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Abstract We aim to structure the maintenance policy selection process for ships, using the Analytic Hierarchy Process (AHP). Maintenance is an important contributor to reach the intended life-time of capital technical assets, and it is gaining increasing interest and relevance. A maintenance policy is a policy that dictates which parameter triggers a maintenance action and it appears that selecting the right maintenance policy is a difficult group decision. To investigate maintenance policy selection (MPS), we use an eight stage method to structure the multiple criteria decision making process, and build on previous research to propose a refined decision hierarchy, aiming for a structured abstraction of MPS to reveal the core of the MPS problem. After a preliminary MPS session, this decision hierarchy is applied at a multi-company MPS session, where a group of companies from the same maintenance chain is present. We conclude that the chosen methodology, using our previous results as a starting

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point, greatly improves the workability of the decision hierarchy. Also, it turns out that discussing the exact meanings of the criteria plays a crucial role in the group decision process.

Keywords Maintenance · maintenance policy selection · analytic hierarchy process · group decision making

1 Introduction

How to maintain technical capital assets is a question gaining increasing attention and relevance (Zio 2009), as maintenance is an important contributor to reach the intended life-time of these expensive assets. 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. Maintenance can be 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 (Duffuaa et al 1999; Pintelon and Parodi-Herz 2008).

Based on Pintelon and Parodi-Herz (2008) and Tinga (2010), we define a maintenance policy as a policy that dictates which parameter triggers a maintenance action, a parameter can, for example, be elapsed time or amount of use. Selecting the right maintenance policy is an important group decision in maintenance decision making. In practice, current selection methods do not always fit companies well, and current, mostly quantitative, maintenance optimization and decision models have low applicability. Hence, the need for tailored maintenance models and concepts is raised in the literature (Waeyenbergh and Pintelon 2002; Zio 2009). Several authors argue that practical studies are under-represented, strongly encouraging efforts to close this gap between theory and practice (Nicolai and Dekker 2008; Horenbeek et al 2011; Zio 2009).

We look at maintenance policy selection (MPS) through the use of the Analytic Hierarchy Process (AHP), a multiple criteria decision making (MCDM) method in which the decision problem is structured in a hierarchic way, developed by Thomas Saaty in the 1970s (Saaty 1980). The use of the AHP for (group) decision making has been growing ever since (Ossadnik et al 2015), and its use for maintenance decision making has been recognized (Triantaphyllou et al 1997; Labib et al 1998; Ramadhan et al 1999).

To research maintenance policy selection for ships in a relevant way, we need to draw from two research paradigms, where a research paradigm can be defined as the combination of research questions asked, the research methodologies allowed to answer them and the nature of the pursued research products (Van Aken 2004). These two paradigms are, on the one hand, organisational research, which will help to understand MPS in organisations, and, on the other hand, design research, which will enable the development of an MPS method.

A full integration of these different paradigms is not possible. However, several authors propose a combination of and collaboration between specifically these two paradigms, in which they argue for a design approach to organisational research (Romme 2003; Van Aken 2004). The aim of this approach is to create knowledge that is both actionable and open to validation, and, by that, is reducing the relevance gap between theory and practice. This approach relies on developing and testing solutions in practice as well as grounding the solutions in empirical findings. Hence, this approach cannot deliver conclusive proof (in the formal scientific sense) for the solutions found; however, it generates increasingly supporting evidence by iteration and refinement, which is tested in context, for an increasing confidence in the solutions found.

To apply the proposed design approach to organisational research, and to accumulate the supporting evidence, both Romme (2003) and Van Aken (2004) suggest the *multiple case* method. This method comprises an iterative cycle of cases in close collaboration with people in the field. After the initial case is chosen, each new case:

– is refined by the findings of the previous research;
– tests the knowledge gained during the previous research and the implemented refinements;
– provides new knowledge and refinements to be tested in subsequent cases; and
– thus contributes to the supporting evidence for, and increases the confidence in the solution to the research problem under investigation.

Applying this approach, we take the following three steps.

1. Investigate methodologies to refine the decision hierarchy and to structure the MCDM process.
2. Methodologically refine the decision hierarchy, using the results and feedback from practice.
3. Use this renewed hierarchy at a final, multi-company MPS session with participants from various companies within the same maintenance chain (from supplier to user).

Following these steps, we build on previous research, in which we have investigated the most important criteria and considerations for ship maintenance policy selection (MPS), while generalizing our AHP-based MPS approach from naval ships towards ships in general (Goossens and Basten 2015a,b). This research shows that *crew safety* is the most important criterion for ship MPS, followed by *reliability* and *availability*. Furthermore, we found that softer, qualitative criteria play an important role and should be included in ship MPS (see Appendix A for an overview of these results).

In this paper, we shift the focus back on naval ships. To keep these ships operational and up to date throughout their life-time, maintenance plays a crucial role. 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 2015 (Ministry of Defence 2013; Royal Netherlands Navy 2013).

The current paper builds on this multiple case cycle and focusses on refinement by means of a structured abstraction of the AHP-based MPS approach in order to reveal the core of ship MPS. Insight in the core of ship MPS provides the means to expand the investigation by shaping our findings into a refined decision hierarchy and by testing this new decision hierarchy in a final, multi-company group session, as opposed to the single company sessions in the previous research. Hence, this paper contributes in two ways.

1. We methodologically refine the decision hierarchy. We do so based not only on the results and outcomes of the six sessions in general ship practice, but also on the feedback of the practitioners. This adds to the literature, as such a methodological approach to structuring decision hierarchies has not been encountered in the literature.
2. We organize a multi-company group AHP session with participants from four different companies within the same maintenance chain, where in previous research we used a single hierarchy of criteria at multiple companies, one at a time.

This paper is structured according to the steps explained above. In Section 2, we explore various methods to renew the decision hierarchy and explain the implementation thereof in the research. Next, the decision hierarchy is reviewed after which we construct a renewed decision hierarchy in Section 3. The set-up and results of the multi-company MPS session are presented in Section 4. We then draw conclusions and propose recommendations for further research in Section 5.

2 Structuring MCDM

To methodologically refine the decision hierarchy, choosing the most relevant criteria with which to make a decision hierarchy, a method or structure is needed. Although it seems that organizing and structuring criteria and objectives, and subsequently designing a decision hierarchy, is more an art than a science (Saaty and Peniwati 2013; Hammond and Keeney 1999), several structured approaches have already been formalized in the literature. We discuss three of such approaches that we could use in our research.

First, Saaty and Peniwati (2013, p. 71) state that there is one basic principle to follow for structuring an AHP decision hierarchy. It is to see if one can answer the following question: "can I compare the elements on a lower level using some or all of the elements on the next higher level as criteria or attributes of the lower level elements?"

According to Saaty and Peniwati (2013), the elements (being criteria, sub-criteria and alternatives) should be clustered into homogeneous groups of at least three, where the AHP often uses clusters of 7 ± 2 elements. The hierarchy should include as much detail as needed to understand the decision problem, as unimportant criteria will be eliminated by the judgement process. This means that seemingly unimportant criteria that are nonetheless needed to understand the problem should be included. The only restriction is that the elements in a cluster must be related to the element beneath which they are clustered, because it is this element that is used to assess the impact of the cluster beneath it.

Second, a method called *value-focussed thinking* promotes that values, which define all that one cares about in a specific decision situation, should be the primary focus of decision making. Value-focussed thinking aims at identifying the underlying value system for a decision situation and it involves clearly defining these values in terms of objectives that have influence on the decision (Keeney 1994). It provides five steps for systematically identifying and organizing these objectives (Hammond and Keeney 1999).

1. Write down all the concerns, considerations, and criteria you want to address through your decision.
2. Convert your general concerns into succinct objectives and organize them.
3. Separate ends from means to establish your fundamental objectives.
4. Clarify what you mean by each objective.
5. Test your objectives to see if they capture your interests.

Third, the most comprehensive and complete method that we are aware of, proposes a methodology not only for designing and structuring criteria trees (i.e., decision hierarchies), but also for the entire MCDM process (Brugha 2004). It aims to replace the several structuring ways into a single way of structuring. The method presents MCDM as an eight-stage process of shaping information that satisfies eight corresponding criteria: the information should be accessible, differentiable, abstractable, understandable, verifiable, measurable, refinable and usable. For each criterion a corresponding guideline is presented to clarify the stage. These are as follows.

1. Accessible: access the basic information of the decision problem. To access the right information, the decision should concern a real problem, involve the actual decision makers, and the information should be accessed at a time when the intent to solve the problem is real (i.e., the problem should be current).
2. Differentiable: differentiate the criteria from one another to form a criteria tree. To check differentiability, the alternatives should be comparable with each other, the formed clusters should be separable from each other, and the alternatives should have measurable aspects.
3. Abstractable: ensure robustness and usability under changing circumstances. This means that the criteria incorporated in the decision tree should be based on a set of empirical criteria that can be used to identify and abstract the actual and real criteria for the decision problem at hand and its underlying processes.
4. Understandable: construct a criteria tree, having several levels with no more than four sub-criteria for any criterion. By understanding the underlying processes, a meaningful and appropriate criteria tree can be formed, in which the criteria wordings clearly reflect what the criteria mean.
5. Verifiable: verify the criteria tree with decision makers. Start by verifying the names and phrasing of the criteria, extend this to the criteria tree as a whole, and end by revealing the underlying processes back to the decision makers.
6. Measurable: facilitate the measurement of the preferences. Start by scoring the alternatives, where the alternatives' scores should have meaning at every level of the criteria tree, then use an appropriate method to produce criteria weights. Together, the scores and weights develop the decision makers' preference scores.
7. Refinable: facilitate interactive refinement of scores and weights. For the decision makers to 'own' the process, allow modifiable scores and weights. Furthermore, it should be possible to exclude truly unwanted alternatives.
8. Usable: check the usability of the developed MCDM system. The most obvious aspect is that the system provides preferences. Furthermore, to make a new MCDM

system usable it should relate to the generics of the decision problem at hand. Lastly, it should be made usable to distribute decisions throughout the company.

The structuring method proposed by Brugha (2004) provides the most complete method to structure an MCDM process, it is highly workable and offers an overarching set of eight criteria with eight accompanying stages. Therefore, we use this method to structure our efforts. How we implement this structure is presented in Table 1, in which the eight stages, along with their corresponding criteria are linked to our research. Stages 1 – 4 consider the renewal of the decision hierarchy and are discussed in Section 3. Stages 5 – 8 are covered in the two MPS sessions that we have conducted and are discussed in Section 4.

Table 1 The MCDM structuring stages and the implementation thereof.

Stage	Criteria	Implementation
1	Accessible	Use the general ship hierarchy from previous research as starting point.
2	Differentiable	Use the participants' evaluations of the previous hierarchy.
3	Abstractable	Use the results of the six general ship sessions.
4	Understandable	Restructure and reformulate the hierarchy.
5	Verifiable	Organize a preliminary session, using the renewed hierarchy.
6	Measurable	Elicit the participants' preferences during the actual session using the AHP.
7	Refinable	Allow the participants to discuss and refine their judgements before the final results are displayed.
8	Usable	Present and explain the final preferences to the group of participants.

3 The decision hierarchy

The starting point, and Stage 1 of the structuring method, is the general ship decision hierarchy as used by Goossens and Basten (2015b). To restructure the hierarchy we take into account the following (see also Appendix A):

- the average relative priorities of the lowest level criteria;
- criteria with similar, discriminant policy scores, which might be clustered;
- the inconsistency ratios per session for each comparison matrix, which could indicate that participants do not understand these comparisons; and
- comparisons matrices where participants indicated equal importance for every comparison (i.e., give only judgement scores of 1), which could also indicate that participants do not understand the comparisons or find them irrelevant.

3.1 Restructuring the decision hierarchy

Our aim is to construct a decision hierarchy that is as concise and balanced as we believe possible, based on the feedback and results from practice. For Stages 2 and 3 we look at the results of the previous sessions, from which several facts stand out:

– *crew safety*, *reliability* and *availability* are the three most important criteria;
– relative to the other criteria, *cost minimization* is only of mediocre importance; and
– the three criteria that we previously clustered under *fit to relations* are of relatively little importance (the first, second and fifth most unimportant criteria).

Regarding inconsistent comparisons and comparisons receiving equal importances (i.e., judgements scores of 1), the following facts are noteworthy:

– *fit to relations* and its three sub-criteria obtain the highest amount of only 1s (two and six respectively); and
– some inconsistencies did occur during the sessions; however, looking at all the sessions, there is no comparison that is uniformly inconsistent, the inconsistent comparisons seem to be spread out evenly.

This gives reason to consider *availability*, *safety* and *reliability* as the top-level criteria, and to eliminate the cluster *fit to relations*. Besides these three, it appears that the following three discriminant clusters can be formed from criteria favouring the same maintenance policy.

1. A *costs* cluster, favouring condition-based maintenance, combining:
   – *cost minimization*; and
   – *spare parts cost*.
2. A *fit to system* cluster, favouring time/use-based maintenance, combining:
   – *commonality presence*;
   – *redundancy presence*;
   – *consequences of poor maintenance*;
   – *spare parts availability*;
   – *mission profile*; and
   – *criticality of parts*.
3. A *fit to company operations* cluster, also favouring time/use-based maintenance, combining:
   – *crew educational level*;
   – *crew size*;
   – *experience with maintenance*;
   – *compliance with existing policies*; and
   – *planability*.

The criterion *criticality of parts* scores marginally higher on condition-based maintenance than on time/use-based maintenance, yet seems to belong to the *fit to system* cluster. Because the difference of favour is so small and non-discriminating, we feel it would indeed fit best under the *fit to system* cluster.

The criterion *drive for innovation* needs special attention, since it does not fit in one of the clusters. After careful consideration, we feel that innovation is not a true driver for maintenance, but in itself always is driven by either an innovative system, an innovative company or innovative operations. Hence, we feel it is justified to exclude *drive for innovation* as separate criterion.

To summarize, these efforts result in three main criteria and three clusters of sub-criteria. These three clusters of sub-criteria seem to be relevant considerations for all three main criteria. This notion leads to the highly balanced structure for the renewed hierarchy, as presented in Table 2: three main criteria with three considerations per criterion and three alternatives.

Table 2 The conceptual 3 × 3 hierarchic structure.

Criteria	Considerations	Alternatives
Availability	Fit to system	Failure-based maintenance
Reliability	Fit to company operations	Time/use-based maintenance
Safety	Costs	Condition-based maintenance

3.2 The final decision hierarchy

For Stage 4 of the structuring method, we further develop this 3 × 3 structure, since it provides both conciseness and balance. Compared to the general ship hierarchy, this structure reduces the total number of criteria and sub-criteria in the hierarchy from 29 to 12. Furthermore, it also reduces the total number of required pairwise comparisons from 98 to 39.

Continuing Stage 4, we formulate the criteria and considerations such that the hierarchy can operate as a stand-alone decision hierarchy. The final decision hierarchy obtained in this way is presented below and shown in Figure 1.

The criteria are as follows, their definitions are drawn from relevant standardization norms:

- *availability realisation*: to realise the desired availability, where availability is the ability to be in a state to perform as and when required, under given conditions, assuming that necessary external resources are provided (definition based on European Committee for Standardization (2010));
- *reliability realisation*: to realise the desired reliability, where reliability is the ability to perform a required function under given conditions for a given time interval (definition based on European Committee for Standardization (2010)); and
- *safety assurance*: to assure the desired level of safety for everyone involved, where safety considers the ability of a machine to perform its intended function(s) during its life cycle where risk of physical injury or damage to health has been adequately reduced (definition based on International Organisation for Standardization (2010)).

The considerations we define as follows:

– *what best suits the system*: from a system point of view, think about: criticality, commonality, redundancy, use profile, spare parts and maintenance induced failures;
– *where the expertise lies*: from a company point of view, think about: company experience, educational levels, personnel and planning; and
– *what the cheapest option is*: from a financial point of view, think about: maintenance costs, maintenance budgets and austerity measures.

The maintenance policies are the same as in previous research:

– *failure-based maintenance*: corrective maintenance, where a failure triggers the maintenance;
– *time/use-based maintenance*: planable maintenance, where either the elapsed time or the amount of use triggers the maintenance; and
– *condition-based maintenance*: preventive maintenance, where a measured condition triggers the maintenance.

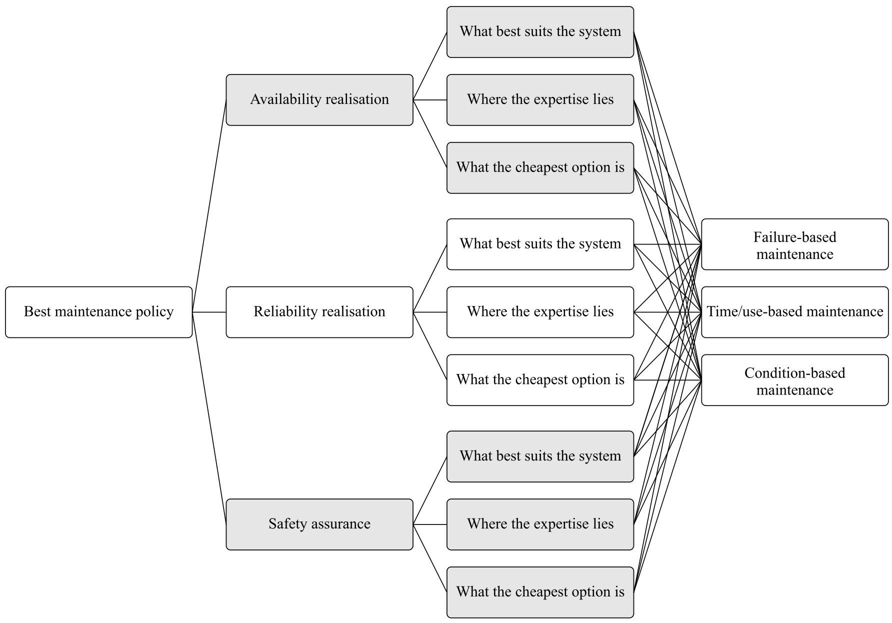

Fig. 1 The decision hierarchy.

4 The MPS session

The MPS sessions cover Stages 5 – 8 of the structuring method. Stage 5, the verification, is executed by performing a preliminary session. Stages 6 – 8 are incorporated in the structure of the multi-company session. To incorporate the judgement refinement of Stage 7, the session structure is:

1. An introductory presentation on planning of the session and the nature of our research.
2. A fictitious example case to get the participants acquainted with the AHP.
3. The selection and the execution of the company case (Stage 6):
   (a) selection of the group case;
   (b) individual judgements by the participants where they manually fill out the pairwise comparisons;
   (c) discussing the individual judgements in the group, focussing on where the participants disagree most, while allowing refinement (Stage 7); and
   (d) aggregation of the individual judgements into the group preference.
4. Presentation and discussion of the final results including a sensitivity analysis for the three main criteria (Stage 8).
5. An evaluation of the session by means of a questionnaire, in order to check Stage 8, focussing on the session itself, the hierarchy of criteria and the final decision (see Appendix B).

When using the AHP in a group setting, the AHP prescribes that the geometric mean

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

must be used to synthesize individual comparisons (Saaty 2008), where a_i is the score or weight per pairwise comparison, given by participant i, with $i \in \{1, \ldots, n\}$ and n being the number of participants present at the session. The geometric mean, not the common arithmetic mean, is proven to be the correct way to aggregate individual judgements, due to the ratio scale used for the pairwise comparisons are rated on (see also Saaty 2013, ch. 7).

The geometric standard deviation can then be used to investigate where the participants agree and disagree most in the pairwise comparisons:

$$\sigma_g = \exp\left(\sqrt{\frac{\sum_{i=1}^{n} (\ln \frac{a_i}{\bar{a}^{\mathrm{g}}})}{n}} \right) \tag{2}$$

where $\bar{a}^{\mathrm{g}}$ is the geometric mean of the scores or weights a_i per pairwise comparison, given by participant i, with $i \in \{1, \ldots, n\}$ and n being the number of participants present at the session.

To draw the relative priorities from the aggregated comparison matrices the so called geometric means approach is used to approximate the principal eigenvector (Hummel et al 2014; Williams and Crawford 1980). The software that we use during the session is a regular spreadsheet program (LibreOffice Calc).

4.1 Preliminary session

To validate the refined decision hierarchy, a preliminary session is organized at the Dutch pilot service, the *Loodswezen*. The case concerns their three 81.2 m long pilot vessels that operate as pilot stations at sea, from which pilots are brought to and from ships or shore. This is the second session held at the Dutch pilot service and one participant had also been present during the previous session (on which we report in (Goossens and Basten 2015b)). The session was attended by five participants with various roles throughout the company.

In their evaluations of the hierarchy, all five participants are unanimous. They state that the hierarchy is clear and understandable and matches the sector. The divisions into clusters are clear and logical, one participant explicitly praises the definitions. In contrast to the evaluation on which we reported in previous research, none of the participants indicate lacking or excludable criteria. One participant states that more criteria would make the hierarchy unclear, and another participant states that this hierarchy is better than the lengthy previous one.

For the final policy preferences, as shown in Table 3, the participants feel that the detailed comparisons quantify their gut feelings. They do not see time/use-based maintenance as the 'winner', but recognise the final policy preferences as the right mix and quantification of maintenance policies for the pilot vessels, towards which the company is already working.

Based on these promising evaluations, we keep the hierarchy as it is for the final session.

Table 3 Final preferences of alternative maintenance policies at the Loodswezen session.

	Failure-based	Time/use-based	Condition-based
Pilot vessel	0.133	0.447	0.421

4.2 Set-up of the final session

For the final session, we go back to the first ship type that we have investigated: naval ships. We have already encountered the maintenance chain of naval ships. However, instead of organizing a session at each individual company as we did in previous research (Goossens and Basten 2015a), we organize one multi-company session. Of these companies, two participants per company attend the session. An overview of the company, the roles and the participants is given in Table 4.

During the case selection within the context of the maintenance chain of the participants, debate arose on the most relevant level in the system. The discussion considered the complete Thales radar system or a line replaceable unit (LRU) of the radar system, both as installed on ships of the Royal Netherlands Navy built by Damen Schelde Naval Shipbuilding. To correspond to the high level in the system for which our AHP-based MPS approach seems to work best, the radar system itself is chosen as case.

4.3 Results of the final session

After the participants individually filled out the pairwise comparisons, their judgements are compared and discussed within the group. This discussion proved to be extensive, with the participants giving and defending their views, each from their own area of expertise. As revealed in the next sections, this discussion had great influence on the session and the evaluations of the session.

Although the debate was extensive, no refinements have been made by the participants. The final judgements are remarkably consistent; the highest consistency ratio is 4%. This results in the final policy preferences that are presented in Table 5. The results show that failure-based maintenance is the least preferred policy, while time/use-based maintenance and condition-based maintenance obtain a similar preference.

Table 4 Final session companies, roles and participants.

Role	Company	Participants
OEM	Thales Netherlands	2
Shipbuilder	Damen Schelde Naval Shipbuilding	2
Owner/regulator	Ministry of Defence – Defence Materiel Organisation	2
Owner/maintainer	Royal Netherlands Navy – Directorate of Materiel Support	2

Table 5 Final preferences of alternative maintenance policies.

	Failure-based	Time/use-based	Condition-based
Radar system	0.220	0.383	0.398

These results are in line with our previous findings that the actual consideration is between time/use-based maintenance and condition-based maintenance (Goossens and Basten 2015b). The relatively high preference of failure-based maintenance, compared to the previous sessions, can be explained by the high number of electrical components within the system. These components have a constant failure rate, which means that their probability of failure does not change over time and that thus time/use-based and condition-based maintenance cannot reasonably be applied.

4.4 Evaluation of the final session

As the final part of the session, all participants are handed an evaluation form (see Appendix B). The evaluation is divided into three categories: the session itself, the hierarchy of criteria, and the final choice made.

The first part of the evaluation considers the session itself. This part consists of questions about the session in general, its usefulness and the groups with which the sessions are held.

- All participants enjoy doing the session and find the session useful. They indicate that it was interesting and insightful. They particularly like sharing knowledge throughout the maintenance chain and the discussions that took place. Learning from the different points of view on the problem from the different companies and their position in the maintenance chain is seen as one of the main benefits. However, these different points of view also led to interpretation issues regarding the definitions of the criteria, the chosen case, and on how to judge the pairwise comparisons. This made some participants doubt the accuracy, and thus usefulness, of the final policy preferences.
- To do such a session again, the participants indicate that the session should be more result oriented, with a clearer goal and more concrete results, perhaps with an adjusted hierarchy. The right moment to do such a session seems to be at the start of significant developments concerning the system, such as at the start of the design phase of a system, the start of a new materiel project, or at the introduction of new systems within the fleet.
- The diversity and size of the group with which the session was held are highly regarded. One participant even states that the group was almost perfect, but two participants pitied the lack of actual end users of the system (i.e., naval crew members).

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.

- The hierarchy is generally well received and understandable. However, after considerable discussion on the criteria, the participants seem to agree on the following four comments:
  1. although safety plays an important role within maintenance, safety should be a pre-condition for maintenance, so that the inclusion of safety within the hierarchy is debatable;
  2. a focus on life-cycle costs would be more relevant than the current focus on maintenance costs;
  3. availability and reliability are too much alike, including either one would be sufficient; and
  4. the definitions are too generic and using more precise definitions, such as formulas, could help.
- Several suggestions are made regarding lacking criteria: maintainability, functionality, sustainability and performance.

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.

- The participants indicate that they would not have chosen for the same final policy preference and four participants specifically indicate that they would intuitively have given failure-based maintenance a higher preference.
- However, six participants indicate that they now better understand how the final selection was made. Two participants are indifferent.
- After the initial debate and the session, for the ideal level in the system for which a maintenance policy can be selected using such a session, the participants indicate either system level or line replaceable unit (LRU) level equally. Again, the design phase of the system is mentioned as a suitable moment to conduct a session.
- Two participants draw a comparison with Reliability Centred Maintenance (RCM), a widely used maintenance concept (Smith and Hinchcliffe 2004). Feeling that the uses differ, they are interested in how the AHP-based MPS approach could complement RCM.

These evaluations are partly in line with the results from our previous research. Based on the comments by the participants, we think that the differences relate to the participation of multiple companies, each with their own background and view on the maintenance chain. The increased amount of different views seem to lead to more insightful discussions, but to less usable final policy preferences.

Furthermore, it is remarkable that the renewed decision hierarchy as well as the final policy preferences obtain such different evaluations from the preliminary session and from the multi-company session. At the preliminary session, the hierarchy was undisputed and the results proved accurate. At the final session, the hierarchy was extensively debated and the accuracy of the results was doubted. An explanation could lie in the homogeneity (or diversity) of the group. It seems that a diverse group allows for more learning from extensive debate on the different views, while a homogeneous group (already holding similar views) provides more accurate results for actual decision making.

5 Conclusions

This paper set out to structure our AHP-based MPS approach by following the MCDM method proposed by Brugha (2004). We have refined the decision hierarchy and validated it by organizing and evaluating a final multi-company group session, in which participants from four different companies participated. Based on the results and evaluations of both the preliminary session and the multi-company session, several conclusions can be drawn.

- The methodology proposed by Brugha (2004) provides a workable set of 8 stages and guidelines to structure an MCDM process.
- This structure, in combination with our previous results, enabled us to successfully create a workable and concise decision hierarchy. The renewed decision hierarchy retains the core of ship MPS, while greatly reducing the total number of criteria and sub-criteria and the amount of pairwise comparisons required.
- However, the reactions to this hierarchy are mixed. Most importantly, the role of the safety criterion is debatable. If safety should act as a pre-condition for

maintenance, it could arguably be removed from the hierarchy. However, the impact that safety has on maintenance should not be neglected. Furthermore, in some cases, such as in the multi-company case, the line between availability and reliability seems to fade. In this case a straightforward explanation was given by the participants: a naval system has to finish its mission and, therefore, can only be considered available if it is reliable enough to finish its mission.
- The preliminary and multi-company sessions suggest that there is a trade-off between group diversity and usefulness of the results. A diverse group will have various points of view that allow a broader discussion, while a more uniform and like-minded group will have less interpretation issues that will result in more accurate final preferences. The former could be used to emphasize on learning, the latter to emphasize on the actual decision.
- Our previous research revealed that the strength of the AHP-based MPS approach lies in high system level strategic maintenance thinking. This paper adds nuance to these previous findings. It seems that the best moment to use this approach is at the start of 'something', where that 'something' can be the design phase, an acquisition project, the introduction of new systems or the development of a maintenance philosophy.

The research and its conclusions give rise to several recommendations for further research.

- The relations and interdependency of the three top-criteria can be investigated using the Analytic Network Process—however, at the cost of a higher complexity of the model.
- Although availability and reliability are clearly defined in literature, an empirical investigation into their actual uses and roles in practice is recommended.
- Finally, a continuation of this research and further investigation into the decision hierarchy, and new iterations in practice, could create an even more concise decision hierarchy.

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A Criteria weights and policy scores

The idealised average global weights of the lowest level criteria and their average policy scores, used as the basis for this paper, are shown in Figure 2.

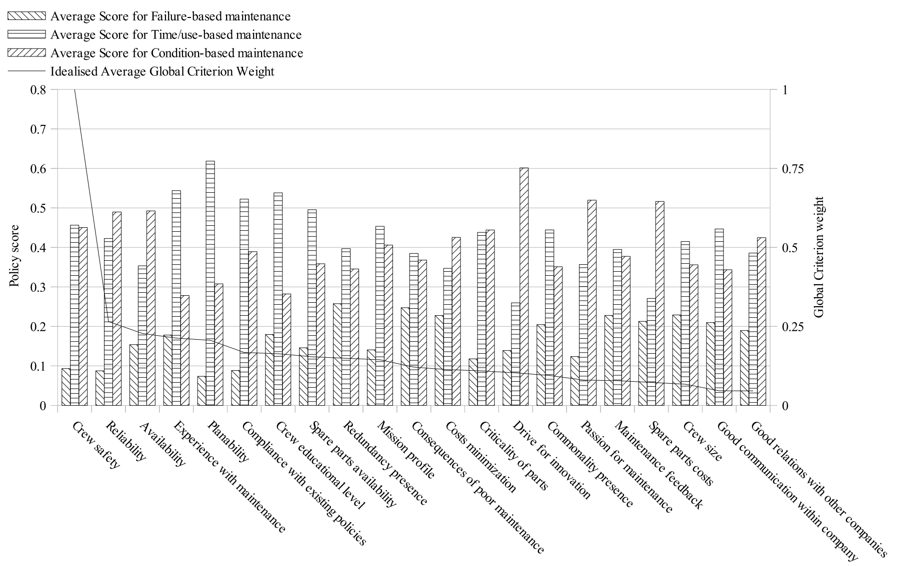

Fig. 2 Idealised average global weights of the lowest level criteria and their average policy scores, from Goossens and Basten (2015b).

B Evaluation form questions

1. The session
   (a) What did you think of the session?
   (b) Did you find it useful? Why or why not?
   (c) Did you enjoy it? Why or why not?
   (d) What do you think of the duration of the session?
   (e) Would you want to do such a session more often? Why or why not?
   (f) If so, at which kind of moments, and at which intervals?
   (g) What did you think of the group? For example, of the number of participants and their various roles.
   (h) Do you have any suggestions for improvement?
2. The hierarchy of criteria
   (a) Do you think the hierarchy is clear and understandable? Why or why not?
   (b) What do you think of the groupings and divisions made in the hierarchy?
   (c) Are any criteria lacking? If so, which?
   (d) Are any criteria redundant or unnecessary? If so, which?
3. The decision
   (a) During the session, one of the maintenance policies emerged as the best. Would you yourself have chosen for the same policy? Why or why not?
   (b) Do you feel that you now better understand how the choice is made? How come?
   (c) For which level in the system would you ideally select a maintenance policy during a session like this one?
4. Do you have any other remarks?