A photograph of a ship's hull in a dry dock. A yellow forklift is parked in the foreground, and a large, multi-story staircase with metal railings runs up the side of the hull. The scene is dimly lit, with a strong light source from the left creating a bright area on the hull and the forklift.

Maintenance Policy Selection for Ships

An investigation using the Analytic Hierarchy Process

Adriaan Goossens

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Ph.D. thesis, University of Twente, Enschede, the Netherlands

Typeset with L^AT_EX 2_ε and Kp-Fonts

The photo on the cover shows the RNLN's vessel *Zr. Ms. Mercurur* in the dry dock, and is used by courtesy of the Netherlands Defence Audiovisual Service.

This research has been funded by Lloyd's Register Foundation. Lloyd's Register Foundation helps to protect life and property by supporting engineering-related education, public engagement and the application of research.

MAINTENANCE POLICY SELECTION FOR SHIPS
AN INVESTIGATION USING THE ANALYTIC HIERARCHY PROCESS

PROEFSCHRIFT

ter verkrijging van
de graad van doctor aan de Universiteit Twente,
op gezag van de rector magnificus,
prof. dr. H. Brinksma,
volgens besluit van het College voor Promoties
in het openbaar te verdedigen
op woensdag 30 september 2015 om 12:45 uur

door

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geboren op 28 januari 1984
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ISBN 978-90-365-3927-2x

DOI 10.3990/1.9789036539272

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Little snail
Inch by inch, climb
Mount Fuji!
—Issa

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PREFACE

BEFORE you lies the result of four years of research, captured on paper. Looking back, it does not seem much, but I wouldn't have missed it for the world. It were four fascinating years. I have explored the Netherlands, from Vlissingen to Den Helder. I have travelled the world: Seoul, Southampton, Dublin, Palermo and Nashville. I have engaged in conversation with scientists, CEOs, CTOs, managers, engineers, technicians, soldiers, consultants, lifeguards, and many, many more. I had the opportunity to take a close look at high-tech equipment, such as jet fighters, trains, radar systems, ship yards, submarines and the brand new *Zr. Ms. Karel Doorman*. About this, I have not only written scientific papers, but also articles for industry and the military. I even wrote a book.

However, I didn't do it all alone. Getting this far would not have been possible without the never-ending support of my loving wife. Sanne, I wholeheartedly thank you for your faith in me, for your patience with me, and for marrying me.

Also, I would like to thank my family for their continuous encouragements: my parents Arie and Ria, my parents-in-law Wim and Wilma, and of course Peter, Mirjam and Matt.

Where would a PhD student be without his peers? Probably in a very empty office. So thank you Jorge, Wienik and Taede, and also Boris and Krijn, for putting up with me, discussing our brilliant ideas, and not taking it all too seriously.

Besides peers, a PhD student also has superiors—formal interference is prescribed. Leo, I thank you for your supervision, advice, and life lessons on how to catch a stone marten. Rob, thank you for your guidance, our weekly *bila's*, and the (what must have been) gallons of ink spent scrutinizing my work.

All this is, of course, based on the foundations of the chair of Maintenance Engineering and all its members, as well as the whole of OPM.

Lastly, I would like to thank all interviewees and session participants for their hospitality and willingness to share their knowledge: Isaac Barendregt, Gerard Burema, Jan Busscher, Annebel de Deugd, Leon van den Einden, Henk Fischer, Jan Hendriks, Ewoud Hoek, Koen ter Hofstede, Rinze Huisman, Hidde Hylarides, David Janse, Alwin Kleinepier, Leontine de Koning, Jan Kooistra, Kasper Kools, Desmond Kramer, Harry Lijzenga, Rick Maliepaard, Niek Marsé, Riemert Moleman, Hans van der Molen, Taco Moll, Yuri Nieuwenhuizen, Arnout Oosterhof, Cristi Petrescu, Jacques van der Puil, Jerry van Rees, Chris de Ron, Arjen Schaper, Niels van Schijndel, Fred Schulte, Ferit Serti, Erik Sikma, Mark Snijders, Jouke Spoelstra, Patrick Tit, Bart Uitendaal, Rick van Vliet, Tjeerd de Vos, Koen Willems, Martin Wouters, Rindert Ypma, André Zijderveld, and Michal Zulawinski.

Here's to the future!

Enschede, August 30, 2015

Adriaan Goossens

SUMMARY

MAINTENANCE is an important contributor to reach the intended life-time of capital technical assets. How to maintain these assets is gaining increasing attention and relevance. 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. The increasing complexity and changing demands of technical capital assets have led to a change in the way maintenance is viewed. Nowadays, maintenance is not seen as a necessary evil any more, but as a strategic concern for many businesses, with many of them nurturing effective maintenance organisations.

Maintenance is a broad term, affecting decisions at all levels of an organization, from the strategic level to the operational level. One of these decisions is selecting the right maintenance policy, which we call *maintenance policy selection* (MPS). A maintenance policy is a policy that dictates which parameter triggers a maintenance action: for example, failure-based maintenance is triggered by the failure of a component and time-based maintenance is triggered by a pre-defined amount of elapsed time. Selecting the right maintenance policy appears to be a difficult decision: current selection methods do not always fit companies well, the mostly quantitative content of scientific efforts preserve a gap between theory and practice, and there is still a scarcity of practical approaches to maintenance decision making.

The research focusses on technical capital assets, by which we mean capital intensive, technologically advanced systems that have a designed life-time of at least 25 years. Within this classification our research aims at—but does not limit itself to—a type of so called transportable mobile technical capital assets, namely naval ships. In the Netherlands, the owner, operator and foremost maintainer of these ships is the Royal Netherlands Navy (RNLN). With a designed life-time of 25 years, an average age of 17 years, and estimated

acquisition costs of € 100 to € 400 million, the RNLN's sea going vessels are excellent examples of technical capital assets.

The aim of this thesis is twofold: first, to investigate which factors truly play a role for MPS and, second, to develop an MPS method incorporating these factors. To structure the research, we identify three key challenges for the investigation: the fit of the MPS method to companies; the applicability of the MPS method in practice; and the practicality of the research. The first means that the MPS method should be relevant to the company and situation at hand. To increase the fit of the MPS process to companies the relevant criteria should be used during the selection process and companies should be able to indicate what they feel is important to their specific situation. The second means that practitioners should be able to use and apply the MPS method. To increase the applicability of the MPS method in practice an MPS method should be understandable for practitioners, be easy to use, and provide insight in the MPS process. Lastly, the third means that the research should be performed in a practical way. To obtain a practical study, the research should integrate knowledge from both literature and practice, actively involve cooperation with practitioners, and use the feedback obtained from practice to improve the MPS method.

To reach these objectives, we apply a design approach to organizational research and use a multiple case approach. For this, we turn to multiple criteria decision making (MCDM) methods and propose the use of the Analytic Hierarchy Process (AHP). The AHP appears to be highly suitable for MPS as it fits the key challenges, and has not yet been applied to MPS in a broad and structured way (Chapter 2). Hence, we explore the use of the AHP for MPS in a broad way, applying the method for naval ships at three different companies: a naval shipyard, a naval original equipment manufacturer (OEM) and the RNLN itself. The criteria that play a role for naval MPS are drawn from the literature and eight interviews in practice. The obtained criteria are structured into a first decision hierarchy, usable with the AHP. Using this hierarchy along with the AHP, we organize three sessions in practice to test the approach in industry (Chapter 3). Next, to further investigate MPS, we broaden our approach towards ships in general. Using the feedback from the naval sessions, we improve the decision hierarchy and use this hierarchy at six more sessions at six different ship companies: a shipbuilder, two ship maintainers, and three ship operators. During these sessions, we inherently elicit the participants' preferences, giving insight in the most important criteria and considerations for ship MPS (Chapter 4). Following that, we go back to naval ships by using the AHP-based MPS approach in a multi-company session, with participants from various companies within the naval maintenance chain. As

opposed to the previous naval sessions at one company at a time, during this session participants from four companies are present: the naval shipbuilder, the naval OEM, the Defence Materiel Organisation, and the RNLN. For this session, we methodologically review the decision hierarchy based on the results and feedback from the sessions in general ship industry, and first apply this new hierarchy during a preliminary session at a ship operator (Chapter 5). We propose a final decision hierarchy consisting of three main criteria, each followed by three considerations and three alternative maintenance policies. The three criteria, found to be the three most important, are *availability realisation*, *reliability realisation* and *safety assurance*. The three considerations are *what best suits the system*, *where the expertise lies* and *what the cheapest option is*. The three alternative maintenance policies are *failure-based maintenance*, *time/use-based maintenance* and *condition-based maintenance*.

In our research, literature and practice have worked together. Combining literature and practice in this way secures both scientific and practical results. We have captured the relevant criteria and have shown that not only hard, quantifiable criteria, but also softer criteria should be included in ship MPS. The AHP allows these criteria and alternatives to be incorporated into one MPS method and facilitates the MPS process. For this, the AHP proves to be a highly elegant and suitable method. It is an understandable and easy to use process that provides the means to gain a thorough insight in the decision process. The use of the AHP-based MPS method is not so much in making the actual decision, but in providing a structured way to think about MPS and in facilitating a structured and meaningful discussion. The AHP-based MPS approach works best for considering high levels in the system in a strategic way, even up to fleet level. The best moment to use this method would be at the start of new developments, such as a new design phase, an acquisition project, the introduction of new materiel, or the development of new maintenance plans. Furthermore, there appears to be a trade-off between the diversity within a group of participants and the accuracy—and thus usefulness—of the final policy preferences.

Besides broadening the research to other application areas, we propose several paths for further research. First, further research is needed into the exact roles of *availability*, *reliability*, *safety* and *costs* for MPS. Second, we propose an investigation on how the AHP-based MPS approach can complement the often used Reliability Centred Maintenance. Third, we see relevance in exploring how the designers and the design phase of the asset can be structurally incorporated in the AHP-based MPS approach.

SAMENVATTING

ONDERHOUD levert een belangrijke bijdrage aan het halen van de ontworpen levensduur van technische kapitaalgoederen. Onderhoud kan gedefinieerd worden als alle activiteiten die als doel hebben een systeem in een conditie te houden die nodig wordt geacht voor het naar behoren functioneren. De vraag hoe deze systemen het best onderhouden kunnen worden wordt steeds belangrijker. De toenemende complexiteit en veranderende eisen van technische kapitaalgoederen hebben namelijk een verandering teweeg gebracht: onderhoud wordt tegenwoordig niet meer gezien als noodzakelijk kwaad, maar als een strategisch middel voor goede bedrijfsvoering, dat juist waarde toe kan voegen.

Onderhoud is een breed begrip, dat invloed heeft op besluitvorming in alle lagen van een organisatie. Eén van deze zaken is de keuze van de juiste *maintenance policy*: *maintenance policy* selectie (MPS). Een *maintenance policy* is een beleid dat voorschrijft welke parameter tot onderhoudsactie leidt. Zo wordt tijdsafhankelijk onderhoud, bijvoorbeeld, toegepast op basis van enkel de verstreken tijd, en bij conditie-afhankelijk onderhoud wordt van de waargenomen conditie uitgegaan. Het selecteren van de juiste *maintenance policy* blijkt in de praktijk een lastige keuze: niet alle selectiemethoden passen even goed bij elk bedrijf, het meestal kwantitatieve wetenschappelijke werk zorgt voor een gat tussen de theorie en de praktijk, en er is een tekort aan praktijkgerichte aanpakken voor onderhoudsbeslissingen.

Dit onderzoek richt zich dus op technische kapitaalgoederen. Hieronder verstaan we kapitaalintensieve, technologisch geavanceerde systemen die een ontworpen levensduur van minstens 25 jaar hebben. Hierbinnen richt het onderzoek zich op—maar limiteert zich niet tot—de zogenoemde verplaatsbare, mobiele technische systemen, en wel marineschepen. In Nederland is de eigenaar, gebruiker en voornaamste onderhouder van deze schepen de Koninklijke

Marine. Met een ontworpen levensduur van 25 jaar, een gemiddelde leeftijd van 17 jaar, en geschatte aanschaffkosten van € 100 tot € 400 miljoen zijn hun schepen een uitstekend voorbeeld van technische kapitaalgoederen.

Het doel van het onderzoek is tweedelig: ten eerste het achterhalen welke factoren een rol spelen bij MPS, en ten tweede om een MPS-methode te ontwikkelen die deze factoren meeneemt. Om het onderzoek te structureren, zijn er drie *key challenges* geformuleerd: de passendheid van de MPS-methode bij bedrijven; de toepasbaarheid van de methode in de praktijk; en een praktijk-gerichte aanpak van het onderzoek. De eerste houdt in dat methode relevant moet zijn voor bedrijven en hun specifieke situatie. Hiervoor zullen de relevante criteria in acht moeten worden genomen, en de belangrijkheid ervan moet door de bedrijven zelf bepaald kunnen worden. De tweede houdt in dat de methode in de praktijk gebruikt moet kunnen worden. Hiervoor moet de methode begrijpbaar zijn, gemakkelijk toe te passen zijn, en inzicht geven in het beslissingsproces. De derde houdt in dat het onderzoek op een praktische manier uitgevoerd moet worden. Hiervoor zal kennis uit zowel wetenschappelijke literatuur als uit de praktijk gecombineerd moeten worden, een samenwerking met de praktijk gezocht moeten worden, en moet de terugkoppeling van de praktijk gebruikt worden om de methode te verbeteren.

Om dit te kunnen bereiken, combineren we onderp- en organisatieonderzoek, gebruikmakend van meerdere casussen in de praktijk. Hiervoor stellen we het gebruik van een multi-criteria belissingsmethode voor, namelijk de *Analytic Hierarchy Process* (AHP). De AHP lijkt uitermate schikt voor MPS, omdat het goed aansluit bij de *key challenges* en het nog niet eerder op een brede en gestructureerde manier voor MPS is gebruikt (Hoofdstuk 2). Als eerste onderzoeken we daarom de toepasbaarheid van de AHP voor MPS op een brede manier, waar we de AHP toepassen voor marineschepen bij drie verschillende bedrijven: een scheepswerf, een *original equipment manufacturer* (OEM), en de Koninklijke Marine zelf. De criteria die een rol spelen voor MPS voor marineschepen zijn verkregen uit de literatuur en uit acht interviews in de praktijk. Deze criteria zijn tot een beslissingshiërarchie gevormd die te gebruiken is met de AHP. Met deze hiërarchie en de AHP hebben we drie sessie's georganiseerd bij de drie genoemde bedrijven om deze aanpak te testen in de praktijk (Hoofdstuk 3). Om MPS vervolgens verder te onderzoeken, verbreden we onze aanpak naar de commerciële scheepvaart. Nadat de terugkoppeling van de eerste drie sessie's is gebruikt om een tweede versie van de beslissingshiërarchie te ontwikkelen, is deze hiërarchie gebruikt bij zes nieuwe sessie's bij zes verschillende bedrijven: een scheepswerf, twee maritieme onderhoudsbedrijven en drie scheepseigenaren. Tijdens deze sessie's achterhalen we tegelijkertijd de voorkeuren van de deelnemers, waardoor we inzicht krijgen in welke cri-

teria het belangrijkste zijn voor MPS schepen (Hoofdstuk 4). Als laatste keren we terug naar de marineschepen door een laatste sessie te organiseren met verschillende bedrijven binnen de onderhoudsketen van marineschepen. In tegenstelling tot de eerdere sessie's, waar steeds één bedrijf aanwezig was, zijn er tijdens deze sessie deelnemers aanwezig van vier verschillende bedrijven: de scheepswerf, de ОЕМ, de Defensie Materieel Organisatie en de Koninklijke Marine. Voor deze sessie herzien we de beslissingshiërarchie volledig, waarbij we gebruik maken van de resultaten van de commerciële scheepvaart, en testen deze nieuwe hiërarchie tijdens een voorbereidende sessie (Hoofdstuk 5). Deze uiteindelijke beslissingshiërarchie bestaat uit drie hoofdcriteria, elk gevolgd door drie overwegingen en drie *maintenance policies* om uit te kiezen. De drie hoofdcriteria zijn *beschikbaarheidsrealisatie*, *betrouwbaarheidsrealisatie* en *veiligheidsgarantie*. De drie overwegingen zijn vervolgens *wat het beste bij het systeem past*, *wat het beste bij de expertise past*, en *welke de goedkoopste optie is*. De drie *maintenance policies* waaruit gekozen kan worden zijn *correctief onderhoud*, *tijds-/gebruiksafhankelijk onderhoud* en *conditie-afhankelijk onderhoud*.

Tijdens het onderzoek is veel met de praktijk en het bedrijfsleven samengewerkt, dit heeft zowel wetenschappelijke als praktische resultaten opgeleverd. De relatieve criteria die een rol spelen bij MPS voor schepen zijn gevonden, en het blijkt dat niet alleen harde, kwantificeerbare criteria, maar dat ook zachtere criteria een rol spelen. De АНР zorgt ervoor dat deze criteria en *policies* samengevoegd kunnen worden in methode die het MPS proces faciliteert. Hiervoor blijkt de АНР een elegante en goed toepasbare methode, die niet zozeer dwingt tot het maken van een besluit, maar juist een manier is om gestructureerd na te denken over MPS en betekenisvolle discussies teweeg brengt. De resulterende MPS-methode gebaseerd op de АНР lijkt dan ook het best te werken voor hoge niveau's in het systeem, tot aan vlootniveau toe. Het beste moment om de methode te gebruiken lijkt aan het begin van nieuwe ontwikkelingen, zoals een nieuw ontwerpproject, de introductie van nieuw materieel of de ontwikkeling van nieuwe onderhoudsplannen. Er lijkt echter een afweging te bestaan tussen de diversiteit binnen een groep deelnemers en de directe bruikbaarheid van de resultaten.

Behalve een verbreding naar andere toepassingsgebieden, stellen we een aantal richtingen voor vervolgonderzoek voor. Als eerste is er meer onderzoek nodig naar de precieze rollen die beschikbaarheid, betrouwbaarheid, veiligheid en kosten spelen voor MPS. Een tweede vraag is hoe de MPS-methode het veelgebruikte *Reliability Centred Maintenance* kan aanvullen. Als laatste zien we mogelijkheden om te onderzoeken hoe de ontwerpers en de ontwerpfase van een systeem structureel bij MPS kunnen worden betrokken.

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Maintenance is an important contributor to reach the intended life-time of technical capital assets, which are capital intensive, technologically advanced systems that have a designed life-time of at least 25 years, such as trains, ships and aeroplanes. Maintenance is needed to keep a system in, or restore it to, the condition that is necessary for it to function as intended. How to maintain these assets is a question that is gaining increasing attention and relevance. This is further discussed in Section 1.2, where an overview of maintenance is given, after which maintenance policy selection is explained. The difficulties concerning maintenance policy selection are explained in Section 1.3, leading to the aim of this thesis underpinned by three key challenges. Section 1.4 elaborates on technical capital assets and in this section the application area of the research is defined. The approach of the research and the overview of this thesis are presented in Section 1.5.

1.2 MAINTENANCE

The increase of attention on and relevance of maintenance has several underlying reasons. Namely, along with the increasing complexity of systems, the organisational view on maintenance has evolved during the past decades, and maintenance has found its way to national agendas.

The increasing complexity and changing demands of, firstly, military systems called for a different way of thinking [1, 2]. Halfway the twentieth century, the emphasis on production changed to an emphasis on service delivery; not the product, but the service it could deliver was starting to be valued. The component-centric focus that served well in the first half of the twentieth century shifted towards an interest in system-level aspects. This led to the awareness that systems are more than just their hardware component. Instead, the hardware interacts with software, and organizational and human components. This, in turn, increased attention and relevance to the question of what, how and how often to maintain.

The organisational view on maintenance changed as well. Halfway the twentieth century, maintenance was regarded a necessary evil, lagging behind other areas of industrial management [3–5]. With the realization that maintenance is an important factor in product quality and performance, and the understanding of the impact that poor maintenance has on profitability [3, 4], maintenance has become essential for many organisations. Nowadays, it has grown into a strategic concern for businesses and is used for successful competition [3, 5], with many organisations encouraging effective maintenance organisations [4].

Maintenance is further getting national attention, simply because of the sheer amount of money involved (examples of the costs involved with maintenance are plenty and have been well documented [4, 6–9]). For example, for the Netherlands, it is estimated that 10% of the gross domestic product is spent on maintenance annually [10] (accounting to roughly € 64 billion in 2013 [11]). This has led to the formation of partially state sponsored programmes and institutions that aim to bring maintenance to the agendas of both industry and academia, such as the maintenance oriented Dutch Institute for World Class Maintenance and the service logistics oriented Dutch Institute for Advanced Logistics.

Maintenance is most commonly 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 [3, 5, 10, 12, 13]. Other definitions include purposes such as providing a service to enable an organisation to achieve its objectives [4] and sustaining the capability of the system to provide a service [14]. Although its definition is quite broad, five specific responsibilities of maintenance are generally recognized [4]:

- keeping assets and equipment in good condition, well configured and safe to perform their intended functions;

- performing all maintenance activities including preventive, predictive and corrective maintenance, overhauls, design modification and emergency maintenance in an efficient and effective manner;
- conserving and controlling the use of spare parts and material;
- commissioning new plants and plant expansions; and
- operating utilities and conserve energy.

1.2.1 An overview of maintenance

The maintenance of technical capital assets can be split up into several tiers, ranging from the strategic level to the operational level [3, 5, 9, 15]. An overview of maintenance, its tiers and nomenclature is given in Figure 1.1. In each tier, decisions are made regarding, for example, what the maintenance objectives are, which maintenance concept to implement, which maintenance policy to select, and so on. Viewed top-down, i.e., from the strategic level to the operational level, these tiers can be classified by the following questions.

What is achieved by maintenance? The answer to this is the maintenance objective. It is the reason why maintenance is done in the first place and is closely related to the company's mission, vision and revenue model.

How can the objective be reached? The maintenance objective can be reached by implementing a suitable maintenance concept. A maintenance concept is a structured way to plan and control the various maintenance policies and actions, as well as to improve the applied maintenance actions and policies. The most well known example of a maintenance concept is Reliability Centred Maintenance (corresponding with a reliability focussed maintenance objective).

What triggers the maintenance action? Here, a maintenance policy prescribes which parameter triggers a maintenance action. Such parameters can be a failure, a certain amount of elapsed time or a measured condition, resulting in failure-based maintenance, time-based maintenance and condition-based maintenance respectively. We come back to maintenance policies in Section 1.2.2.

What is the preferred maintenance approach? Once the maintenance policy is selected, the preferred maintenance approach must be chosen. For example, a choice must be made between repair or replacement.

FIGURE 1.1
An overview of maintenance.

How is the maintenance done? Once the maintenance approach has been decided on, it needs execution. Here, decisions have to be made regarding the method of executing the maintenance, for which materials, machines and manpower need to be allocated.

How well was the maintenance done? Closing the figurative loop, maintenance performance can be measured. To do this, the right performance measures, corresponding to the followed strategy, must be chosen and monitored. This serves as feedback on how well the maintenance objective is reached.

1.2.2 Maintenance policy selection

Our research focusses at one tier of these decisions: maintenance policy selection (MPs). To avoid confusion, we first clearly define the term *maintenance policy*. Based on [5], we define a maintenance policy as a policy that dictates which parameter (for example, elapsed time or amount of use) triggers a maintenance action. Consistent with this definition, we distinguish six basic maintenance policies [16]:

- *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.

1.3 RESEARCH AIM AND KEY CHALLENGES

Selecting the right maintenance policy appears to be a difficult decision. There are several reasons for this. First, current selection methods do not always fit companies well, as all of these methods have specific drawbacks, as will be further outlined below. Therefore, the need for development of tailored maintenance is raised in the literature: maintenance needs to be tailored to the specific needs of a company in a structured way, allowing for flexibility, feedback and improvement [5, 17].

Furthermore, a significant gap between theory and practice still exists, in terms of both content and approach. Regarding the content, current, mostly quantitative, maintenance optimization and decision models are often too detailed and over-parametrized to have a high applicability in practice [2]. Moreover, they are mostly aimed at optimizing efficiency, rather than creating effectiveness—although it is effectiveness in which practitioners are often interested [18]. Considering the approach, there is a scarcity of practical approaches to maintenance modelling. This was already pointed out in 1992 [19], and not much has changed since. Although maintenance is something that should be done in practice, several authors argue that practical studies are still under-represented [20, 21].

The aim of this thesis is twofold: first, to investigate which factors truly play a role for MPS and, second, to develop an MPS method that incorporates these factors and that mitigates the above mentioned difficulties. These two research aims are intertwined: on the one hand, we aim to incorporate the factors into the MPS method and, on the other hand, we aim to use the MPS method to gain more understanding of the factors that play a role. To structure the research, we identify three key challenges for the investigation of MPS, based on the above.

1. *The fit of the MPS method to companies.* The MPS method should be relevant to the company and the situation at hand. To increase the fit of the MPS process to companies, the relevant criteria should be used during the selection process and companies should be able to indicate what they feel is important for their specific situation.
2. *The usability of the MPS method in practice.* Practitioners should be able to use and apply the MPS method. To increase the applicability of the MPS method in practice, an MPS method should be understandable for practitioners and easy to use, and it should provide insight in the MPS process.

3. *The practicality of the research.* The research should be performed in a practical way. To obtain a practical study, the research should integrate knowledge from both literature and practice, actively involve cooperation with practitioners, and use the feedback obtained from practice to improve the MPS method.

Key challenges 1 and *2* directly relate to the two research aims by focussing on the relevant criteria and on a usable MPS method. *Key challenge 3* concerns the approach of the research and the way the MPS method is developed.

1.4 APPLICATION AREA

This thesis regards the maintenance of technical capital assets. By technical capital assets we mean technical systems that need to be managed as capital asset: highly technological, long life-time and high cost systems. A classification of technical capital assets is provided by [10] and shown in Table 1.1. Within this classification our research focusses on ships, a type of transportable mobile technical capital assets. However, ships are still a broad type by itself and further classification into the different ship types is required [22, 23]. An overview of ship types is presented in Table 1.2. Within ships, we aim our research at—but do not limit our research to—naval ships. Naval ships allow us to firstly focus our investigation on the technological aspects of the assets, versus the financial aspects, as naval ships are in a part of the government where no money has to be made. Concentrating on the technological aspects, we limit our investigation to the physical systems of naval ships, excluding non-physical systems such as software. Furthermore, naval ships are a good example of technical capital assets and are considered a distinguishable ship type within the classification of ships (see also [24]).

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 [25, 26]. The RNLN's vessels have a designed life-time of 25 years and the average age of the vessels is 17 years, of which the oldest vessel went into service in 1985 and the youngest in 2015. Furthermore, naval ships are indeed capital assets. The recent acquisition of four offshore patrol vessels is estimated to have cost around € 500 million, the acquisition of the youngest vessel, the Joint Support Ship, is estimated to have cost around € 400 million. To keep these ships operational and up to date throughout their life-time, maintenance plays a crucial role.

TABLE 1.1
A classification of technical capital assets, from [10].

Transportable		Static		
Portable	Mobile	Distributed		Concentrated
		Network	Standard	Specific
Consumer goods, professional goods	Aircraft, ships, trains, trams, buses	Roads, canals, distribution systems	Utilities, HVAC ^a , rotary equipment	Production systems, buildings, land

^a Heating, ventilating and air conditioning

1.5 APPROACH AND OVERVIEW

To be able to reach the research aim and address the key challenges, we need to draw from two research paradigms—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 [27]. These two paradigms are organisational research, which will help to understand MPS in organisations, and design research, which will enable the development of an MPS method.

1.5.1 A design approach to organisational research

Recognizing that a full integration of these two different paradigms is not possible, several authors propose a combination of and collaboration between specifically these two paradigms, in which they argue for a design approach to organisational research [27, 28]. The aim of this approach is to create knowledge that is both actionable and open to validation, and, by that, 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 found solutions; however, it generates increasingly supporting evidence by iteration and refinement, which is tested in context, for an increasing confidence in the found solutions.

To apply the proposed design approach to organisational research, and accumulate the supporting evidence, both [27] and [28] suggest the *multiple*

TABLE 1.2
A overview of ship types, based on [22, 23].

Dry cargo	Tankers	Passenger ships	Other
Anchor handler	Chemical tanker	Passenger ferry	Inland waterway
Barge & pontoon	Double hull oil tanker	Passenger/vehicle ferry	Liquefied chemicals in bulk
Bulk carrier	Liquefied gas carrier	Passenger ship	Liquefied gasses in bulk
Container ship	Liquefied gas tanker	Passenger yacht	Naval ships
Diving support ship	Oil barge	Roll on-roll off passenger	Special service craft
Dredger	Oil or bulk carrier	Sailing passenger ship	Trimaran
Fire fighting	Oil recovery ship		
Fishing vessel	Oil tanker		
Icebreaker	Ore or oil carrier		
Launch			
Livestock carrier			
Offshore support			
Ore carrier			
Pipe laying			
Reclamation ship			
Refrigerated cargo ship			
Research			
Roll on-roll off cargo			
Standby ship			
Trawler			
Tug			
Vehicle carrier			

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.

1.5.2 Overview of the thesis

Applying the multiple case approach proposed by [27, 28], we have taken several steps in this research, providing the structure for this thesis.

In Chapter 2, we elaborate on the applicability of multiple-criteria decision making (MCDM) methods to maintenance decision making, allowing for the use of relevant criteria and company specific importances as posed in *key challenge 1*. We argue for the use of the Analytic Hierarchy Process (AHP) for the research and review the literature concerning the use of the AHP for MPS. We conclude that the AHP is highly suitable for MPS as it fits the requirements in *key challenge 2*, but has not yet been applied to MPS in a broad and structured way, only for single cases at single companies. Finally, we explain of the workings of the AHP, illustrated by an example.

In Chapter 3, we explore the use of the AHP for MPS in a broad way, applying the method for naval ships at three different companies. Following *key challenge 3*, the criteria that play a role for naval MPS are drawn from the literature and eight interviews at relevant companies. The obtained criteria are structured in a decision hierarchy. To explore *key challenges 1* and *2*, using this hierarchy along with the AHP, we organize three sessions in naval practice to test the approach. We conclude that the AHP is well suited for naval MPS, providing a structured approach and facilitating discussion and a strategic way of thinking. This chapter is based on [29, conference proceeding] and [30, journal paper].

In Chapter 4, to further investigate *key challenges 2* and *3*, we broaden our approach towards ships in general, moving to several ship types other than naval ships. At the same time we address *key challenge 1* by eliciting the most

important criteria and considerations for ship MPS. Using the feedback from the naval sessions, we improve the decision hierarchy and use this hierarchy at six more sessions at six different ship companies. During these sessions, we inherently elicit the participants' preferences, giving insight in the most important criteria and considerations for ship MPS. We conclude that our AHP-based MPS approach can be successfully generalized towards ships in general. Furthermore, we reveal that *crew safety*, *availability* and *reliability* are the most important criteria, and that softer, qualitative criteria play an important role in MPS and must be included. The actual maintenance policy consideration is between time/use-based maintenance and condition-based maintenance. This chapter is based on [31, working paper].

In Chapter 5, we stretch our investigation into *key challenges 1* and *2* by using the AHP-based MPS approach in a multi-company session. Pursuing *key challenge 3*, we methodologically review the decision hierarchy based on the results and feedback during the ship sessions and propose a new decision hierarchy. This decision hierarchy consists of three main criteria, each followed by three considerations. Going back to naval ships, we use this hierarchy in a multi-company session, where participants from various companies in the naval maintenance chain are present. The renewed hierarchy proves to be a concise and workable hierarchy, although especially the role of a safety criterion within the hierarchy leaves room for debate, as it can also be seen as a pre-condition for maintenance. Furthermore, it seems there is a trade-off between group diversity and usefulness of the results.

In Chapter 6, conclusions are drawn with respect to the aim of this thesis, underpinned by the three posed key challenges. Finally, recommendations for further research are presented.

CHAPTER 2

THE ANALYTIC HIERARCHY PROCESS

2.1 INTRODUCTION

To investigate maintenance policy selection, we turn to the field of multiple criteria decision making (MCDM)—oftentimes also called multiple criteria decision aiding or decision analysis. MCDM provides the means to address *key challenge 1*, for it allows incorporating desired criteria into MPS and to vary their importances. Furthermore, the benefits of MCDM appear to match the requirements set in *key challenge 2*, providing an understandable, easy to use and insightful MPS process.

Multiple criteria decision making can be seen as an umbrella term to describe a collection of formal approaches which aim to take explicit account of multiple criteria while helping decision makers explore decisions that they are making [32]. MCDM involves the decomposition of a decision problem into a set of smaller and, hopefully, more clear and easier to handle problems. After each smaller problem has been dealt with separately, decision analysis provides a formal approach for integrating the results so that a course of action can be either selected, recommended or simply favoured [33, 34].

MCDM does not focus on making the actual decision or finding the optimal answer; its emphasis and goal are different and wider [32–34]. Its emphasis and goal are to help decision makers make better decisions and also to provide

insight in the decision process, the context of the decision problem, and the priorities, values and objectives involved. It does so by contributing to analysing the decision making context, 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. Hence, the results of MCDM can not be seen as final decisions, but as so called conditionally prescriptive recommendations. They show the decision maker what he should do, given the analysis and judgements made, where everyone involved must be aware that the decision maker is, in the end, completely free to behave as he sees fit after the recommendation is made.

The use of MCDM approaches to maintenance decision making emerged in the 1990s, when decision theory had already become a useful tool to many professionals, including engineers [35, 36]. It is argued that many maintenance challenges and decision problems can be modelled as MCDM problems and should be considered as such. Several reasons form the basis thereof. Maintenance decision making is a multiple criteria process in nature. It operates according to multiple objectives which are often conflicting in nature, where various criteria and courses of actions need to be considered. Also, when uncertainty about the values of variables describing the system exist, owing to the lack of accurate data, subjective expert knowledge can be used instead. Furthermore, it provides a practical approach by focussing on effectiveness. While decision makers and researchers in maintenance seem to focus on efficiency, and the vast majority of maintenance models is aimed at answering efficiency questions, practitioners, on the other hand, are often more interested in effectiveness [18]. Therefore, these studies conclude that MCDM models have a viable future in maintenance as a reliable framework for maintenance decision making, and the further use of decision theory in maintenance engineering and management is encouraged.

The remainder of this chapter is structured as follows. In Section 2.2, the use of the Analytic Hierarchy Process (AHP) is proposed for the research, and the literature on the use of the AHP specifically for maintenance policy selection is reviewed. The workings of the AHP are explained in Section 2.3, followed by an example for the selection of a best new car in Section 2.4. Common criticisms on the AHP is discussed in Section 2.5. Conclusions on the use of the AHP for MPs are drawn in Section 2.6.

2.2 BENEFITS AND LITERATURE

Selecting the right maintenance policy is one of the challenges for which MCDM could be applicable. For the investigation on maintenance policy selection, we propose the use of the Analytic Hierarchy Process. 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 [37–39]. The AHP is a well-established multiple criteria decision-making approach, both in academia and industry [40–42], gaining increasing scientific attention [43], and it provides a convenient approach for solving complex MCDM problems in engineering [44]. Moreover, its specific benefits fit the key challenges described in Chapter 1, as the AHP [32, 33, 39]:

- 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;
- produces plausible and defensible results; and
- can check the consistency of the judgements.

The use of the AHP for maintenance decision making appears to emerge in the second half of the 1990s [18, 36, 45]. To the best of our knowledge, the first study using the AHP for maintenance policy selection is an application of the AHP at an oil refinery [46]. 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 [47].

Since then, the AHP has been applied for MPS in multiple industries. The AHP was combined with a fuzzy prioritization method at a small power plant [48]. 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) [49]. The same case was also studied using fuzzy comparison ratios for the AHP [50]. 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 [51]. Finally, the AHP was

also successfully used to select the best maintenance policies at a newspaper printing facility [52].

These studies provide an overview of the efforts towards use of the AHP for maintenance policy selection. However, it must be noted that all consider single cases at one company, often considering one asset at the company. Hence, they leave room for a broader approach.

2.3 THE WORKINGS OF THE AHP

The AHP decomposes decision-making into the following four steps.

1. Define the problem and determine the kind of knowledge sought.
2. Structure the decision hierarchy from the top, from the goal of the decision, then the criteria that play a role in the decision (if necessary, clustered into sets of related sub-criteria beneath umbrella criteria on which they depend), to the lowest level (which is a set of possible choices).
3. Obtain priorities for criteria and alternatives: for each element in the hierarchy (elements here are the goal, the criteria, and, if present, sub-criteria) compare the elements in the level immediately below it with each other.
4. Obtain the final priorities of the alternatives, using the priorities obtained for the elements at one level to weigh the priorities of the elements in the level immediately below them. Do this recursively for the complete hierarchy.

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. During our research, we use the SuperDecisions software, which is freely available for non-commercial use [53], as well as the freely available spreadsheet software LibreOffice Calc [54].

When using the AHP in a group setting, 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 individual comparisons [38], where a_i is the score or weight per pairwise comparison, given by participant i , with $i \in \{1, \dots, n\}$ 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 the pairwise comparisons are rated on [see also 39, ch. 7].

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

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

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

To derive priorities from the pairwise comparisons, the comparison values are arranged into a comparison matrix. The principal eigenvector of this matrix produces the priorities. Approximation of the principal eigenvector is often necessary, because it can be hard to calculate without using specific software. To approximate the principal eigenvector of a comparison matrix, the so called *geometric means approach* can be used. In this often used approach, the normalized geometric means of each row in the comparison matrix provide the approximation [55, 56].

2.4 AN EXAMPLE OF BUYING A NEW CAR

The working of the AHP is best explained by means of an example. For instance, which new car to buy: *Car A*, *Car B* or *Car C*. In this example, the goal is to select the *best new car*, and the criteria are the *top speed*, the *design* and the *safety* of the car. The alternatives (i.e., the possible choices) are three cars, *Car A*, *Car B* and *Car C*. The corresponding decision hierarchy can easily be structured and is shown in Figure 2.1.

The next step is to obtain the priorities for the criteria and alternatives. For each of the three criteria, the three alternatives are compared with respect to that criterion. For *top speed*, this goes as follows. Say that the top speed of *Car A* is 2 times as high as the top speed of *Car B* and 4 times as high as the top speed of *Car C*. Then, these values, along with their reciprocals, can be

FIGURE 2.1
The example decision hierarchy.

structured in a 3×3 comparison matrix, of which the principal eigenvector provides the relative priorities of the cars, such as in Table 2.1a. Similar 3×3 matrices can be structured for the other two criteria: Table 2.1b for *design* and Table 2.1c for *safety*. In the tables, *cr* stands for the consistency ratio, which we discuss in Section 2.5.

The three criteria are compared in the same way. Again, a 3×3 matrix is constructed in which the comparisons are indicated: one might favour *safety* 2 times over *top speed* and 6 times over *design*, and favour *top speed* 3 times over *design*. Table 2.1d shows the matrix and relative priorities of the criteria with respect to the goal.

Now, the global, or final, priorities can be calculated by structuring the relative priorities of the cars for each criterion in a matrix and multiplying each column of relative priorities by the priority of the corresponding criterion and adding across each row. Table 2.2 shows this matrix, in which we find that *Car A* obtains a final priority of 0.292, *Car B* obtains a final priority of 0.502 and *Car C* obtains a final priority of 0.206, so that we favour *Car B*.

2.5 CRITICISM ON THE AHP

At this point it must be noted that the AHP is not free from criticism. These criticisms originate from the fact that the AHP allows for two effects that defy two often used axioms: intransitivity and rank reversal [40, 57]. We discuss both.

The AHP allows for inconsistent judgements, i.e., intransitive judgements. This means that one is able to favour, for example, *a* over *b*, *b* over *c* and *c* over *a*. To mitigate transitivity problems, a way of checking the inconsistency exists by means of the so called consistency ratio (*cr*) [39, 58]. When comparing

TABLE 2.1
Example comparison matrices.

	Car A	Car B	Car C	Relative priority
Car A	1	2	4	0.571
Car B	$\frac{1}{2}$	1	2	0.286
Car C	$\frac{1}{4}$	$\frac{1}{2}$	1	0.143
CR = 0.000				

(a) Car comparison with respect to *top speed*.

	Car A	Car B	Car C	Relative priority
Car A	1	3	2	0.540
Car B	$\frac{1}{3}$	1	$\frac{1}{2}$	0.163
Car C	$\frac{1}{2}$	2	1	0.297
CR = 0.009				

(b) Car comparison with respect to *design*.

	Car A	Car B	Car C	Relative priority
Car A	1	$\frac{1}{6}$	$\frac{1}{2}$	0.111
Car B	6	1	3	0.667
Car C	2	$\frac{1}{3}$	1	0.222
CR = 0.000				

(c) Car comparison with respect to *safety*.

	Top speed	Design	Safety	Relative priority
Top speed	1	3	$\frac{1}{2}$	0.300
Design	$\frac{1}{3}$	1	$\frac{1}{6}$	0.100
Safety	2	6	1	0.600
CR = 0.000				

(d) Criteria comparison with respect to the goal, *best new car*.

TABLE 2.2
Global priorities of the alternatives.

	Top speed 0.300	Design 0.100	Safety 0.600	Global priority
Car A	0.571	0.540	0.111	0.292
Car B	0.286	0.163	0.667	0.502
Car C	0.143	0.297	0.222	0.206

3 or more items, inconsistency is possible and the CR can be calculated. To calculate the CR of a given comparison matrix, first the consistency index CI of the matrix needs to be calculated. The CI of a given $n \times n$ (for $n \geq 3$) comparison matrix is a measure for its degree of consistency, and is based on the maximum eigenvalue λ_{max} of the matrix. It is defined as:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

To learn what the CI of a particular matrix means, it is compared to an average random inconsistency: the random index (RI). Namely, the RI is the mean CI of a series of randomly generated comparison matrices for each size n , using the scale $1/9, 1/8, \dots, 1, \dots, 8, 9$. For matrices up to $n = 10$ the RI is reproduced in Table 2.3 (see also [59]). Hence, the CR is a measure of how a given matrix compares to a purely random matrix of the same size in terms of consistency and can be calculated by dividing the so called consistency index (CI) by the random index (RI):

$$CR = \frac{CI}{RI}$$

TABLE 2.3
The random index of matrices up to $n = 10$, based on [39, p. 99].

n	3	4	5	6	7	8	9	10
RI	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

Indeed, inconsistency in the comparisons can easily arise, but the opinions on how problematic this actually is vary [40]. It seems a little inconsistency is not a problem as long as the consistency ratio can be kept lower than about 10%.

This does not solve the fundamental issue, but it does provide a workable way of dealing with inconsistency when using the AHP.

Rank reversal happens when, if alternatives are added or removed, the ranking of other alternatives reverse as a result thereof. Rank reversal in the AHP has been widely discussed in literature, of which [57] provides a thorough overview, and is an ongoing debate already spanning over three decades. The debate seems to have reached a bipartisan status quo, in which one side criticizes it, and the other side legitimises it. Although it is beyond the scope of this thesis to take side in this debate, it is important to be aware of the rank reversal debate.

2.6 CONCLUSIONS

This chapter shows that, despite the criticism, the AHP can successfully be applied for maintenance decision making and, specifically, maintenance policy selection. Hence, using the AHP for our research provides a basis for addressing all three *key challenges*, as it supports the fit to companies and applicability in practice. However, the mentioned 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. In the following chapters, we investigate the use of the AHP for MPS in a broader setting.

CHAPTER 3

EXPLORING MPS FOR NAVAL SHIPS USING THE AHP¹

3.1 INTRODUCTION

In this chapter we set out to investigate maintenance policy selection (MPS) through the use of the Analytic Hierarchy Process (AHP). The aim is to explore if an AHP-based MPS method can indeed provide both a fit to companies and applicability in practice, thus addressing *key challenges 1* and *2*. For this investigation, we focus on one type of asset: naval ships.

We take a five-step approach to structure the investigation into naval MPS, actively involving practitioners as proposed by *key challenge 3*.

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 sessions in industry (at the RNLN, a shipbuilder and an OEM) to test the AHP-based MPS approach in practice.

¹This chapter is based on [30]; part of it has been presented at the 2013 ESREL conference [29].

5. Evaluate these sessions 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 Chapter 2). The main question that this chapter 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 chapter contributes in four ways:

- the asset: we focus on one type of asset, namely naval ships, instead of on one specific asset;
- the company: we look at the perspective of various companies, instead 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 chapter is structured according to the five-step approach explained above, of which step 1 has already been introduced in the previous chapter.

3.2 THE ALTERNATIVES

Based on [5], we have defined 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 [16]:

- *failure-based maintenance*;
- *calendar-time based maintenance*;
- *use-based maintenance*;
- *use-severity based maintenance*;

- *load-based maintenance*; and
- *condition-based maintenance*.

However, to be used as the alternatives within the AHP, this list is too long. These six policies require 15 pairwise comparisons per each lowest level criterion of the hierarchy. As the number of required pairwise comparisons grows quadratically with the number of alternatives, a reduction of the alternatives improves usability of the method by reducing complexity as well as the total amount of pairwise comparisons needed. To illustrate, five alternatives require 10 pairwise comparisons, 4 alternatives require 6 comparisons, and 3 alternatives require only 3 comparisons. 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 3.1 (note that in the table [49, 50] 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.

TABLE 3.1
Alternatives used by the case studies

Maintenance policy	Used by					
	[46]	[47]	[48]	[49, 50]	[51]	[52]
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

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 policies to be used as alternatives with the AHP. Hereby, the number of pairwise comparisons per each of the lowest level criteria is reduced from 15 to three pairwise comparisons per each lowest level criterion. These three are:

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

This means that compared with the list of six policies, *calendar-time based maintenance* is combined with *use-based maintenance*, since these both concern preventive maintenance that can be planned. To further downsize the list, *use-severity* and *load-based maintenance* are not included, as these seem the least relevant based on the case studies. Compared with Table 3.1, *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.

3.3 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 3.1). 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 [60] 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 3.2 for an overview. The interviews were recorded and afterwards analysed to find the criteria that are mentioned.

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

TABLE 3.2
Company and interviewee roles

Company	Company role
Royal Netherlands Navy	Vessel owner and operator
Thales Netherlands	Naval specific OEM
Damen Schelde Naval Shipbuilding	Naval specific shipbuilder
Imtech Marine	General maritime maintainer
Lloyd's Register EMEA ^a	General maritime classification society

^a Europe, the Middle East and Africa

(a) Company and company role.

Company	Interviewee role
Royal Netherlands Navy	User, maintainer, regulator
Thales Netherlands	Designer, ILS ^a provider
Damen Schelde Naval Shipbuilding	ILS provider
Imtech Marine	Maintainer
Lloyd's Register EMEA	Regulator

^a Integrated logistics support

(b) Company and interviewee role.

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 [33]. 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 to omit costs for two reasons: first, in order to keep the focus on the goals and fit, and, second, when profits do not play a role, costs can be seen as a precondition in which all maintenance takes place—we get back to this in Sections 3.5 and 3.6.

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*:

- *key performance indicators (KPIs)*: measurable reasons for doing maintenance; and
- *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 the spare parts*: the spare parts and the presence of commonality; and
- *fit to tasks*: the influences on performing maintenance tasks.

The full hierarchy is presented in Figure 3.1, the definitions of the criteria are included in Appendix C.

FIGURE 3.1
The hierarchy of criteria.

TABLE 3.3
Session, participant and case overview

Company	Participant role	Case
DSNS	3× ILS provider	Single ship
RNLN	User, maintainer, 2× regulator	Single ship
Thales NL	Designer, 2× ILS provider	System on the ship

3.4 THE MPS 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 Netherlands 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 3.3.

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 presented. The focus of the company case is then chosen by the participants, while the participants receive a copy of the hierarchy (Figure 3.1) 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. The geometric mean is used accordingly to calculate the group's aggregated scores and weights. The geometric standard deviation 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, 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.

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.

3.5 RESULTS OF THE SESSIONS

The sessions provide two types of results: the final policy preferences for the cases and the evaluation of the sessions by their participants.

3.5.1 Final policy preferences

Table 3.4 presents the final maintenance policy preferences resulting from the AHP. The AHP presents these final preferences as fractions totalling to 1. These fractions quantify the preference of each policy: the policy with the highest fraction is the most preferred policy, the policy with the lowest fraction is the least preferred policy. A comparison of the differences between final preferences is possible too. The comparisons that lead to these final preferences all show acceptable consistency ratios, except for a two outliers well above 10%: in the DSNS case we observe one CR of 20.9%, and also in the Thales case we observe one CR of 20.9%. However, in each case these values are observed for a different comparison.

TABLE 3.4
The final preference of the alternative maintenance policies

Company	Case	Failure-based	Time/use-based	Condition-based
DSNS	Single ship	0.250	0.359	0.390
RNLN	Single ship	0.236	0.354	0.410
Thales NL	System on a ship	0.197	0.324	0.479

Table 3.4 reveals both similarities and differences in policy preference. For all three companies *condition-based maintenance* is the preferred policy, while *failure-based maintenance* is the least preferred policy. Although the three companies show the same order of preference, the differences lie in the distribution across the three policies. DSNS and the RNLN show a similar distribution for their cases. The Thales case shows a different distribution in which condition-based maintenance obtains a notably higher preference, and failure-based

maintenance a notably lower preference. We expect that this difference relates to the lower level of the system in the ship hierarchy of the Thales case, as well as the different nature of the system (a radar system) demanding a different maintenance approach.

3.5.2 Evaluations of the sessions

The results (i.e., the answers given) of the session evaluation 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 consists 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 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 other 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.

- 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 3.4, most participants would have chosen for the same maintenance policy that was indicated by the AHP to be the optimum. They state that it matches either reality, their own vision, it seems to be the most balanced choice or would be 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. We suspect their preferences relate to the area of expertise of the individual participants and the companies they represent. 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.

We think that this relates to the levels in the system the companies chose as cases, as high level systems are chosen during the sessions. For such high levels in the system, applying a single maintenance policy for all its sub-systems might not be feasible. For instance, a ship cannot be maintained solely condition-based. It always requires a mix of policies, because not all of its sub-systems have relevant variables to monitor. However, one can *aim* for a ship to be maintained condition-based as much as possible, and steer company practices towards it. Here we see the applicability of the AHP-based approach: to investigate if—and if so, why—one should aim for, in this example, condition-based maintenance.

3.6 CONCLUSIONS

We set out to investigate maintenance policy selection through the use of the Analytic Hierarchy Process, focussing on naval ships. Following *key challenge 3*, we were able to cooperate with practitioners by organizing the three sessions. Reflecting on *key challenges 1* and *2*, 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 is not making the actual decision, but in providing a thought-structuring method that provides insight by eliciting preferences and facilitating discussion. This way of maintenance policy selection 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.

CHAPTER 4

FINDING THE MOST IMPORTANT FACTORS FOR SHIP MPS¹

4.1 INTRODUCTION

In the previous chapter, we have investigated maintenance policy selection (MPS) for naval ships, where we developed a hierarchy of criteria usable with the AHP based on both interviews in practice and the relevant literature. We then conducted a series of three MPS sessions in the naval sector: at the owner, the shipbuilder and an original equipment manufacturer of naval ships in the Netherlands. We concluded that the AHP is well suited for maintenance policy selection and that it provides a structured and detailed approach for MPS.

Building on this previous research, this chapter focusses on MPS for ships in general and aims to contribute in three ways. The first two ways further investigate *key challenges* 2 and 3, the third aims to strengthen *key challenge* 1.

1. We construct a new hierarchy of criteria, taking into account the evaluations of the naval hierarchy by the participants of the three sessions in Chapter 3. We have not encountered the use of such feedback in

¹This chapter is based on [31].

the literature. We use this hierarchy at six new sessions at six different companies that maintain, use or own various ship types.

2. With the six sessions, we aim to further generalize the previous findings towards ships in general. During these sessions the participants go through the AHP using the new hierarchy of criteria and they evaluate the sessions afterwards. These evaluations provide insight in applicability and generalization of our AHP-based MPS method: can a single hierarchy of criteria be used at various companies for various ship types and provide meaningful outcomes?
3. We conclude on the most important criteria and considerations for ship MPS. During these sessions we inherently elicit the preferences of all the participants on both the weights of the criteria and the scoring of the maintenance policy per criteria. These preferences give insight in what is—and what is not—considered to be important in practice when selecting a maintenance policy.

The chapter is structured as follows. In Section 4.2, we explain how we use the feedback to construct the new hierarchy of criteria and then present this hierarchy. In Section 4.3, the MPS sessions are explained. The sessions generate two types of results: the quantitative outcomes of the criteria weights and policy preferences and the participants' qualitative evaluation of the sessions. These results are discussed in Section 4.4. Lastly, the conclusions on the three main points of this chapter are drawn in Section 4.5.

4.2 THE HIERARCHY OF CRITERIA

Constructing the hierarchy of criteria, we build upon the earlier version of the hierarchy that was used for naval ships in Chapter 3 (see Figure 3.1). The initial criteria for this naval hierarchy are drawn from the eighth interviews in industry and case studies in literature that use the AHP for MPS [46–52]. Of the list of 187 criteria (see Appendix B), the 46 criteria that were mentioned three times or more in total were used as the basis to construct the naval hierarchy.

For the construction of the new hierarchy, we take several steps. Most importantly, taking into account the evaluations of the naval hierarchy by the participants of the three sessions in Chapter 3, we remove the criteria that received very low weights (i.e., were seen as not important) and we merge criteria that were considered overlapping. Furthermore, to reduce the size of

TABLE 4.1
Session, company, ship sector and case overview.

Company	Company role	Participants
Alewijnse	Maintainer	2
Damen Shipyards Gorinchem	Shipbuilder	3
Fugro Marine Services	Maintainer	3
KNRM ^a	Owner & operator	6
Loodswezen	Owner & operator	3
SmitLamnalco	Owner & operator	4

^a Royal Netherlands Sea Rescue Institution

(a) Company role and number of participants per session.

Company	Ship sector
Alewijnse	Various
Damen Shipyards Gorinchem	Tugs
Fugro Marine Services	Research vessels
KNRM	High speed service crafts
Loodswezen	High speed service crafts
SmitLamnalco	Tugs

(b) Company ship sector.

Company	Company case
Alewijnse	General cargo ship
Damen Shipyards Gorinchem	Tug product group
Fugro Marine Services	System on research vessels
KNRM	Class of RHIB ^a
Loodswezen	Fleet of pilot tenders and swaths ^b
SmitLamnalco	Class of tug

^a Rigid-hulled inflatable boat ^b Small waterplane area twin hull

(c) Company cases.

the hierarchy, and thus reduce the number of pairwise comparisons and the time needed to do these comparisons, the criteria that are mentioned four times or more in total in the original list of 187 are used as the starting point (see Appendix B). The initial number of criteria used as the basis for constructing the hierarchy is brought down from 46 to 24 by this step only. The new hierarchy of criteria is presented in Figure 4.1 and is discussed top-down, per level in the hierarchy.

4.2.1 The complete hierarchy

The goal of the decision hierarchy is to select the best maintenance policy. We maintain the general structure for the hierarchy, because it was found to be clear and understandable. The hierarchy starts with a division into *goals* and *fit*. Beneath these two top level criteria, the hierarchy is structured into six second level sub-criteria and 21 lowest level criteria.

4.2.2 The first level of criteria: *goals* and *fit*

The division into *goals* and *fit* was well-received. Therefore, we keep this top-level division in the hierarchy. *Goals* focusses on the maintenance goals of the company, while *fit* considers how well the maintenance and maintenance process fits to the company.

4.2.3 The sub-criteria

To bring more balance in the hierarchy, the difference in number of sub-criteria beneath *goals* and *fit* is downsized by reducing the number of criteria beneath *fit* from six to four. The number of sub-criteria beneath *goals* remains two. The resulting sub-criteria are as follows.

Beneath *goals*:

- *key performance indicators* (KPIs): measurable reasons for doing maintenance; and
- *desirables*: reasons for doing maintenance that cannot be easily measured or quantified.

Beneath *fit*:

- *fit to operations*: the operational aspects to consider;
- *fit to relations*: the internal and external relations of the company;

FIGURE 4.1
The hierarchy of criteria.

- *fit to spare parts*: the spare parts and the presence of commonality; and
- *fit to tasks*: the influences on performing maintenance tasks.

4.2.4 The lowest level criteria

To continue bringing balance in the hierarchy, all lowest level criteria are clustered in similar size groups of three or four criteria. *Costs minimization* is included as КР1; in Chapter 3, it was deliberately chosen not to focus on costs, to not get distracted from the focus on the goals and fit. However, during the evaluations all naval participants stated a costs criterion should be included. Furthermore, all criteria concerning the mission are merged into one: *mission profile*. Lastly, we do not incorporate *warranty periods and rules and regulations*, as they do not offer a choice, they are evidently fixed. Instead, to allow for deviation from these fixed rules, we incorporate the criterion *drive for innovation*.

Overall, a reduction from 29 to 21 criteria in the lowest level of criteria in the hierarchy is obtained. The definitions of the criteria, as used during the sessions, are listed in Appendix C.

4.2.5 The alternatives: the maintenance policies

As mentioned in Chapter 1, we define a maintenance policy as a policy that dictates which parameter (for example, elapsed time or amount of use) triggers a maintenance action. In the previous chapter, three policies are used as alternatives and during the evaluation these three were well received by the participants. Therefore, we keep the three policies:

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

4.3 THE MPS SESSIONS

To put the hierarchy to practice, we organize six sessions at six different ship companies. For an overview of these companies, see Table 4.1. During these sessions a maintenance policy is selected for a system chosen by the participants: the company case. The sessions take about three to four hours per session and all six are structured identically in five steps.

1. An introductory presentation.
2. A fictitious example case.
3. The selection and the discussion of the company case.
4. Discussion of the results.
5. Evaluation of the session.

During the introductory presentation (1) the planning of the session and the nature of our research are presented. To get the participants acquainted with the AHP, they are guided through a fictitious example case (2) about the purchase of a new car. At the start of the company case (3), the participants are handed a copy of the hierarchy (Figure 4.1) and a list of definitions of the criteria (see Appendix C). The company case is then chosen by the participants (see Table 4.1c), which can be any system of interest with no limitations on, for example, type of system or level in the system.

Doing the company case, the participants are asked to individually and manually fill out the pairwise comparisons, starting with the scoring of the alternatives and followed by the weighing of the criteria. When all participants are finished, the geometric mean is used to synthesize the inputs given by the participants and calculate the group's aggregated scores and weights [38, 39]. The geometric standard deviation of the inputs is used to investigate where the participants agree and disagree most within the pairwise comparisons.

Using these calculations, the following results are discussed with the participants (4): the final scoring of the alternatives, the results of the aggregated pairwise comparisons, a sensitivity analysis for the top level criterion *goals* compared to *fit*, and the pairwise comparisons where the participants disagree most.

To evaluate the session (5), each participant receives an evaluation form (see Appendix D) to fill out. This evaluation form consists of 16 questions divided into three categories: the session, the hierarchy of criteria, and the decision.

4.4 RESULTS OF THE SESSIONS

The results are split into three categories: the criteria and hierarchy, the decision and the session itself. Within these categories, the sessions yield results in two ways: for the first two categories the quantitative outcomes of the criteria

weights and policy preferences, and for all three categories the qualitative evaluations by the participants.

4.4.1 The criteria and hierarchy

By the weighing of the criteria and the scoring of the alternatives, the sessions inherently elicit the preferences of the 21 participants in total. Figure 4.2 presents the average importances of the lowest level criteria, presented in the so-called ideal form for which all weights are divided by the largest one [38]. Looking at the criteria per cluster of sub-criteria, we notice the following.

Key performance indicators The top three criteria are all KPIS. *Crew safety* is by far the most important criterion, over three times more important than *reliability*, the second most important criterion, and *availability*, the third most important one. The fourth KPI, *cost minimization*, remarkably ranks only 12th.

Desirables The criteria *planability* and *compliance with existing policies* rank 5th and 6th, but *drive for innovation* and *passion for maintenance* rank 14th and 16th.

Fit to operations Ranking 4th, *experience with maintenance* is the most important criterion after three of the KPIS. Ranking 7th, *crew educational level* is of remarkably higher importance than *crew size*, ranking 19th. *Mission profile* sits right in the centre with rank 10.

Fit to relations The three criteria from *fit to relations* are of notably low importance. *Maintenance feedback*, *good communication within the company* and *good relations with other companies* rank 17th, 20th and 21st respectively.

Fit to the spare parts Only *spare parts availability* seems to be of moderate importance, being ranked 8th. *Commonality presence* and especially *spare parts costs* are of low importance.

Fit to tasks The three criteria under *fit to tasks* are roughly in the middle, *redundancy presence* ranking 9th, *consequences of poor maintenance* ranking 11th and *criticality of parts* ranking 13th.

As in Chapter 3, some inconsistencies in the comparisons are observed. And as in that chapter, there is no comparison uniformly inconsistent throughout the sessions (we will come back to this in Section 5.3).

The evaluation of the hierarchy of criteria by the participants is meant to determine if the hierarchy is clear and understandable, and if any criteria

FIGURE 4.2
Idealised average global weights of the lowest level criteria and their average policy scores.

are lacking or redundant. The evaluations reveal that all but two participants find the hierarchy of criteria clear and understandable. Out of these two, one participant disagreed and reckons he lacks prior knowledge. The other did not fully understand the division into *goals* and *fit*. Besides this one participant, the groupings and divisions made in the hierarchy are also clear to the participants and the participants had no further comments on this.

On the criteria, most participants do not miss any criteria or alternatives and find the hierarchy complete. This is an improvement compared to the naval hierarchy in Chapter 3, where considerably more and more coherent remarks were made. Comments on the current hierarchy are quite minor, as only three participants state that mandatory maintenance by class surveys and rules and regulations should be included. As for the alternatives, one participant would like to include opportunity-based maintenance and another participant would include load-based maintenance. The participants of one company share the feeling that the hierarchy could be made more specific to their company by changing a few criteria.

Concluding, the new hierarchy is better received than the naval hierarchy it is based on. This shows that taking the feedback from practice into account makes the hierarchy more acceptable. The comments the participants do make are minor and seem quite specific to the interest of that participant. Only the lack of mandatory maintenance by class surveys and rules and regulations is mentioned by multiple participants (three out of 21). However, this does not justify adding the criterion to the hierarchy, as it offers no choice.

Eliciting the participants' preferences, we expected the *KPIs availability* and *reliability* to obtain the highest global importances. Surprisingly, this is not the case, as *crew safety* obtains the highest global importance—not only of the *KPIs*, but of all the criteria. We also did not expect the low global importance of *cost minimization*, as it was specifically added to the hierarchy because of the evaluations of the naval sessions. It appears that a costs aspect is too important to leave out of the hierarchy. In other words, a costs aspect is needed to fully portray the *MPS* problem. However, when included, it obtains only a moderate importance. Lastly, besides the *KPIs*, all (but one) clusters of sub-criteria appear to play a role in ship *MPS*, especially *fit to operations* and *desirables*, providing five of the top ten criteria. This reveals that these qualitative criteria play an important role for ship *MPS* and cannot be excluded from the decision. The exception is *fit to relations*, of which all criteria obtain notably low global weights. Apparently, considering the relations with other companies is not that important for ship *MPS*.

4.4.2 The decision

The final policy preference per case is shown in Table 4.2. It reveals that failure-based maintenance is never the preferred alternative. In three cases time/use-based maintenance is the preferred alternative, in the other three cases condition-based maintenance is preferred. The differences between time/use-based maintenance and condition-based maintenance are small in each case, and no single maintenance policy can be regarded as overall best.

TABLE 4.2
The final preference of the alternative maintenance policies per case.

Company and case	Failure-based	Time/use-based	Condition-based
Alewijnse General cargo ship	0.190	0.423	0.387
Damen Shipyards Gorinchem Tug product group	0.107	0.430	0.463
Fugro Marine Services System on a research vessel	0.131	0.523	0.345
KNRM Class of RHIB	0.131	0.416	0.454
Loodswezen Fleet of pilot tenders and swaths	0.092	0.490	0.417
SmitLamnalco Class of tug	0.131	0.434	0.435

When the average policy scores are considered (see Figure 4.2), the underlying rationales for the preferences become apparent. There is no criterion for which failure-based maintenance is, on average, the preferred policy. Time/use-based maintenance and condition-based maintenance take turn at being most preferred. The top five most important criteria are exemplary: for *crew safety* time/use-based maintenance and condition-based maintenance score almost equal. For *reliability* and *availability* condition-based maintenance is preferred, while for *experience with maintenance* and *planability* time/use-based maintenance is preferred.

However small, the largest differences between time/use-based maintenance and condition-based maintenance are seen at Fugro Marine Services and Loodswezen, that both prefer time/use-based maintenance. At the former case, this is because time/use-based maintenance receives equal or higher scores

than condition-based maintenance for a remarkably high number of criteria: all but three. This overall preference for time/use-based maintenance might be explained by the combination of a highly redundant system configuration in combination with a project-based work approach. At the latter case, a comparatively high importance of *planability* strengthens the preference for time/use-based maintenance. An explanation for the emphasis on *planability* could be that because the company has its own maintenance facility where the space and resources are limited, maintenance time needs to be planned carefully and well in advance.

In the evaluation of the final decision, 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, most participants would have chosen for the same maintenance policy as indicated by the AHP. Some participants expect a different order of preference and one participant would have liked to see a larger difference between the final preferences. Adding to that, all but two participants indicate that they now better understand the selection process and the decision made. The two who do not, state that the choice matched the idea already in their minds. On the level in the system for which a maintenance policy should be selected by a session like this, all but one participants agree that it would work best for high levels. While the disagreeing participant suggests every level, the others range from component-level to fleet-level, where some participants propose a selection based on criticality.

Concluding, it appears that failure-based maintenance is never an option, and that the main consideration is between time/use-based maintenance and condition-based maintenance. Using the AHP creates insight in this consideration and provides a plausible final preferred policy, useful for high levels in the system.

4.4.3 The session

The sessions themselves are evaluated by all participants. The evaluation consists of questions about the session in general, its usefulness and the groups with which the sessions are held. The outcomes of the evaluations of the sessions are in line with those in Chapter 3.

In general, all participants show a positive attitude towards the session. They find the session interesting, instructive and clarifying. Also, all participants liked doing the session. The participants indicate that the session offers a new perspective on maintenance and provides insight and knowledge. Further-

more, it facilitates a structured discussion on maintenance within the group, eliciting and aligning the opinions in the group. On the time needed to do such a session, three to four hours seems the right amount of time. Although one participant labelled the session as intensive and one recognizes that sessions like this take time to do well, only two participants explicitly state the session is too short. The other participants state that the duration is fine. Reflecting on the group, the participants indicate that the groups should be diverse. Participants in already diverse groups value this diversity, participants in less diverse groups state the need for diversity. Lastly, all but one participant would do a similar session again, either for other systems or sub-systems of their case. The one participant who would not do such a session again does not see a need for it, as he sees the session as a confirmation of the current approach.

4.5 CONCLUSIONS

This chapter aims to generalize the AHP-based MPS method, along with the hierarchy of criteria, from the previous chapter with a naval application towards application for ships in general, and to investigate the most important criteria for ship MPS. Hereby, it contributes to all three key challenges. Based on the six sessions in industry, we conclude that we have successfully been able to generalize the AHP-based MPS approach, noting the following:

- by taking the feedback from practice into account, the hierarchy of criteria improved;
- it is possible to use the same hierarchy of criteria at multiple companies and obtain meaningful outcomes;
- the use and value lie not so much in the actual selection of a policy, but in facilitating a structured discussion on maintenance and its policies; and
- the proposed method appears to work best when high levels in the system are considered, even up to fleet level.

By doing the sessions, we have inherently elicited the preferences of the participants. This reveals importances of the criteria. In other words, it reveals what practitioners find important when considering maintenance policy selection:

- *crew safety* is the most important criterion when selecting a maintenance policy, followed by *reliability* and *availability*;

- softer, qualitative criteria play an important role, as *experience with maintenance* and *planability* complete the top five criteria. These criteria must not be precluded;
- *cost minimization* plays only a moderate role; nevertheless, to fully portray the MPS problem, a costs criterion needs to be included;
- for the final preferred maintenance policy, the actual consideration is between time/use-based maintenance and condition-based maintenance.

CHAPTER 5

STRUCTURING SHIP MAINTENANCE POLICY SELECTION

5.1 INTRODUCTION

In Chapter 4, 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. We improved the hierarchy of criteria and found 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 cannot be excluded from ship MPS.

This chapter first focusses on *key challenge 3*, for which we go back to the literature. We seek for a methodological abstraction of the AHP-based MPS approach in order to reveal the core of ship MPS in a structured way. Insight in the core of ship MPS provides the means to expand the investigation into *key challenges 1* and *2*, by shaping our findings into a renewed decision hierarchy and by testing this new decision hierarchy in a final, multi-company session—vis-à-vis the single company sessions in the previous chapters. Hence, this chapter contributes in two ways.

1. We methodologically renew 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 (as we did in Chapter 4). This adds to the literature, as such a methodological approach to structuring decision hierarchies has not been encountered in the case studies [46–52].
2. We organize a multi-company session with participants from four different companies within the same maintenance chain, where in the literature single cases [46–52] are studied, and in the previous chapters we used a single hierarchy of criteria at multiple companies, one at a time.

To reach these objectives, we take the following three steps.

1. Investigate methodologies to renew the decision hierarchy and to structure the MCDM process.
2. Methodologically renew the decision hierarchy, using the results and feedback from practice, as discussed in Chapter 4.
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).

This chapter is structured according to the three steps explained above. In Section 5.2, 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 5.3. The set-up and results of the multi-company MPS session are presented in Section 5.4. We then draw conclusions in Section 5.5.

5.2 STRUCTURING MCDM

To methodologically renew the 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 [61, 62], 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 (the developer of the AHP) states 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 [61, p. 71]: “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 [61], 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* propagates 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 [63]. It provides five steps for systematically identifying and organizing these objectives [62].

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 by combining similar objectives into categories.
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 [64]. 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, using eight criteria that correspond to each stage: the information should be accessible, differentiable, abstractable, understandable, verifiable, measurable, refinable and usable. For each criterion a guideline is presented. These guidelines can be summarized as follows.

- 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).
- 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.
- 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.
- Understandable* Construct a meaningful and appropriate 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.
- 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.
- 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.
- 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.
- 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 [64] 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 5.1, 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 5.3. Stages 5 – 8 are covered in the two MPS sessions that we have conducted and are discussed in Section 5.4.

TABLE 5.1
The MCDM structuring stages and the implementation thereof.

Stage	Criteria	Implementation
1	Accessible	Use the general ship hierarchy (from Chapter 4) 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 the final preferences to the group of participants.

5.3 THE DECISION HIERARCHY

The starting point, and Stage 1 of the structuring method, is the general ship decision hierarchy as used in Chapter 4. To restructure the hierarchy we take into account the following:

- the average relative priorities of the lowest level criteria, as presented in Chapter 4;
- 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.

5.3.1 Restructuring the decision hierarchy

Our aim is to construct a decision hierarchy that is as concise and balanced as 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:

- the KPIs *crew safety*, *reliability* and *availability* are the three most important criteria;
- relative to the other criteria, the KPI *cost minimization* is only of moderate importance; and
- the three criteria under *fit to relations* are the first, second and fifth most unimportant criteria.

Regarding inconsistent comparisons and comparisons receiving equal importances (i.e., all comparisons in a comparison matrix obtain judgements scores of 1), the following is noteworthy:

- *fit to relations* and its three sub-criteria receive the most ‘equal importances’ in which all judgement scores are 1; 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 evenly.

This gives reason to consider the three KPIs *availability*, *safety* and *reliability* as the top-level criteria, and to eliminate the cluster *fit to relations*. Besides these three KPIs, 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: three main criteria with three considerations per criterion and three alternatives.

FIGURE 5.1
The decision hierarchy.

5.3.2 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, and the number of lowest level criteria from 21 to nine. Furthermore, it also reduces the total number of required pairwise comparisons from 98 to 39: three comparisons to weigh the top-level criteria, three times three comparisons to weigh the considerations under each top-level criterion, and nine times three comparisons to score the maintenance policies for each consideration.

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 5.1. The explanation below is identical to the definitions given to the session participants (see also Appendix C).

The criteria are as follows, their definitions are drawn from relevant standardization norms [65, 66]:

- *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 [65]);
- *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 [65]); 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 [66]).

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 Chapters 3 and 4:

- *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.

5.4 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 session. To incorporate the judgement refinement of Stage 7, the session structure has changed slightly compared to the sessions discussed in the previous chapters. The structure is now:

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 D).

As explained in Chapter 2, the geometric mean is used to calculate the average judgements of the participants [38, 39], and to draw the relative priorities from the comparison matrices the so called geometric means approach is used [55, 56]. The software that we use during the session is a regular spreadsheet software (LibreOffice Calc).

5.4.1 Preliminary session

To verify the renewed 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 Chapter 4). 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 the previous chapters, 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 5.2, 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.

5.4.2 Set-up of the final session

For the final session, we go back to the first ship type that we have investigated: naval ships. In Chapter 3, we already encountered the maintenance chain

TABLE 5.2
Final preferences of alternative maintenance policies at the Loodswezen session.

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

of naval ships. However, instead of organizing a session at each individual company as we did in Chapter 3, 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 5.3a.

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 MFS approach seems to work best, the radar system itself is chosen as case.

5.4.3 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 CR is 4%. This results in the final policy preferences that are presented in Table 5.3b. 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.

These results are in line with our previous findings that the actual consideration is between time/use-based maintenance and condition-based maintenance. 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,

TABLE 5.3
Final session overview.

Role	Company	Participants
OEM	Thales Netherlands	2
Shipbuilder	Damen Schelde Naval Shipbuilding	2
Owner/regulator	Ministry of Defence – DMO ^a	2
Owner/maintianer	Royal Netherlands Navy – DMI ^b	2

^a Defence Materiel Organisation ^b Directorate of Materiel Support

(a) Final session companies, roles and participants.

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

(b) Final preferences of alternative maintenance policies.

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.

5.4.4 Evaluation of the final session

As the final part of the session, all participants are handed an evaluation form (see Appendix D). 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:
 - (a) although safety plays an important role within maintenance, safety should act a pre-condition for maintenance, hence, they find the inclusion of safety within the hierarchy is debatable;
 - (b) a focus on life-cycle costs would be more relevant than the current focus on maintenance costs;
 - (c) availability and reliability are too much alike, including either one would be sufficient; and
 - (d) the definitions are too generic and using more precise definitions, such as formula's, 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.

- In line with the statements above, 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). 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 number of different views appear to lead to more insightful discussions, but to seemingly less accurate 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 be 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.

5.5 CONCLUSIONS

This chapter set out to methodologically abstract our AHP-based MPS approach by following the MCDM method proposed by [64], renewing the decision hierarchy and organizing and evaluating a final multi-company 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 with respect to the key challenges.

- The methodology proposed by [64] 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 role of safety should not be overlooked. 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 regards high system level strategic maintenance thinking. This chapter 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.
- Finally, it is worthwhile to mention that, in relation to the well known RCM, the AHP-based MPS approach seems to be able to complement, rather than compete with, RCM.

CHAPTER 6

CONCLUSIONS AND FURTHER RESEARCH

In this final chapter we draw conclusions on the aim of this thesis and the three key challenges that underpin the research. Thereafter we elaborate on the road ahead and provide directions for further research.

6.1 CONCLUSIONS

In this thesis, our two research aims have been addressed: we have investigated which factors play a role for MPS and we have developed an MPS method incorporating these factors. These aims have been underpinned by the formulation of three key challenges to structure the research. The conclusions of the research are discussed per key challenge.

6.1.1 The fit of the MPS method to companies

The first key challenge concerns the fit of the MPS method to companies and states that the MPS method should be relevant to the company and situation at hand. To increase the fit of the MPS method to companies, the relevant criteria should be used during the selection process and companies should be able to indicate what they feel is important to their specific situation.

We have captured the relevant criteria and have shown that softer, qualitative criteria must be included in MPS. We have demonstrated that these criteria can be structured into a workable decision hierarchy, usable for naval as well as general ship MPS.

Furthermore, we used a methodological approach to ultimately structure a concise decision hierarchy, consisting of three criteria with three considerations each. The criteria are *availability realisation*, *reliability realisation* and *safety assurance*. Beneath these criteria, the three considerations are: *what best suits the system*, *where the expertise lies*, and *what the cheapest option is*. The three alternative maintenance policies that are used are *failure-based maintenance*, *time/use-based maintenance* and *condition-based maintenance*. The AHP allows these criteria and alternatives to be incorporated into one MPS method and facilitates the importances to be weighed by the companies themselves.

However, some remarks on the three criteria are in order. First, the relation between availability and reliability seems not as straightforward as the decision hierarchy suggests. Although these terms themselves are widely used and well defined in literature, in practice it seems more complex, as different companies and practitioners have varying views on what these terms mean to them and how they are related.

Second, the exact role of the safety criterion is careful consideration. The fact that safety plays a role for MPS is clear. However, some doubts have been raised whether a trade-off between safety and reliability or availability is actually desirable (or even possible), or that safety should be regarded as a pre-condition for MPS.

The costs consideration also needs further investigation. Although the research revealed that a costs factor must be included, it obtains only moderate relative importance. Yet, debate arises on which type of costs are the most relevant for MPS. Our research has led to the use of maintenance costs in favour of other costs types such as total cost of ownership (TCO) or life-cycle costs (LCC).

Lastly, the three used maintenance policies prove a workable abstraction of the total set of maintenance policies. The actual maintenance policy consideration is between time/use-based maintenance and condition-based maintenance. Failure-based maintenance is never the preferred maintenance policy. However, there are components for which failure-based maintenance is a viable option, or even the only reasonable option. Hence, failure-based maintenance must not be excluded as alternative.

6.1.2 The usability of the MPS method in practice

The second key challenge considers the applicability of the MPS method in practice and states that practitioners should be able to use and apply the MPS method. To increase the applicability of the MPS method in practice, an MPS method should be understandable for practitioners, be easy to use, and provide insight in the MPS process.

Here, the AHP proves to be a usable and suitable method. It is an understandable and easy to use process that provides the means to gain a thorough insight in the decision process. This appears especially so when used in combination with a concise hierarchy. The use of the AHP-based MPS method lies not so much in making the actual decision, but in providing a structured way to think about MPS and in facilitating a structured and meaningful discussion. It has proven to work best for considering high levels in the system in a strategic way, from component or LRU-level up to fleet level. The best moment to deploy this method would be at the start of new developments, such as a new design phase, an acquisition project, the introduction of new materiel, or the development of new maintenance plans.

The AHP itself provides an understandable way of dealing with MPS. However, the total understandability of the MPS process seems to be a combination of the method used, the criteria, their formulations and their definitions. Interpretations easily vary, not only between companies, but also between participants of the same company, depending on their positions, roles and interests. Discussing the most relevant criteria and their definitions is a way to bring varying interpretations closer together during the process. Completely avoiding interpretation differences is arguably impossible.

The interpretation issues could be the reason why there appears to be a trade-off between group diversity and usefulness of the results. A more diverse group allows for more learning from the various views, but less homogeneous, and thus less accurate, results. An already homogeneous group yields more accurate comparisons and thus more useful results. Both approaches allow for thorough discussions and provide insight in the decision, but in a seemingly slightly different way.

6.1.3 The practicality of the research

The third key challenge concerns the practicality of the research and states that the research should be performed in a practical way. To obtain a practical study, the research should integrate knowledge from both literature and practice,

actively involve cooperation with practitioners, and use the feedback obtained from practice to improve the MPS method.

Literature and practice have followed one another in our research. We have used both literature and interviews to obtain the initial criteria list, followed by a series of AHP sessions in industry. Finally, we have used the literature to methodologically review and structure the decision hierarchy, after which we have again sought cooperation with industry. We have actively involved practitioners in the research by the sessions that we have organized and the evaluations that they have provided. Furthermore, we have successfully used the feedback from practice, where both the evaluations and results from the sessions have been important to improve the decision hierarchy. Ultimately, a concise and usable decision hierarchy is obtained.

Combining literature and practice in this way proves to be a successful method to secure both theoretic and practical results. Starting at literature and verifying in practice, and iterating this process, provides a theoretical research basis while at the same time practically relevant findings are being achieved.

6.2 THE ROAD AHEAD

Research is never finished, as it appears to only raise more questions than it answers. For the road ahead, we identify four main paths.

6.2.1 The roles and meanings of *availability*, *reliability*, *safety* and *costs*

During the research, the factors *availability*, *reliability*, *safety* and *costs* have converged to concise and workable meanings. However, in practice the interpretation and relations differ depending on who is asked. The research described in this thesis can serve as a ground to further explore the roles of these factors for MPS.

First, the relation between availability and reliability needs elaboration. Although clear definitions for both are available in literature, practitioners seem to have varying interpretations and views of what these two terms mean to their specific situation, and how they are related. To obtain a better understanding of these interpretation differences and their origin, and how they influence MPS, a structured empirical investigation is encouraged.

Second, a question arises regarding the role of safety within MPS: is a trade-off between safety and availability or reliability desirable (or even possible), or

should safety act as a pre-condition for MPS—although absolute safety is, by definition, impossible? The exact role that safety currently has within MPS, as well as the role it should have, is worth to be further investigated.

Third, minimizing maintenance costs seems to be a good way to create efficient maintenance, especially when one is required to work with annual budgets. Yet, when maintenance investments have to be made to reduce the overall costs (i.e., operations costs), it seems logical to consider the minimization of total cost of ownership (TCO) or the life-cycle costs (LCC) instead. However, the ultimate goal of maintenance cannot be cost reduction only and must be maintaining functionality (at the lowest cost). How costs can best be interpreted in relation to MPS remains to be further explored: as maintenance costs as consideration for the KPIS (like we did in Chapter 5), or as the more overall TCO/LCC.

6.2.2 AHP-based MPS versus RCM

Reliability Centred Maintenance (RCM) is probably the best known maintenance concept and has arguably become the *de facto* maintenance standard (see Chapter 1). Like our AHP-based MPS method, it too provides a way to select maintenance policies, and during the sessions a comparison between our AHP-based MPS method and RCM was suggested. RCM is widely discussed in the literature and the methodology can be completely described by four following features [67, p. 66].

1. Preserve functions.
2. Identify failure modes that can defeat the functions.
3. Prioritize function need (via failure modes).
4. Select applicable and effective preventive maintenance tasks for the high priority failure modes.

Based on our findings, we think that both methods can complement each other, rather than compete with each other. By no means do we regard the AHP-based MPS approach as a replacement for RCM. We see several opportunities where the AHP-based MPS approach could complement RCM; a detailed comparison would provide valuable continuation of the research.

First, RCM obviously emphasises reliability. Other maintenance concepts exist, each with their own emphasis [5, 17]. However, with the ability to also take availability and safety into account at an equal level before any emphasis is given, the AHP-based MPS approach can help develop a broader, and perhaps more balanced, view on maintenance.

Traditionally, RCM concentrates on preventive maintenance. In the AHP-based MPS method, corrective maintenance, i.e., failure-based maintenance, receives equal attention, allowing for a more complete view on MPS.

RCM prescribes the level in the system under consideration based on functionality. According to [68, p. 83], an RCM analysis item is “a grouping or collection of components, which together form some identifiable package that will perform at least one significant function as a stand-alone item (e.g., pumps, valves, and electric motors).” The AHP-based MPS approach can contribute a more conceptual way of thinking, being able to consider higher levels in the system, even up to fleet level.

RCM and naval surface ships historically go well together [1, 2, 69, 70]. However, RCM and commercial maritime practice seem still quite far apart. Although its underlying philosophy seems useful for ships, implementation is found to be difficult: a set of 11 practical problems when aiming to apply RCM to ships has been identified (for instance, that basic equipment conditions cannot be taken for granted, and that ship personnel are already overburdened) [71]. Here, the AHP-based MPS method could provide a more easy to use starting point for developing and implementing new maintenance regimes.

6.2.3 Considering the asset as a given or including the design

The research has started from the point where the asset is considered a given that requires certain maintenance. However, the multi-company session (see Chapter 5) emphasises the relation with the design and design phase of the asset. Namely, the design of the asset has great influence on the maintenance requirements during its further life-cycle.

An investigation into the incorporation of designers and the design phase into maintenance policy selection would be highly relevant. Such an investigation could reveal differences and similarities between the relevant criteria, the interpretations of the criteria and the judgements during different phases in the life-cycle of the asset. The relevance of this is especially notable when seen in the light of the increasing focus on servitization and the integration of assets and services into (industrial) product-service systems, and the shifts in responsibility and involvement that come with it [72, 73].

6.2.4 Broadening the application area and the MCDM method

We see two ways in which our research can be continued and broadened directly. The first is broadening of the application area, the second is broadening

of the method used. Both ways are discussed. First, the application area itself can be broadened in two ways. One way is to move to other sea-based, maritime industry, such as the oil and gas industry. Considering their ship-like nature, floating production, storage and offloading vessels (FPSOs) could act as a starting point, as FPSOs are often conversions of (no longer required) oil tankers. The other way is moving the research towards other transportable mobile technical capital assets such as trains, as shown in Table 1.1. From there, the step towards static assets can be probed.

Second, if the relations between the various criteria in the hierarchy prove to be dependent on each other, a to move towards the Analytic Network Process (ANP) can be considered [61, 74]. The ANP is the figurative younger brother of the AHP which is able to take dependent relations of criteria into account—although at the cost of added complexity of the process.

APPENDIX A

INTERVIEW SCRIPT

The script for the semi-structured interview is originally in Dutch, and is based on [60]. Both the Dutch version and the translated version are shown below.

DUTCH VERSION

- Briefing
 1. Opnemen van het interview
 - (a) Heeft u bezwaar tegen het opnemen van dit interview?
 - (b) Een off-the-record opmerking maken kan: even aangeven.
 - (c) De uitwerkingen stuur ik op voor review.
 2. Uitleg interview
 - (a) Het doel van het interview uitleggen en *maintenance policies* introduceren.
 - (b) Heeft u vooraf nog vragen over dit interview?
 3. Context
 - (a) Wat is uw positie en functie binnen het bedrijf?
 - (b) Wat zijn uw verantwoordelijkheden?

- Body

4. Beeldvorming marine en maritieme wereld

- (a) Wat doet u/uw bedrijf met schepen?
- (b) Hoe wordt een schip eigenlijk onderhouden? Hoe gaat zo iets in zijn werk?

5. Welke criteria worden nu gebruikt bij de keuze tussen *maintenance policies*?

- (a) Waarom wordt er eigenlijk onderhoud gepleegd aan schepen? Wat wordt daar zoal mee gewonnen?
- (b) Wat zijn de gevolgen als er iets stuk gaat aan een schip, midden op zee? En in of dichtbij de haven?
- (c) Wat is dan de *single most* belangrijkste van deze winstfactoren en gevolgen—of is die er niet?
- (d) Waarom is deze dan het belangrijkste?
- (e) Welke van de genoemde *maintenance policies* worden toegepast op schepen? En voor wat voor componenten?
- (f) Verdient een van deze *policies* een voorkeur?
- (g) Welke belangen spelen er allemaal een rol bij het onderhouden van een schip?
- (h) Hebben bepaalde belanghebbenden meer te zeggen dan andere?

6. Welke criteria zouden moeten worden gebruikt bij de keuze tussen *maintenance policies*?

- (a) Heeft u het idee dat sommige belanghebbenden zijn ondergesneeuwd of minder naar geluisterd wordt?
- (b) Zijn er trends of nieuwe ontwikkelingen te ontdekken in het onderhoud van schepen?
- (c) In vergelijking hoe schepen nu worden onderhouden: zou dit handiger, beter, slimmer of praktischer kunnen? En hoe dan?
- (d) Hoe zou een schip idealiter onderhouden moeten worden?

- Debriefing

7. Vragen/opmerkingen

- (a) Zijn er nog zaken die u wilt zeggen voor we het interview eindigen?
- (b) Zeer bedankt voor uw medewerking.

8. Afsluiten

- (a) Dan is nu het interview afgelopen en heb ik nog 1 laatste vraag:
- (b) Wat vond u ervan geïnterviewed te worden over criteria en over de keuze tussen *maintenance policies*?

9. Opnemen uit

- (a) Ik stop nu de opname.

ENGLISH TRANSLATION

- Briefing

1. Recording of the interview

- (a) Do you have any objections against the recording of this interview?
- (b) Making an off-the-record remark is possible, please indicate if you do so.
- (c) I will send you the results of the interview for review.

2. Explanation of the interview

- (a) Explain the purpose of the interview and introduce the maintenance policies.
- (b) Do you have any questions about the interview?

3. Context

- (a) What is your position and function within the company?
- (b) What are your responsibilities?

- Body

4. Familiarization with the marine/maritime world

- (a) What does your company do with ships?
- (b) How is a ship maintained? How does that work?
- 5. Which criteria currently play a role for the choice between maintenance policies?
 - (a) Why is a ship maintained? What is gained by maintaining a ship?
 - (b) What are the consequences of a failure, at sea and close to a port?
 - (c) What is the single most important gain and consequence—if such one exists?
 - (d) Why is this one then the most important?
 - (e) Which of the mentioned maintenance policies are applied at ships? And for which components?
 - (f) Is one of these policies preferred?
 - (g) Which interests and stakes play a role at ship maintenance?
 - (h) Are some stakeholders more important than others?
- 6. Which criteria should play a role for the choice between maintenance policies?
 - (a) Do you think that some stakeholders do not get enough attention or credit?
 - (b) Can you elaborate on trends or emerging developments in ship maintenance?
 - (c) Compared to current practices, could ship maintenance be done in a more practical, more clever or better way?
 - (d) How should a ship ideally be maintained?
- Debriefing
 - 7. Questions and remarks
 - (a) Do you have any remarks before we end this interview?
 - (b) Many thanks for your cooperation.
 - 8. Wrap up

- (a) Before the interview is over, I would like to ask one last question:
 - (b) What do you think of being interviewed on the criteria and the choice between maintenance policies?
9. Stop the recording
- (a) I will now stop the recording.

APPENDIX B

TOTAL LIST OF CRITERIA

The total list of criteria obtained from both the interviews and literature is presented in Table B.1, along with the total times mentioned.

TABLE B.1
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

Continued on next page

Criteria	Times mentioned
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 2 nd 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 2 nd 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., ILS, life cycle thinking)	2

Continued on next page

Criteria	Times mentioned
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
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

Continued on next page

Criteria	Times mentioned
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

Continued on next page

Criteria	Times mentioned
Moisture (environmental condition)	1
Mission predictability	1
Mean time to replacement	1
Mean time to repair	1
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 2 nd parties	1
Difficulty in training	1
Difficulty in implementation	1
Designed life-time	1
Designed for maintenance	1
Dependence on 2 nd 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

Continued on next page

Criteria	Times mentioned
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
1 st line or 2 nd line maintenance	1
Road class	1
Pavement condition	1
Operating traffic	1
Riding quality	1
Importance to community	1

APPENDIX C

CRITERIA DEFINITIONS

DEFINITIONS AS USED DURING THE SESSIONS DESCRIBED IN CHAPTER 3

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 divisions 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

DEFINITIONS AS USED DURING THE SESSIONS DESCRIBED IN CHAPTER 4

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

- *Availability*: the total availability of the system
- *Costs minimization*: the minimization of financial costs made
- *Crew Safety*: the safety of the crew
- *Reliability*: the total reliability of the system
- *Compliance with existing maintenance policies and prescriptions*: the desire to keep doing current maintenance practices
- *Drive for innovation*: the desire to innovate
- *Passion for maintenance*: the desire to do good and responsible maintenance
- *Planability of maintenance*: how well the maintenance can be planned
- *Crew size*: the amount of crew members
- *Crew educational level*: the educational level of the crew
- *Experience with maintenance*: the experience the company has with doing maintenance
- *Mission profile*: the profile of the mission, think of: location, duration, intensity and risk
- *Good communication within the company*: the communication between different divisions within the company
- *Good relations with other companies*: the relations with related companies
- *Maintenance feedback*: feedback of maintenance actions and results throughout the company and supply chain, and vice versa
- *Commonality presence*: the presence of commonality within the system
- *Spare parts availability*: the spare parts readily available where maintenance is needed
- *Spare parts costs*: the financial costs of the spare parts

- *Consequences of bad maintenance*: what happens if maintenance is done incorrectly, maintenance induced failures
- *Criticality of parts*: the criticality of the parts in the system
- *Redundancy presence*: the presence of redundancy within the system

DEFINITIONS AS USED DURING THE SESSIONS DESCRIBED IN CHAPTER 5

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

- *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 [65].
- *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 [65].
- *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 (based on [66]).
- *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.
- *What the cheapest option is*; from a financial point of view, think about: maintenance costs, maintenance budgets and austerity measures.
- *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.

- *Condition-based maintenance*; preventive maintenance, where a measured condition triggers the maintenance.

APPENDIX D

EVALUATION FORM

QUESTIONS

The evaluation form is originally in Dutch. Both the Dutch version and the translated version are shown below.

DUTCH VERSION

1. De sessie
 - (a) Wat vond je van de case-sessie?
 - (b) Vond je het nuttig? Waarom wel/niet?
 - (c) Vond je het leuk? Waarom wel/niet?
 - (d) Wat vind je van de duur van de sessie?
 - (e) Zou je een dergelijke sessie vaker willen doen? Waarom wel/niet?
 - (f) Zo ja, op wat voor momenten en hoe vaak zou je dat willen doen?
 - (g) Wat vond je van de groep? Denk bijvoorbeeld aan het aantal personen en de verschillende functies die zij bekleden.
 - (h) Heb je suggesties voor verbetering?
2. De hiërarchie van criteria

- (a) Vind je de hiërarchie duidelijk? Waarom wel/niet?
- (b) Wat vind je van de indelingen die gemaakt zijn?
- (c) Missen er criteria of alternatieven? Zo ja, welke?
- (d) Zijn er criteria of alternatieven overbodig? Zo ja, welke?

3. De keuze

- (a) Tijdens de sessie is een van de maintenance policies als beste naar voren gekomen. Zou je zelf voor dezelfde maintenance policy hebben gekozen? Waarom wel/niet?
- (b) Heb je het idee dat je beter begrijpt hoe de keuze tot stand is gekomen? Hoe komt dat?
- (c) Voor welk niveau in een systeem zou je door middel van een sessie als deze ideaal een maintenance policy willen kiezen?

4. Heb je nog andere opmerkingen?

ENGLISH TRANSLATION

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?

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
CI	Consistency index
CR	Consistency ratio
DMI	Directie Materiële Instandhouding (Directorate of Materiel Support)
DMO	Defensie Materieel Organisatie (Defence Materiel Organisation)
DSNS	Damen Schelde Naval Shipbuilding
EMEA	Europe, the Middle East and Africa
FPSO	Floating production, storage and offloading
HVAC	Heating, ventilating and air conditioning
ILS	Integrated logistics support
KNRM	Koninklijke Nederlandse Redding Maatschappij (Royal Netherlands Sea Rescue Institution)
KPI	Key performance indicator
LCC	Life-cycle costs

LRU	Line replaceable unit
MAUT	Multiattribute utility theory
MCDM	Multiple criteria decision making
MPS	Maintenance policy selection
MTBF	Mean time between failures
MTTR	Mean time to repair
OEM	Original equipment manufacturer
RCM	Reliability Centred Maintenance
RHIB	Rigid-hulled inflatable boat
RI	Random index
RNLN	Royal Netherlands Navy
SWATH	Small waterplane area twin hull
TCO	Total cost of ownership
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

LIST OF WORKS

SCIENTIFIC PAPERS

- 2015 Goossens, A.J.M. & Basten, R.J.I. *Maintenance policy selection for ships: finding the most important criteria and considerations*. BETA working paper 472. Submitted for publication.
- 2015 Goossens, A.J.M., & Basten, R.J.I. *Exploring maintenance policy selection using the Analytic Hierarchy Process; an application for naval ships*. Reliability Engineering & System Safety, 142, pp. 31 – 41. Doi: 10.1016/j.res.s.2015.04.014.
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- 2015 Goossens, A.J.M. *Multi-criteria beslissingen in onderhoud; een onderzoek bij de marine*, in Dutch (Multi-criteria decisions in maintenance; an investigation at the RNLN). *Arte Pugnantibus Adsum*, Vereniging van Hoger Technisch Gevormde Officieren (July), pp. 20 – 26.
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- 2013 Goossens, A.J.M. *Maintenance Policy Selection, research put to practice*. ESRA Newsletter (December), pp. 3 – 5.

CONFERENCES

- 2015 IIE/ISERC conference, including Doctoral Colloquium, Nashville, Tennessee, USA
- 2014 Euroma conference, including Doctoral Seminar, Palermo, Italy
- 2014 LRF International Technical Colloquium, Southampton, UK
- 2013 ESREL conference, Amsterdam, the Netherlands
- 2013 Euroma conference, including Doctoral Colloquium, Dublin, Ireland
- 2013 LRF Research Workshop, Seoul, South Korea

SUMMER SCHOOLS

- 2013 LRF and University of Southampton Research Collegium, 2 months, Southampton, UK, which resulted in:
Deshpande, A., Goh, A. L., Goossens, A., & Javdani, S. *Biomimicry for coastal eco-cities: towards a carbon Neutral Dover, UK*. (R. A. Sheno, P. A. Wilson, & S. S. Bennet, Eds.) LRF Collegium 2013 Series (Vol. 4). Southampton: University of Southampton, 2013
- 2012 WCM Maintenance Summer School, 1 week, Breda, the Netherlands

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