branch. First of all, it has been stated that there are no legally regulated maintenance measures or procedures for this system. After that a rough separation was performed on the basis of an estimated risk for every failure mode. High-risk failures modes have not been identified. They have been eliminated by high reliability of the installed elements and robustness of the performance. Four failures modes with small risk have been identified. Other failure modes with small risk are not stated, because we judge only the failure modes with reasonable likely failures, those that have already been discovered and those prevented by the existing maintenance programm.

After that, for the remaining failure modes maintenance strategies selection has been performed against other algorithm points: first, group failures according to consequences that are showed in Table 1. It can be seen that most failures have system consequences.

Failure consequences	Total failure modes
Hidden – safety	2
Hidden- system	10
Safety	1
System	24

Table 1 Failures modes grouping according to consequences

Maintenance strategies were selected according to failure consequences and meeting of conditions of technical feasibility and effectiveness and then economy. Most of corrective maintenance activities exist predominantly for electronic components. Predictive activities have also been introduced which user provided for the purpose of extending the useful lifetime of a system. What was achieved is that docking is no longer required as a preventive activity, but only for the needs of corrective maintenance. Previous maintenance programme performed by other Repair Facility did not have that and several preventive activities were performed on the dock. Daily check-ups are not stated in the tables as separate activities and procedures defined in the basic user's documentation are used. In this programme operators received new maintenance tasks. Operators do a six-moth preventive testing which fits into the maintenance programme.

Strategy	Total strategies	Total failure modes
Corrective	10	12
Preventive	5	8
Predictive	6	9
Detective	2	2
Redesign	4	6

Table 2: Number and structure of selected strategies

Afterwards, selected strategies are grouped into maintenance programmes according to planned periods. Every selected strategy is from a technological point of view elaborated and written as a separate procedure. Corrective maintenance also has a worked out repair and replacement technology. The use of *FTA* method enabled creation of a diagnostic diagram for possible multiple failures, on the first place of compression systems, although there was no need for a more significant application of *FTA* method.

In this case, with the use of a detailed "screening", we carefully studied the system, identified critical failures and made maintenance procedures. What were created were conditions for maintenance performance by our own resources, an increase of reliability and availability after the period of predominantly reactive maintenance. Operators have for the first time been in a situation to participate in such an assignment. They showed maximum motivation after they have been introduced with the tools that offered them a possibility to view systems from the point of view required for the maintenance. This is why an increased safety in system exploitation may be expected.

EXAMPLE OF SYSTEM MAINTENANCE STRATEGY SELECTION WHICH HAD A DEFINED MAINTENANCE PROGRAMME

As an example of maintenance strategy selection for systems that did not have prior defined maintenance programm, other pilot-project for FCS-Fire Control System on missile patrol boat type "401" shall be presented.

Figure 2 shows scheme of block subsystems for fire control on ship automatic cannons A and B (which, in this case, are not the subject of analysis). The system consists of 25 blocks altogether. It is a very complex system that on the system level can define 16 basic system functions. The system is particularly convenient for maintenance. It consists of about 80% of typically electronic subsystem and components which require maintenance by modules replacement. Fault location is facilitated by built/in test equipment - *BITE* and functional control -*FC* programme.

The analysis is performed according to *Branch II* that has two basic stages: *reversed FMEA* and maintenance strategies selection against the complete *FMEA* methodology. According to manufacturers' documentation, maintenance strategies are divided into corrective and preventive maintenance alone. By documentation analysis and conversations with maintenance experts and operators, together 241

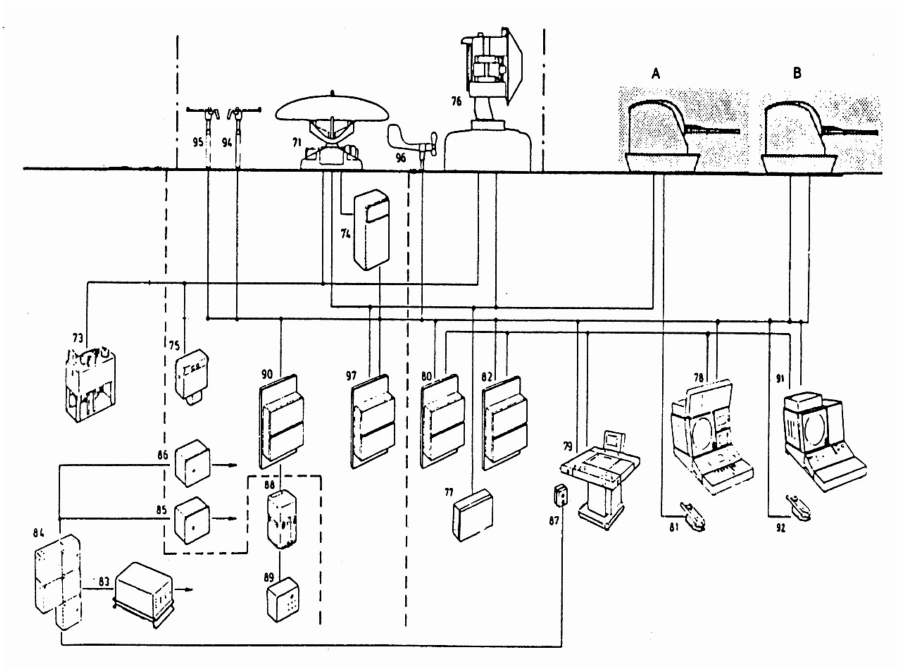

Figure 2. Scheme of FCS subsystems

corrective maintenance activities were identified. A manufacturer defined corrective maintenance as follows: after failure on module level has been localized by *BITE* or *FC* programme, follows replacement of malfunctioning module or component and after that repair of the module in the Naval Repair Facility. Concerning preventive maintenance, documentation defined altogether 73 preventive repairs, replacements or inspections. Some system components should be replaced regularly in accordance with the availability. On the basis of manufacturers recomendations the overhaul cycle of the system lasted only 6 years. Activities of a three-year inspection are already included in preventive control inspections whereas this was not so simple for the six-year overhaul thus special analysis was made. Overhaul included 70 maintenance activities that together with already mentioned 73 activities for the system in the overhaul cycle counted 143 preventive maintenance activities all told.

The last algorithm point is deciding on the maintenance strategy. Every maintenance activity was analyzed against the created algorithm for the selection of a maintenance strategy. For each of them was decided on the required elements: failure modes and failure consequences. For each of them was decided on the required elements: failure modes and failure consequences. A proposal was made that those failure modes which have been identified to meet specially defined effectiveness criteria and technical feasibility keep the previous strategy and schedule.

Strategy	Old Programme	New Programme
Corrective	241	218
Preventive	143	40
Predictive	0	35
Detective	0	3
Redesign	—	2

Table 3. Summarized revision results of FCS maintenance.

The biggest change was proposed in the overhaul cycle. It was suggested mandatory omittance of the overhaul as it was defined that the servo-system of antenna and directing element is sensitive to unnecessary disassembling. The use of technical diagnostics system was proposed: SPM, vibro-analysis, oil leakage inspection, oil analysis, parameter analysis against special programme and thermovision tasks. Thus, it can be said that instead of an overhaul composed of 70 overhaul maintenance activities now can be introduced 6 activities of predictive tasks. Directing elements and antenna's servo-system shall be disassembled only when there is need for such an activity. This created an opportunity to use its service life to the full.

Analysis of consequences of failure showed that some subsystems require redesign. Since these consequences have an impact on system functioning with evident or hidden failures, according to the algorithm in branch II, redesign in favorable and has to be economically justified. It can be stated that, from a technical point of view, the new maintenance programme is improved in comparison to the old one. If performed properly, an increased reliability and readiness of the system are expected.

For the purpose of comparing maintenance costs of the old and new manner, we used the norm of the Naval Repair Facility. It was taken that costs were calculated in average man hours (NH) for one overhaul cycle in duration of six years. It was decided that daily check costs were not included since they were performed by operators. They do it within their regular working hours so it does not incur additional costs. All other works are performed by specialists the Naval Repair Facility or special teams of experts from other companies. According to the old programme this cycle includes: 6 tasks on every six month (30 NH), 4 anual tasks (50 NH), one tasks on every three year (60 NH) and one overhaul (400 NH). Only prevention costs are taken into consideration without corrective maintenance which shall not be included in calculation. This leads to the number 840 NH. New maintenance programme requires 656 NH. In comparison to the old one it is obvious that the new one is cheaper for 22%.

What is interesting is to compare costs occurrence during the overhaul cycle. Figure 3 shows a period of 7 years (14 half-years) to point to the difference between the old and new programme. It is obvious that expenses per one group of preventive inspections are something higher but these relatively low costs are distributed linearly. In the old programme preventive inspections are cheaper but they have high costs during the overhaul. It is obvious from that aspect as well that new programme is more convenient than the old one.

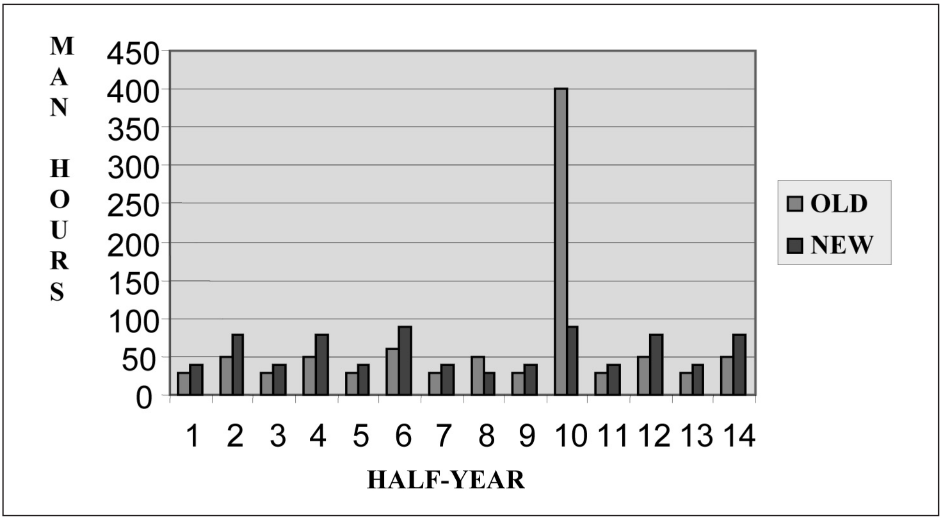

Figure 3. Comparison of maintenance costs of the old and new programme

Costs of detective maintenance activities are not included because they are performed by operators and are considered to be very simple activities. Costs of redesign are estimated to 540 NH of electronics engineer. Importance of FCS as a key combat system of patrol boat justifies the investment.

CONCLUSION

Pilot-analyses made on the basis of this model have showed its applicability and potential to reduce maintenance costs of Naval ship systems. There is no simple model for a big and complex item such as a war ship and only a detailed "screening" can make a significant profit. Since there are no required resources, a balanced approach has been made against the maintenance experience existence criterion and maintenance costs criterion. In this way conditions for achieving positive effects of the new methodology are created with relatively quick applicability. This is possible if an analytical team is well trained for the application of the new methodology and aided by the analytical software based on this methodology and diagnostics resources which create conditions for the application of condition based maintenance.

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