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Exploring maintenance policy selection using the Analytic Hierarchy Process; an application for naval ships

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Abstract

In this paper we investigate maintenance policy selection (MPS) through the use of the Analytic Hierarchy Process (AHP). A maintenance policy is a policy that dictates which parameter triggers a maintenance action. In practice, selecting the right maintenance policy appears to be a difficult decision. We investigate MPS for naval ships, but our results have wider applicability. For our study we cooperate with the owner and operator of the ships, as well as with a shipbuilder and an original equipment manufacturer of naval ships. We apply a structured five step approach to obtain the relevant criteria that may make one policy preferable over another. The criteria are drawn from both literature and a series of interviews at several navy related companies and are structured into a hierarchy of criteria usable with the AHP. Additionally, we organize three workshops at the three different companies to test the AHP-based MPS approach in practice. We conclude that the AHP is well suited for maintenance policy selection in this broad setting, and that it provides a structured and detailed approach for MPS. Adding to that, it facilitates discussions during and after the sessions, creating a better understanding of the policy selection process.

Keywords: maintenance; maintenance policy selection; analytic hierarchy process; naval ships

1 Introduction

Maintenance is an important contributor to reach the intended life-time of technical capital assets, as maintenance is defined as all activities which aim to keep a system in or restore it to the condition deemed necessary for it to function as intended [1, 2]. By technical capital assets we mean capital intensive, technologically advanced systems that have a designed life-time of at least 25 years, such as trains, ships and aeroplanes.

This paper focusses on naval ships, considered a distinguishable ship type within the classification of ships [3, 4]. In the Netherlands, the owner, operator and foremost maintainer of these ships is the Royal Netherlands Navy (RNLN). At the time of writing, detailed information on 27 of the RNLN's fleet of ocean going vessels is publicly available. With a designed life-time of 25 years, the average age of the vessels is 17 years, of which the oldest vessel went into service in 1985 and the youngest in 2013 [5, 6]. To keep these ships operational and up to date throughout their life-time, maintenance plays a crucial role.

A maintenance policy is a policy that dictates which parameter (for example, elapsed time or amount of use) triggers a maintenance action. Selecting the right maintenance policy appears to be a difficult decision. Namely, current selection methods do not always fit companies well and the need for tailored maintenance concepts is raised in the literature [7, 8]. Furthermore, current, mostly quantitative, maintenance optimization and decision models have low applicability in practice, creating a gap between academia and practice: the scarcity of practical approaches to maintenance modelling was already pointed out in 1992 [9], and not much has changed since. Although maintenance is something that

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should be done in practice, several authors argue that practical studies are still under-represented [10, 11]

In the 1990s, a novel approach to maintenance decision making emerged. Arguing that decision theory has become a useful tool to many professionals including engineers, and many maintenance challenges can be modelled as multiple criteria decision making (MCDM) problems, the use of MCDM methods has been suggested for maintenance decision making [12, 13]. Selecting the right maintenance policy is one of these challenges for which MCDM could be applicable.

In this paper we set out to investigate naval maintenance policy selection (MPS) through the use of the Analytic Hierarchy Process, a well established MCDM method that hierarchically structures the goal, criteria and alternatives of the decision problem. We take a five-step approach to structure the investigation:

1. review the literature on the use of the AHP for maintenance policy selection;

2. define maintenance policies and construct a list of maintenance policies to use as alternatives;

3. obtain the relevant criteria from both literature and a series of interviews, and structure them into a hierarchy usable with the AHP;

4. organize three workshops in industry (at the RNLN, a shipbuilder and an OEM) to test the AHP-based MPS approach in practice; and

5. evaluate these workshops and analyse these evaluations.

AHP-based approaches have been followed by others, but only for single case studies focussing on the final policy selected (see Section 2). The main question that this paper aims to answer is if the AHP can be put to a broader use for MPS. And if so, in what situation it is applicable. By broadening and following a structured approach, this paper contributes in four ways:

- the asset: we focus on a type of asset, namely naval ships, instead of one specific asset;

- the company: we look at the perspective of various companies, in stead of one specific company, using the same hierarchy of criteria: owner, shipbuilder and original equipment manufacturer;

- the process: we also focus on tailoring of, and gaining insight in the selection process, and not on merely the outcomes of the process, by explicitly taking into account both the goals of the maintenance as well as the fit of the maintenance process to the company; and

- the approach: we apply a structured approach, where five steps are proposed and subsequently followed to systematically investigate naval MPS using the AHP. Contrary to other studies, for example, the structured approach that we propose can easily be repeated by others to find the relevant criteria.

This paper is structured according to the five-step approach explained above. We explain the AHP and the reasons for selecting the AHP in Section 2. Maintenance policies are discussed in Section 3, where we construct a concise and consistent list to be used with the AHP. In Section 4, we present the hierarchy of criteria that we distill from both the literature and a series of interviews. In Section 5, we discuss the set up of the three workshops that are organized to test the AHP-based MPS approach. The workshops are evaluated by all participants and in Section 6 we present the results of these workshops and their evaluation. In Section 7, we draw conclusions and present recommendations for further research.

2 The Analytic Hierarchy Process

The use of MCDM methods has been proposed for maintenance decision making, because decision theory has become a useful tool to many professionals and because many maintenance challenges can be modelled as MCDM problems [12, 13].

MCDA focusses not only on making a decision, its goal is also to provide insight in the decision process [14]. MCDA contributes to analyzing the decision making context, and organizing the process, increasing coherence on the goals and the final decision, and cooperation between the decision makers, leading to a better mutual understanding and debate [15].

In this paper we investigate naval MPS through one of these MCDM methods: the Analytic Hierarchy Process (AHP). The AHP is developed by Saaty in the 1970s and is a multiple criteria decision method in which the criteria are arranged in a hierarchical structure [16, 17]. It decomposes decision-making into the following four steps.

1. Define the problem and determine the kind of knowledge sought.

   For example, which new car to buy: Car A *or* Car B.

2. Structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which is a set of the alternatives).

   In the example, the goal is selecting the best new car, *the criteria then might be the* top speed, *the* design *and the* safety *of the car. The alternatives are* Car A *and* Car B.

3. Construct a set of pairwise comparison matrices. To obtain the priorities, each element in the hierarchy is used to compare the elements in the level immediately below it.

   Following the example, each criterion is compared with the other two in a matrix structure to calculate the importance of each criterion: top speed *to* design, top speed *to* safety, *and* design *to* safety. *The two cars are compared for how they score on each criterion: in this case,* Car A *might have a higher* top speed *and have a more beautiful* design *and* Car B *might be* safer.

4. Use the priorities obtained from the comparisons to weigh the priorities in the level immediately below, moving down along the decision hierarchy. Do this for every element. Then for each element in the level below add its weighed values and obtain its overall or global priority. Continue this process of weighing and adding until the final priorities of the alternatives in the bottom most level are obtained.

   Concluding the example, the scores of the cars are weighed by the priorities of the criteria, and the totals are added together to obtain the global priorities of the cars. Say safety *obtained the top priority and the other two criteria obtained very low priorities. Then* Car B *will be prioritized over* Car A, *because* Car B *scores high on the most important criterion:* safety—*in favour of* Car A *scoring higher on the two other, but less important, criteria.*

For the pairwise comparisons, a ratio scale is used to indicate how many times more important or dominant one element is over another: 1 to indicate an equal importance, 2 – 9 to indicate a higher importance and their reciprocals to indicate a lower importance. To facilitate the AHP, various software packages are available. For this paper the SuperDecisions software is used, which is freely available for non-commercial use [18].

The AHP was selected for this research because it is a well-established multiple criteria decision-making approach, both in academia and industry, and its specific benefits fit the issues described in Section 1, as the AHP [14, 17, 19–22]:

- is designed to integrate objective, subjective, qualitative and quantitative information;
- creates a thorough understanding of the problem by structuring the problem hierarchically;
- compares the criteria and alternatives pairwise, providing simplicity and ease of use; and
- produces plausible and defensible results.

The use of the AHP for maintenance decision making appears to emerge in the second half of the 1990s [13, 23, 24], when the use of the AHP for engineering applications was already recognized as an effective approach for dealing with a multiple criteria decision problem [25].

To the authors' knowledge, the first study using the AHP for maintenance policy selection is an application of the AHP at an oil refinery [26]. The AHP is found to be an effective approach to arrive at decisions and the maintenance staff and managers were highly satisfied using the AHP. In a follow-up of this study, the AHP was combined with goal programming, and this combination was successfully used for maintenance policy selection for centrifugal pumps in the same oil refinery [27].

Since then, the AHP has been applied for MPS in multiple industries. The AHP was combined with a fuzzy prioritization method at a manufacturing firm [28]. It was found to be a simple and effective tool for this decision problem. At a textile company, the AHP was applied in combination with TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) [29]. The same case was also studied using fuzzy comparison ratios for the AHP [30]. For a rerun column section in a benzene extraction unit of a chemical plant, the AHP was combined with goal programming for a risk based approach to maintenance policy selection, using only cost and risk as criteria [31]. Finally, the AHP was also successfully used to select the best maintenance policies at a newspaper printing facility [32].

The above mentioned papers show that the AHP can be successfully applied for maintenance decision making and, specifically, maintenance policy selection. However, these studies are single cases at one company, often considering one asset; no attempts have been made to generalize the use of the AHP for maintenance policy selection at a wider range of assets or industries. We investigate the use of the AHP in a broader setting.

3 The alternatives: the maintenance policies

The definitions and classification of maintenance policies used in the literature are inconsistent [compare for instance 1, 33, 34]. Furthermore, terms such as maintenance philosophy, strategy and policy are often used interchangeably. We define a maintenance policy as a policy that dictates which parameter (for example, elapsed time or amount of use) triggers a maintenance action.

A suitable list consisting of six maintenance policies, consistent with our definition, has already been formalized in [35]:

- *failure-based maintenance*: maintenance is performed correctively only, meaning that one deliberately waits for something to break or fail;
- *calendar-time based maintenance*: maintenance actions are performed at fixed time intervals, for example, every month or year;
- *use-based maintenance*: the actual use triggers maintenance, such as kilometres driven or operating hours;
- *use-severity based maintenance*: not the use, but its severity triggers maintenance, for instance off-road kilometres compared with on road kilometres instead of just the total kilometres driven;
- *load-based maintenance*: maintenance is triggered by measured internal loads, such as the measured strain in a certain structural component;
- *condition-based maintenance*: a measured condition dictates maintenance actions, such as particular levels of vibration or amounts of dissolved metal parts in oil.

However, to be used as the alternatives within the AHP, this list is too long, as it will result in too many pairwise comparisons: 15 pairwise comparisons for each lowest level criterion of the hierarchy. Therefore, we look at the aforementioned case studies to investigate which and how many alternatives were used in these cases. These are presented in Table 1 (note that in the table [29, 30] are combined, as they concern the same study). From these case studies, note that only one uses five alternatives, the others use either four or three alternatives.

To keep the final selection as straightforward and small as possible and to stay consistent with our definition of maintenance policies, we have selected the following three maintenance polices to be used as alternatives with the AHP, resulting in only three pairwise comparisons for each lowest level criterion:

- *failure-based maintenance*;
- *time/use-based maintenance*; and

Table 1
Alternatives used by the case studies

Maintenance policy	Used by [26]	[27]	[28]	[29, 30]	[31]	[32]
Corrective maintenance	•	•	•		•	•
Predictive maintenance		•		•		•
Preventive maintenance	•	•		•		
Condition based maintenance				•	•	
Condition based maintenance (diagnostic)	•		•			
Predictive maintenance (prognostic)	•		•			
Time based maintenance			•		•	
Opportunistic maintenance	•					
Periodic maintenance						•
Reliability Centred Maintenance				•		
Shutdown maintenance					•	
Number of policies used	5	3	4	4	4	3

- *condition-based maintenance*.

This means that compared with the list of six policies, *calender-time based maintenance* is combined with *use-based maintenance*, since these both concern preventive maintenance that can be planned. *Use-severity* and *load-based maintenance* are not included, as these are the least relevant based on the case studies and our own experience. Compared with Table 1, *corrective maintenance* is incorporated in *failure-based maintenance*. *Preventive*, *time based* and *periodic maintenance* are incorporated in *time/use-based maintenance*, and the *predictive* and *condition based maintenance* policies are incorporated in *condition-based maintenance*. Finally, *opportunistic maintenance*, *shutdown maintenance* and *Reliability Centred Maintenance* are omitted, because they are not consistent with our definition of a maintenance policy, as these do not directly trigger a maintenance action.

4 The criteria and hierarchy

The criteria that play a role for naval maintenance and naval maintenance policy selection are investigated in two ways: a series of interviews and a study of the previously mentioned case studies (see also Table 1). The interviews provide insight in current practice and specific on naval vessels, whereas the case studies provide criteria with proven applicability for MPS using the AHP in industry in general. The results of both are combined and structured into a hierarchy of criteria.

The series of interviews is set up at the RNLN and four related companies. These 60 to 90-minutes long, semi-structured interviews [36] focus on three things: getting a better understanding of the maritime sector, investigating which criteria currently play a role for maintenance policy selection, and exploring which criteria should play a role for maintenance policy selection. The used interview script is included in Appendix A. In total eight interviews are conducted at five different companies with interviewees that have various roles, see Table 2 for an overview (ILS stands for Integrated Logistics Support, EMEA stands for Europe, the Middle East and Africa). The interviews are recorded and afterwards analysed to find the criteria that are mentioned.

Table 2
Company and interviewee roles

Company role	Company	Interviewee role
Vessel owner and operator	Royal Netherlands Navy	User, maintainer, regulator
Naval specific OEM	Thales	Designer, ILS provider
Naval specific shipbuilder	Damen Schelde Naval Shipbuilding	ILS provider
General maritime maintainer	Imtech Marine	Maintainer
General maritime classification society	Lloyd's Register EMEA	Regulator

The criteria that are obtained from the interviews are combined with those found in the case studies in the literature. This results in a list of 187 criteria, which can be found in Appendix B. To create a workable and concise set of criteria and to clear out the case specific criteria that are relevant only for the case study in which they are used, we have selected only the criteria that are mentioned three times or more in total. This results in a list of 46 criteria used for the construction of the hierarchy.

Constructing the hierarchy, similar criteria are combined and not all criteria can be used, because redundancy within the criteria needs to be avoided and the criteria need to be independent [14]. This results in a final list of 29 criteria. As our interest lies in both the goals of the maintenance and fit of the maintenance process to the company, we have constructed the hierarchy with *goals* and *fit* being the top-level criteria. Here we have deliberately chosen not to focus on costs, to not get distracted from the focus on the goals and fit—we get back to this in Sections 6 and 7.

Beneath *goals* and *fit*, we divide the criteria in two and six clusters, respectively, of highly related criteria. These clusters are as follows.

- Beneath the top-level criterion *goals*:
  - *KPIs (Key Performance Indicators)*: measurable reasons for doing maintenance;
  - *Desirables*: reasons for doing maintenance that cannot be easily measured or quantified;
- Beneath the top-level criterion *fit*:
  - *Fit to crew*: the size and educational level of the on-board crew;
  - *Fit to knowledge*: the available knowledge and experience with maintenance within the company;
  - *Fit to mission*: the mission profile of the ship;
  - *Fit to relations*: the internal and external relations of the company;
  - *Fit to spare parts*: the spare parts and the presence commonality;
  - *Fit to tasks*: the influences on performing maintenance tasks.

The full hierarchy is presented in Figure 1, the definitions of the criteria are included in Appendix C.

5 The sessions

We have organized test sessions to investigate the practicality and use of the AHP-based MPS method along with the constructed hierarchy. These sessions are organised at the three companies from our interviews specifically involved with naval ships: the RNLN as owner and operator, Thales as naval specific original equipment manufacturer (OEM), and Damen Schelde Naval Shipbuilding (DSNS) as naval specific shipbuilder. Participants of each session were the interviewee(s) from each company along with a number of his colleagues. During these sessions a maintenance policy is selected for a system chosen by the participants: the company case. The participants are allowed to choose any system of interest, no limitations on, for example, type of system or level in the system are given. An overview of the companies, the roles of the participants and the case is given in Table 3.

Table 3
Session, attendee and case overview

Company	Participant role	Case
DSNS (shipbuilder)	3× ILS provider	Single ship
RNLN (owner/operator)	User, maintainer, 2× regulator	Single ship
Thales (OEM)	Designer, 2× ILS provider	System on the ship

These three to four-hour sessions are structured as follows. First, the nature of the research and the planning of the session are introduced. Next, a fictitious case to get acquainted with the AHP is

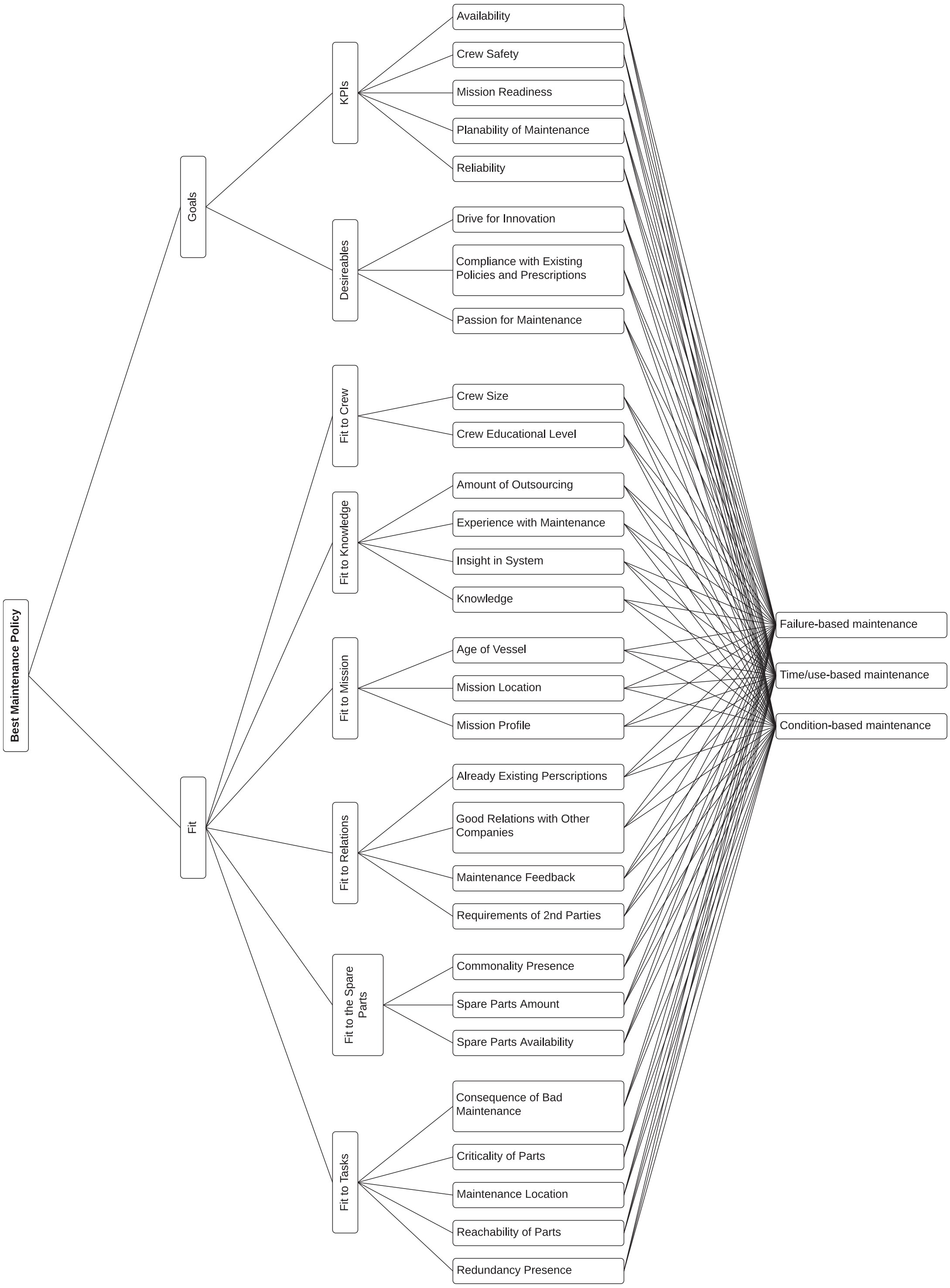

Figure 1
The hierarchy of criteria

presented. The focus of the company case is then chosen by the participants, while the participants receive a copy of the hierarchy (Figure 1) and the list of definitions of the criteria (Appendix C).

For the company case, the participants are asked to individually fill out the pairwise comparisons. When this is done, the AHP prescribes that the geometric mean

$$\bar{a}^{g} = \sqrt[n]{a_1 \cdot a_2 \cdots a_n} = \left(\prod_{i=1}^{n} a_i\right)^{1/n}$$

must be used to synthesize the inputs given by the participants [17].[1] This is used accordingly to calculate group's aggregated scores and weights. The geometric standard deviation is then used to investigate where the participants agree and disagree most in the pairwise comparisons.

Afterwards the results are discussed with the participants: the final scoring of the alternatives, shown in Table 4, as well as the results of the aggregated pairwise comparisons, the sensitivity analysis for the top level criterion *goals* compared to *fit*, and the pairwise comparisons where the participants disagree most.

Table 4
The final preference of the alternative maintenance policies

		Final policy preference		
Company	Case	Failure-based	Time/use-based	Condition-based
DSNS (shipbuilder)	Single ship	0.250	0.359	0.390
RNLN (owner/operator)	Single ship	0.236	0.354	0.410
Thales (OEM)	System on a ship	0.197	0.324	0.479

To end, each participant is given an evaluation form. The evaluation form consists of 16 questions divided into three categories: the session, the hierarchy of criteria, and the decision. The form is in Dutch, as are the answers; the translated list of questions can be found in Appendix D. The answers are discussed in the following section.

6 Results of the evaluation of the sessions

The results (i.e., the answers given) of the session evaluation are are discussed per category: the evaluation of the session, the evaluation of the hierarchy of criteria, and the evaluation of the decision. The first part of the evaluation considers the session itself. This part consist of questions about the session in general, its usefulness and the groups with which the sessions are held.

- All participants find the session interesting, useful and enjoying. The participants indicate that the sessions help to understand the process, reveal the relations and trade-offs between the criteria and reflect on the used arguments. They regard the sessions as a novel, out-of-the-box and playful way to engage MPS. Furthermore, the participants value how the interactive approach triggers the right the discussions. One participant concludes that understanding the process is more useful than the decision itself.
- On the duration of the session, one participant states that the session took too long, one participant finds that the session took too little time to do well. The other participants find the duration of the session sufficient.
- Most participants find the group with which they attended the session satisfactory. Also, most participants suggest, and see the value of, a more diverse and multi-disciplinary group. Some participants even suggest having a session with members from various companies, such as suppliers, customers and maintainers, or shipbuilders and classification societies. Some participants suggest a larger group.
- All participants would do a similar session again, either for different parts or systems, or with a different or larger group of people.

The second part of the evaluation is about the hierarchy of criteria. The questions are meant to determine if the hierarchy is clear and understandable, and if any criteria are lacking or redundant.

[1] Because the pairwise comparisons are rated on a ratio scale, the geometric mean, not the common arithmetic mean, is the correct way to aggregate individual judgements. The interested reader may consult [37].

- Most participants find the hierarchy of criteria clear and understandable. However, some participants indicate that some meanings and definitions of the criteria are not fully clear.
- The groupings and divisions made in the hierarchy are well-received, one participant explicitly appreciates the division in *goals* and *fit*. One participant questions the balance of this division and thinks *fit* is over represented as it has more sub-criteria than *goals*.
- The participants are quite unanimous on missing and redundant criteria. They indicate that costs should be included, that *availability* and *mission readiness* are similar, as are *insight in system* and *knowledge*. Some participants suggest that risks should be included, as well as to merge *spare parts amount* and *spare parts availability*.

The third and final part of the evaluation considered the decision. Here the questions focus on the final maintenance policy selected during the session, insight gained during the session and the level in the system for which a policy was selected.

- For the final policy selected, as presented in Table 4, most attendees would have chosen for the same maintenance policy, because they indicate it matches either reality, their own vision, it seems to be the most balanced choice or is the long term cheapest option. Two participants state that the final maintenance policy still depends on the component, the task, failure mode or risks involved.
- All participants indicate they now better understand the selection process and the decision made. They express that the sessions reveal the important considerations, arguments and connections between the criteria, elicit the underlying foundations of their vision on maintenance, and provide a more detailed view on the decision by zooming in on the decision. Furthermore, the discussions that emerged on the various insights and interpretations is stated to contribute to the understanding of the decision and the process.
- Although the cases are all done for high levels in the system (twice for a ship, and once for a system on the ship), the participants disagree on the ideal level in the system for which a maintenance policy should be selected by a session like this. Six participants favour high levels in the system: no deeper than installation level. Three participants want to look deeper into the system: on a sub-system level, per line replaceable unit or maintenance significant item.

These results confirm the literature in that the AHP provides plausible results and that its structured approach gives insight in the decision problem. Again, the discussions are mentioned as an important contribution. This leads to the notion that our AHP-based method for naval MPS can be regarded less as an actual decision method, and more of a thought-structuring and insight-providing discussion method. This might relate with the levels in the system the companies chose as cases: high level systems are chosen during the sessions, for which it is difficult to select a single maintenance policy. For instance, a ship cannot be maintained solely condition-based, it always requires a mix of policies. However, one can *aim* for a ship to be maintained condition-based as much as possible. Here we foresee the applicability of the AHP-based approach: to investigate why, and if indeed, one should aim for condition-based maintenance.

7 Conclusions & recommendations

We set out to investigate maintenance policy selection through the use of the Analytic Hierarchy Process, focussing on naval ships. We can now draw conclusions on the main question of this paper: can the AHP be put to a broader use for MPS? And if so, in what situation is it applicable?

Foremost, we conclude that the AHP is well suited for naval maintenance policy selection. We have shown that the AHP can be applied for MPS problems in a broad way: for a type of asset, at multiple companies, using the same hierarchy of criteria. It appears that the applicability lies not in making the actual decision, but in providing a thought-structuring method that provides insight by eliciting preferences and facilitating discussion. This seems to be a more strategical way of approaching MPS, because in such strategic decisions high levels in the system are able to be considered and maintenance aims can be set.

Based on the results of this paper, continuing the investigation of using MCDM methods and the AHP for maintenance policy selection is recommended. We especially see contribution in the continuation of this AHP-based approach with the presented hierarchy by further broadening the application areas: from naval ship towards ships in general, from naval ships towards general military transportation (including the army and air force), or moving deeper into the system level towards sub-systems and components. Furthermore, we recommend exploring the use of the other MCDM methods for MPS, with the Analytic Network Process as a starting point to investigate any dependency and interrelations of the criteria in the hierarchy. Also, the hierarchy of criteria needs a review, as several improvements are suggested by the participants of the sessions. Finally, we recommend further investigation into the preferred maintenance policy for naval ships, as the results shown in Table 4 seem to be remarkably consistent.

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A Interview script

The script for the semi-structured interview is originally in Dutch, the translated version is shown below.

- Briefing
  - Recording of the interview
    - Do you have any objections against the recording of this interview?
    - Making an off-the-record remark is possible, please indicate if you do so.
    - I will send you the results of the interview for review.
  - Explanation of the interview
    - Explain the purpose of the interview and introduce the maintenance policies.
    - Do you have any questions about the interview?
  - Context
    - What is your position and function within the company?
    - What are your responsibilities?
- Body
  - Familiarization with the marine/maritime world
    - What does your company do with ships?
    - How is a ship maintained? How does that work?
  - Which criteria currently play a role for the choice between maintenance policies?
    - Why is a ship maintained? What is gained by maintaining a ship?
    - What are the consequences of a failure, at sea and close to a port?
    - What is the single most important gain and consequence—if such one exists?
    - Why is this one then the most important?
    - Which of the mentioned maintenance policies are applied at ships? And for which components?
    - Is one of these policies preferred?
    - Which interests and stakes play a role at ship maintenance?
    - Are some stakeholders more important than others?
  - Which criteria should play a role for the choice between maintenance policies?
    - Do you think that some stakeholders do not get enough attention or credit?
    - Can you elaborate on trends or emerging developments in ship maintenance?
    - Compared to current practices, could ship maintenance be done in a more practical, more clever or better way?
    - How should a ship ideally be maintained?
- Debriefing
  - Questions and remarks
    - Do you have any remarks before we end this interview?
    - Many thanks for your cooperation
  - Wrap up
    - Before the interview is over, I would like to ask one last question:
    - What do you think of being interviewed on the criteria and the choice between maintenance policies?
  - Stop the recording
    - I will now stop the recording.

B Total list of criteria

The total list of criteria obtained from both the interviews and literature is presented in Table 5, along with the total times mentioned. A line is drawn to indicate the criteria that are mentioned three times or more, and have thus been considered during the hierarchy formation.

Table 5
The total list of criteria

Criteria	Times mentioned
Costs (minimization)	11
Availability	8
Maintenance or failure feedback	7
Experience (with maintenance)	7
Reliability (mission and operational)	7
Spare parts availability	6
Mission duration/time on sea	6
Good relations with other companies and institutions	6
Earlier/old/already existing prescriptions	6
Criticality	6
Rules and regulations	5
Redundancy presence	5
Planability	5
Mission/operation/use profile	5
Crew safety	5
Consequences of bad maintenance or failures	5
Warranty periods	4
Taking responsibility	4
Spare parts costs	4
Passion for maintenance, preference for minimal or maximal maintenance	4
Good communication with 2nd parties	4
Crew size	4
Crew educational level	4
Commonality presence	4
Usefulness of monitoring data	3
Training costs	3
Spare parts amount	3
Risk during mission or operation	3
Requirements of 2nd parties	3
Reachability of parts	3
Production loss (MTBF, MTTR, downtime)	3
Mission readiness	3
Mission location	3
Maintenance location (on board or on shore)	3
Knowledge	3
Insight in system	3
Influence on and control over customers and their demands	3
Amount of faith in existing policies and prescriptions	3
Drive for innovation or change	3
Costs of change of policy (investment required)	3
Commercial interests	3
Austerity measures (imposed/required)	3
Amount of outsourcing	3
Amount of available funding/budget	3
Age of vessel (and remaining useful life)	3
Added quality	3
Workers' acceptance	2
Undesirability of over-maintenance	2
Technique reliability (failure identification, as good as new)	2
Support within company (e.g., integrated logistics support, life cycle thinking)	2
Staff skill	2
Staff level of education	2
Spare parts location	2
Spare parts lead time	2
Software costs	2
Seaworthiness of vessel	2
Relation with the government	2
Personnel safety	2
Number of operational days/year	2
Making money (added profit)	2
Maintenance induced failures (and the probability thereof)	2
Maintenance concept already in place	2

Continued on next page

Table 5
The total list of criteria – continued

Criteria	Times mentioned
Long term vs short term vision	2
Internal safety	2
Initial quality of the system or component	2
Hardware costs	2
Good Relations within company	2
Frequency (number of maintenance calls)	2
External safety	2
Experience with the different policies	2
Environment (environmental damage, external & internal)	2
Detectability	2
Current fixed planning	2
Crew skills	2
Crew knowledge	2
Crew continuity	2
Contract form	2
Company structure	2
Capacity of maintainer	2
Available time for maintenance	2
Availability of existing facilities	2
Added image	2
Actual use versus intended use	2
Intrinsic safety	2
Who pays	1
Who maintains	1
Vessel operational or not	1
User profile	1
Use of commercially of the shelf components	1
Up-to-dateness of knowledge	1
Undesirability of making costs	1
Understandability of the policies	1
Trust in mathematics	1
Time to policy decision	1
Technology implementation	1
Technological advancedness of the system	1
Technical feasibility	1
Staff continuity	1
Staff amount	1
Skill level	1
Severity	1
Sector in question	1
Safety of the world	1
Rule bending	1
Role of company (e.g., original equipment manufacturer, system integrator)	1
Risks and criticality of degradation	1
Risk of failure	1
Risk	1
Rigidity of existing planning	1
Required accuracy for maintenance	1
Reliability of monitoring equipment	1
Product damage	1
Presence of electronic resource planning	1
Plant damage (direct & indirect)	1
Performance killers presence	1
People damage	1
Parade	1
On board replacability of spare parts	1
On board amount of spare parts	1
Number of engineers on board	1
MTTR costs	1
MTBF costs	1
MTBF	1
Moisture (environmental condition)	1
Mission predictability	1
Mean time to replacement	1
Mean time to repair	1

Continued on next page

Table 5
The total list of criteria – continued

Criteria	Times mentioned
Maturity of the system	1
Mathematical skills and affinity	1
Material costs	1
Management acceptance	1
Life time maximization	1
Knowledge of labour	1
Key Performance Indicators	1
Interests of other parties	1
Infrastructure costs	1
Influence on building process	1
Improper sequence	1
Image	1
Ideal maintenance moment	1
Higher utilization	1
Gut feeling versus documentation	1
Foregone earnings minimization	1
Flexibility/adaptability of the maintenance	1
Fixedness of budget	1
Entertain	1
Employability	1
Efficient maintenance	1
Ease of handling	1
Duration of relation with 2nd parties	1
Difficulty in training	1
Difficulty in implementation	1
Designed life-time	1
Designed for maintenance	1
Dependence on 2nd parties	1
Degradation speed (amount/time)	1
Degradation predictability	1
Damage of a failure	1
Current maintenance policy	1
Crew roles and responsibilities	1
Crew health	1
Crew costs	1
Costs predictability	1
Cost drivers	1
Consultation costs	1
Conservative or progressive approach	1
Complacency	1
Company's ability to cope with change	1
Choking (environmental condition)	1
Changing use profiles over time	1
Bottlenecks	1
Available (correct) documentation	1
Availability of historical data	1
Availability killer presence	1
Assurance costs	1
Asset policy	1
Added value of measurements	1
Added know-how	1
Added delivery	1
Acceptability of degradation	1
Ability to go from data to information	1
1st line or 2nd line maintenance	1
Road class	1
Pavement condition	1
Operating traffic	1
Riding quality	1
Importance to community	1

C List of definitions as used during the sessions

The definitions of the criteria incorporated in the hierarchy, given to the participants during the sessions, are the following.

- *Availability*: the total availability of the system
- *Crew Safety*: the safety of the crew
- *Mission Readiness*: the system is ready for a mission when needed
- *Planability of maintenance*: how well the maintenance can be planned
- *Reliability*: the total reliability of the system
- *Drive for innovation*: the desire to innovate
- *Compliance with existing maintenance policies and prescriptions*: the desire to keep doing current maintenance practices
- *Passion for maintenance*: the desire to do good maintenance
- *Crew size*: the amount of crew members
- *Crew educational level*: the educational level of the crew
- *Amount of outsourcing*: the amount of outsourcing in place
- *Experience with maintenance*: the experience the company has with doing maintenance
- *Insight in system*: the amount of insight the company has in the system
- *Knowledge*: the knowledge the company has about maintenance
- *Age of vessel*: the age of the vessel
- *Mission location*: the location of the mission
- *Mission profile*: the duration and intensity of the mission
- *Already existing prescriptions*: the maintenance prescriptions already in place
- *Good relations with other companies*: the relations with related companies
- *Maintenance feedback*: feedback of maintenance actions and results throughout the company and supply chain
- *Requirements of 2nd parties*: Requirements of different devisions within the company
- *Commonality presence*: the presence of commonality within the system
- *Spare parts amount*: the number of spare parts
- *Spare parts availability*: the spare parts readily available where maintenance is needed
- *Consequences of bad maintenance*: what happens if maintenance is done incorrectly
- *Criticality of parts*: the criticality of the parts in the system
- *Maintenance location*: the location where the maintenance is done
- *Reachability of parts*: the ability to physically reach the parts in the system
- *Redundancy presence*: the presence of redundancy within the system

D Evaluation form questions

The evaluation form is originally in Dutch, the translated version is shown below.

1. The session
   (a) What did you think of the session?
   (b) Did you find it useful? Why?
   (c) Did you enjoy it? Why?
   (d) What do you think of the duration of the session?
   (e) Would you want to do a similar session again? Why?
   (f) If so, when and how many times would you want to this?
   (g) What did you think of the group? Think, for example, about the number of people and the various functions they have.
   (h) Do you have any suggestions for improvement?
2. The hierarchy of criteria
   (a) Do you think the hierarchy is clear and understandable? Why?
   (b) What to you think of the clusters/divisions/categories made?
   (c) Are any criteria lacking? If so, which?

   (d) Are any criteria redundant? If so, which?

3. The decision
   (a) During the session one of the policies ended up being most favourable. Would you have chosen for the same policy? Why?
   (b) Do you feel you better understand the way the decision was made?
   (c) For which level in the system would you ideally want to select a maintenance policy using such a session?

4. Do you have any other remarks?

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nr.	Year	Title	Author(s)
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