THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Method Development for Environmental Risk Assessment of Shipwrecks

HANNA LANDQUIST

The department of Shipping and Marine Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
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The department of Shipping and Marine Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
SE-412 96 Göteborg
Sweden
Phone +46 (0)31-772 1000

Cover: Oil leakage from the shipwreck of Harburg. Courtesy of William Hemberg.

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HANNA LANDQUIST
Department of Shipping and Marine Technology
Chalmers University of Technology

ABSTRACT

Potentially polluting shipwrecks containing oil or other hazardous substances may pose a threat to the marine environment. This is a global problem and many shipwrecks stem from the Second World War and have been deteriorating on the sea floor since then. Only in Swedish waters there are more than 2,700 wrecks that warrant further investigation and 31 of these are given a very high priority due to the environmental threat they pose. These wrecks are together estimated to contain between 1,000 and 15,000 tonnes of bunker oil. Every shipwreck poses a unique threat depending on, for example, the type of vessel, cause of sinking and environmental preconditions. Currently, there is no comprehensive method for assessing the environmental risk posed by shipwrecks and providing necessary support to decision-makers.

It is not feasible to remediate all shipwrecks due to costs but a proactive approach would make it possible to avoid the need and high cost of reactive response in case of an oil leakage. In order to effectively use resources, proper decision support is needed. Risk assessments and the overall process of risk management are important means to provide such decision support. The purpose of this thesis has therefore been to develop a framework for risk management of potentially polluting shipwrecks and a tool for quantification of the probability of release of hazardous substances from such shipwrecks. This was achieved through a comparison of current methods for risk assessment of shipwrecks in order to identify development needs. Based on the comparison, a generic framework for risk management of shipwrecks was suggested. Furthermore, the tool for estimating release probabilities was developed based on a probabilistic fault tree approach with the aim to support the risk assessment part of risk management. The tool makes it possible to consider possible events that may damage the wreck as well as physical and environmental conditions affecting the wreck.

The results from the comparison of current methods for risk assessment of shipwrecks showed that none presented a holistic risk assessment guide and that there is a lack of quantitative risk assessment tools for shipwrecks. Few methods considered uncertainties and the need of sensitivity analysis.

The generic framework for risk management of shipwrecks clearly shows the important steps that need to be performed and how they are linked. It also emphasizes the need of proper assessments to facilitate an efficient resource allocation for these types of environmental threats. The tool for probabilistic risk assessment of shipwrecks enables uncertainty analysis and is a first step towards a holistic risk assessment method for shipwrecks.

Keywords: environmental risk assessment, shipwreck, fault tree analysis, decision support

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Hanna Landquist
Göteborg, April 2013

List of papers

The thesis is based on the work presented in the following papers, referred to in the text by Roman numerals:

I. **Landquist, H.,** Hassellöv, I.-M., Rosén, L., Lindgren, J.F. and Dahllöf, I. (2013). Evaluating the needs of risk assessment methods of potentially polluting shipwrecks. *Journal of Environmental Management*, 119 (85-92).

II. **Landquist, H.,** Rosén, L., Norberg, T., Lindhe, A., Hassellöv, I.-M. and Lindgren, J.F. (2013). A fault tree model to assess probability of contaminant release from shipwrecks. Manuscript for submission to the *Journal of Environmental Management.*

Division of work between the authors

In Paper I, all the authors participated in stating the aim and scope and took active part in performing the work. Rosén outlined the framework for risk management of shipwrecks. Landquist performed the comparison and evaluation of methods for risk assessment of shipwrecks and was the main author of the paper.

All the authors contributed when the aim and scope of Paper II were defined. Landquist developed in close collaboration with Rosén, Lindhe and Hassellöv the fault tree model. Norberg was the main developer of the mathematical foundation which was based on discussions in the group. Lindhe and Rosén contributed largely to the theoretical description of the fault tree model. Landquist performed the simulations and was the main author.

Other work and publications not appended

- **Landquist, H.** (2013). Environmental Risk Assessment of Shipwrecks: A Fault-tree Model for Assessing the Probability of Contaminant Release. Accepted for publication in *Integrated Environmental Assessment and Management (IEAM) by the Society of Environmental Toxicology and Chemistry (SETAC),.*

- **Landquist, H.,** Rosén, L., Hassellöv, I-M., Lindgren, J.F., Norberg, T. and Lindhe, A. (2012). Environmental risk assessment of shipwrecks: a fault-tree model for assessing the probability of contaminant release. Poster at the *SETAC North America 33rd Annual Meeting,* Long Beach, November 11-15.

- Contribution to, *Environmental risks posed by shipwrecks* (2011). In Swedish, *Miljörisker från Fartygsvrak*, pp. 48-53. The Swedish Maritime Administration.

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1

Introduction

This chapter gives an introduction to shipwrecks as an environmental problem. It also briefly describes how this problem is handled today. Furthermore, the aim, limitations and the scope of the thesis is presented.

1.1 Shipwrecks, an environmental problem

Oil can be released into the environment in a number of different ways. Ships in operation, coastal facilities, natural seeps and accidents at sea are just a few examples of sources of marine oil pollution (GESAMP, 2007). A growing concern for oil pollution into the marine environment stems from shipwrecks (Basta and Kennedy, 2004). Numerous shipwrecks have been deteriorating on the sea floor for several years, the larger part since the Second World War, with unknown amounts of oil and other hazardous substances contained. The threat from shipwrecks requires attention, and there is a need for guidance and methods to efficiently handle this problem and facilitate resource allocation for mitigation measures.

Shipwrecks are a global problem and pose little to quite harmful pollution threats (Albertson, 2004). According to a modest estimate there are 8,000 or more potentially polluting shipwrecks (included tank vessels ≥150 GT and non-tank vessels ≥ 400 GT) in the world's oceans containing an accumulated amount of oil exceeding 2 million tonnes (Michel et al., 2005). A report by the Swedish Maritime Administration (2011) states that in Swedish waters 2,700 shipwrecks (included vessels ≥ 100 GT) would warrant further investigation and 316 of these wrecks were immediately assumed to pose a potential environmental threat. The same study prioritizes 31 shipwrecks in Swedish waters based on the estimated probability of carrying bunker oil or cargo and the potential of a leakage given the location of the wreck. These 31 wrecks were estimated to contain between 1,000 and 15,000 tonnes of bunker oil.

If petroleum products are released into the marine environment some of it will be mixed with the water by wave action resulting in an emulsion. Light components of the oil will evaporate, water-soluble components dissolve and UV-radiation from the sun will degrade the oil. The oil can also be oxidised, primarily by bacteria and fungi by consumption of biodegradable parts of the oil (Jernelöv, 2012; NRC, 2003). Oil released into the marine environment has negative effects on living organisms. The impacts are governed by a number of factors such as the composition of the oil, spill size, location of the spill and environmental conditions (McCay et al., 2004). The effects in biota can range from acute toxic (short-term) to chronic (long-term) and can be manifested in a number of ways. Acute effects can vary between hypothermia and smothering of seabirds to poisoning of organisms in the inter-tidal zone. Sub-lethal effects can cause reduced reproduction and growth, and genotoxic effects which can lead to a changed community composition in marine communities (Lindgren et al., 2012).

Another impact of oil spills are the economic effects. These effects can be categorized into: direct costs such as clean-up and financial damage cost (physical damage to property), market costs such as tourism and fisheries and non-market costs such as recreational and non-use values (Fejes et al., 2011).

Shipwrecks pose an environmental threat and each wreck is unique regarding the probability of leakage and the impacts thereof. A wreck is specific in its number of fuel tanks, damage at wreckage, water depth and water temperature, just to mention a few factors (Schmidt Etkin et al., 2009). Additionally, effects will differ depending on when oil is released, where the release occurs, the spread rate of the oil slick and the type of oil as mentioned above (Michel et al., 2005). Consequently, the variety of factors implies that there are several uncertainties affecting the risk assessment of shipwrecks, and by that the mitigation of the risk of oil release.

Etkin (2009) argues that a reactive response to oil leakage from a shipwreck would lead to higher response and damage cost than would a proactive and well-planned oil removal operation. Nevertheless it is very costly to mitigate the risk of shipwrecks. A remediation operation will incur costs for mobilising equipment and personnel depending on the condition of the wreck and whether the carried oil would need heating, due to its viscosity, before it can be pumped to response vessels at the surface (Hassellöv, 2007). It is estimated that remediation of one wreck costs between 1 and more than 100 million USD (Michel et al., 2005), therefore it is not economically feasible to remediate all sunken shipwrecks. The 316 wrecks in Sweden, mentioned previously, would cost hundreds of millions of dollars to remediate. To deal with the problem of potentially polluting shipwrecks there is a crucial need for decision support regarding prioritization of wrecks and where available resources can be used most efficiently (Schmidt Etkin et al., 2009).

Risk assessments can provide valuable decision support and are practiced in several disciplines such as engineering, ecotoxicology, public health and economics (Burgman, 2005). Risk assessment and risk analysis can be part of risk management often described as a process including: (1) *risk analysis*, with scope definition, hazard identification and risk estimation; (2) *risk evaluation*, including risk tolerability decisions and analysis of mitigation options; and (3) *risk reduction/control*, where decision-making, implementation and monitoring is performed (IEC, 1995). According to IEC (1995), *risk assessment* includes risk analysis and risk evaluation.

There are a number of suggested methods specific for risk assessment of shipwrecks (Alcaro et al., 2007; Schmidt Etkin et al., 2009; Idaas, 2005; Konstantinos et al., 2009; Michel et al., 2005; NOAA, 2009; SPREP and SOPAC, 2002). However, the work in this thesis shows that none of these studies suggests a comprehensive framework for risk assessment and risk management, which entails inefficient resource use (Landquist et al., 2013). It can be concluded that there is a need for a framework and appropriate risk assessment methods that facilitates comprehensive risk management of shipwrecks.

1.2 Aim

The overall aim of this thesis is to:

> *develop a framework for risk management of potentially polluting shipwrecks and a tool for quantifying the probability of release of hazardous substances from such shipwrecks.*

A framework for managing the risks associated with shipwrecks will provide structured guidance on important steps needed to handle this environmental problem. Understanding the risk from potentially polluting shipwrecks entails handling of uncertainties. To cope with uncertainty, a quantitative probabilistic approach is applied by using a fault tree model for estimating the probability of release of hazardous substances.

Three specific objectives are set to fulfil the overall aim:

- Compare and analyse identified current risk assessment methods for potentially polluting shipwrecks with respect to how these methods comply with an international standard for risk management.

- Suggest a generic framework for risk management and assessment of shipwrecks including risk identification, risk analysis and risk evaluation.

- Develop a tool to quantitatively estimate the probability of release of hazardous substances from shipwrecks.

1.3 Limitations

Risk and risk management are widely used terms and there are a number of frameworks describing the process and many tools for performing risk analysis and risk assessment. However, this thesis does not discuss the wide spectrum of risk and therefore the following limitations need to be highlighted:

- The suggested framework for risk management and assessment of shipwrecks describes the entire risk management process. However, the comparison between the identified methods is focused on risk assessment.

- The framework and tool presented in this thesis are intended to facilitate a proactive approach and specifically the assessment of potentially polluting shipwrecks. The assessment results aim to support decisions on measures for

preventing leakage of oil. The actual process of selecting and performing preventive measures is, however, not addressed in this thesis.

- There are shipwrecks all over the world containing a wide range of different hazardous substances. This thesis is focused on shipwrecks located in Scandinavian waters and that contains oil. A wider geographical scope and an expansion to other substances are possible future developments.

1.4 Structure and scope of the thesis

The thesis is structured in the following way:

- An introduction describing the purpose and objectives of the study is presented in Chapter 1.

- Background to risk and risk management is described in Chapter 2.

- In Chapter 3, the risk from shipwrecks is explored.

- Chapter 4 is a summary of the appended papers. Firstly, a literature review of risk assessment methods for shipwrecks is presented. Here, identified current methods are compared with relevant parts of the risk management standard by the International Standards Organisation (ISO, 2009). Moreover, a framework for risk management and assessment is presented. This is based on the findings from the literature review. The framework presents a comprehensive structure for risk management and assessment of shipwrecks. Lastly, the chapter contains a description of a tool for quantification of the probability of release of hazardous substances from shipwrecks. This method is based on a probabilistic fault tree analysis.

- The findings presented in this thesis are discussed in Chapter 5 along with suggestions of possible further work.

- Chapter 6 summarises the main conclusions.

- The two papers, "*Evaluating the needs of risk assessment methods of potentially polluting shipwrecks*" and "*A fault tree model to assess probability of contaminant release from shipwrecks*", are appended as well an appendix with the supplementary data for Paper I.

2

The concept of risk and the risk management process

Risk management is performed in a number of areas. The focus of this chapter is environmental risk management and assessment. The purpose of risk management and concepts related to this work are presented. Moreover, the importance of proper handling of uncertainties is stressed. Risk management is also described in the context of decision-making and some potential actors of the process, stakeholders and experts, are presented.

2.1 Why environmental risk assessment?

> *"To live is to choose. But to choose well, you must know who you are and what you stand for, where you want to go and why you want to go there."*
>
> Kofi Annan

In order to choose well and make informed decisions, risk assessment can be applied. A risk assessment can provide powerful decision support when future events are uncertain. Environmental risk assessment in specific can help evaluating risks to ecosystem processes, natural communities and to species (Burgman, 2005). The ability to define events that might occur in the future and to choose among alternative actions is a key component of modern societies. Understanding risk allows us to rationally make decisions (Bernstein, 1996). Society is constantly subject to change; e.g. complex technology with inherent risk and uncertainty and an increased vulnerability is emerging rapidly. Environmental groups work more intensely and people require increased safety and reliability. As a consequence, the need for decision support tools addressing risk and uncertainty is obvious (Aven, 2003).

Primarily, the purpose of risk assessment is to serve as input to decision-making. Risk assessment can provide decision support when prioritizing hazards, comparing alternative actions, managing land use and much more. Risk assessment can also be carried out for cost-benefit analyses and exploring potential consequences of performing a certain action (Suter, 2007).

2.2 Risk, what does it mean?

Risk assessment is carried out in many areas such as engineering, medicine and environmental regulation (Suter, 2007). The concept of risk as we see it today originates from the Hindu-Arabic numbering system and deeper studies emerged during the Renaissance. In 1645 Blaise Pascal and Pierre de Fermat discovered the theory of probability which is the core of the concept of risk. They did the finding when solving a gamblers problem (Bernstein, 1996).

Etymologically, risk stems from the early Italian *risicare*, meaning *to dare*. When looking at risk from that perspective, there is a choice involved rather than dependence on faith which was the prevailing view of life in the past (Bernstein, 1996). Many definitions exist but a general view of risk is that it is the chance of an adverse event within a time frame, with specific consequences (Burgman, 2005). Another definition is that risk is a combination of the severity and the probability of effects from a certain action, where severity is the nature and magnitude of the effects (Suter, 2007). Moreover, Kaplan and

Garrick (1981) states that a quantitative risk analysis in specific shall answer the following three questions:

- What can happen?
- How likely is it?
- What are the consequences?

When trying to answer the three questions stated by Kaplan and Garrick (1981) one might encounter a number of terms associated with risk. There is an ambiguity surrounding risk, and the terminology and methods applied differ greatly (Aven, 2003). Some of the commonly used definitions are described in Table 2.1 to define what is meant by the different terms in this thesis.

Table 2.1. Definitions of terms based on ISO 31000 (2009) and IEC (1995).

Consequence	Outcome of an event affecting objectives.
Hazardous event	An event that can cause harm.
Hazardous substance	Substance with the potential to cause harm.
Likelihood	Chance of something happening.
Risk	Combination of the frequency, or probability, of occurrence and the consequence of a specified hazardous event.
Risk analysis	Process to comprehend the nature of risk and to determine the level of risk.
Risk assessment	The overall process of risk identification, risk analysis and risk evaluation.
Risk evaluation	Process of comparing the results of risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable.
Risk identification	Process of finding, recognising and describing risks.
Risk management	Coordinates activities to direct and control an organisation with regard to risk. Includes risk assessment and risk reduction and control.
Risk management framework	Set of components that provide the foundations and organisational arrangements for designing, implementing, monitoring, reviewing and continually improving risk management throughout the organisation.

2.3 Uncertainty

Two common denominators for problems concerning risk are firstly, that a decision is to be made and secondly, that there are uncertainties involved (Suter, 2007). The sources of uncertainties may be many, but they are in general categorised into two types; *epistemic* and *aleatory*. An epistemic uncertainty is assumed to be derived from lack of data while the aleatory (stochastic) refers to intrinsic randomness and describes natural variability in populations (Aven, 2003; Kiureghian and Ditlevsen, 2009).

It is important to be aware of and handle uncertainties since the quality of the risk assessment largely will depend on how they are dealt with. Uncertainties must be treated in a comprehensive, repeatable and transparent manner (Burgman, 2005). The aleatory type of uncertainty is set by the circumstances and cannot be reduced, only acknowledged; however, the epistemic uncertainties can be reduced by increased information. There are several techniques for evaluating and handling uncertainties. One technique is probabilistic risk assessment representing risk as a distribution rather than a point estimate (Paté-Cornell, 1996).

Other means to evaluate and handle uncertainty is to apply a Bayesian approach. About one hundred years after the theory of probability was discovered by Fermat and Pascal, as mentioned in Section 2.1, Thomas Bayes discovered how new information could be mathematically combined with old information to provide better decisions (Bernstein, 1996). Bayesian probability is a belief-type approach an assessor can apply to rationally change a belief when new evidence is found (Hacking, 2001). When applying Bayes' theory, a prior distribution can be updated to a posterior distribution. The prior distribution consists of knowledge and expertise collected by the model constructor while the posterior distribution also can contain results of e.g. an experiment. The possibility of the Bayesian approach to combine expert judgments with scientific evidence has made it widely used (Bedford and Cooke, 2001). Updating the prior knowledge will contribute to a more certain outcome.

Additionally, it is crucial to be humble to the fact that there is an uncertainty in unknown unknowns, aspects not possible to know on beforehand. It is impossible to include all relationships and variables (IPCC, 2007).

2.4 Decision-making and the risk management process

There are several frameworks describing the risk management process. In general they share some basic steps (Figure 2.1). These steps are risk assessment, consisting of risk analysis and risk evaluation, and in addition, risk reduction and control are included to complete a full risk management process.

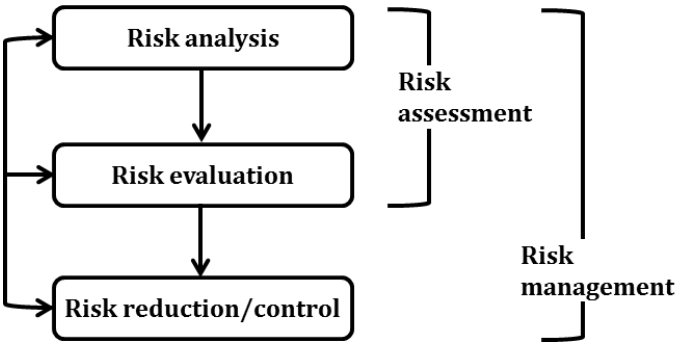

Figure 2.1. A simplified scheme of the risk management process (after IEC, (1995)).

An expanded framework is provided by e.g. ISO (2009) (Figure 2.2) where a broader presentation of the risk management process is given. In an *establishment of the context*, the organisation sets the scope and risk criteria for the process. Within *risk identification*, the aim is to produce a comprehensive list of what might affect the achievement of the objectives. *Risk analysis*, the process to understand the nature and determine the level of risk, should provide input to the risk evaluation step and act as decision support concerning risk treatment. Moreover, the *risk evaluation* involves comparing the results of the risk analysis to the risk criteria and to evaluate possible actions. This will show whether the risks found are acceptable or not. During the final step, *risk treatment*, one or more actions are chosen and implemented to mitigate the risk.

In order to ensure that relevant parties such as authorities receive the proper information, communication and consultation is important during all phases of risk management. Monitoring and review should also be a part of a risk management process, including e.g. providing input to improve the process, detecting changes that should be reflected in earlier stages, and identifying emerging risks (ISO, 2009).

Risk management can enable an organisation to establish a basis for decision-making. It can be a help to decision-makers in taking informed actions and prioritize between options (ISO, 2009). More specifically, it is within risk assessments and risk analyses information to support good decisions can be elicited (Aven, 2003).

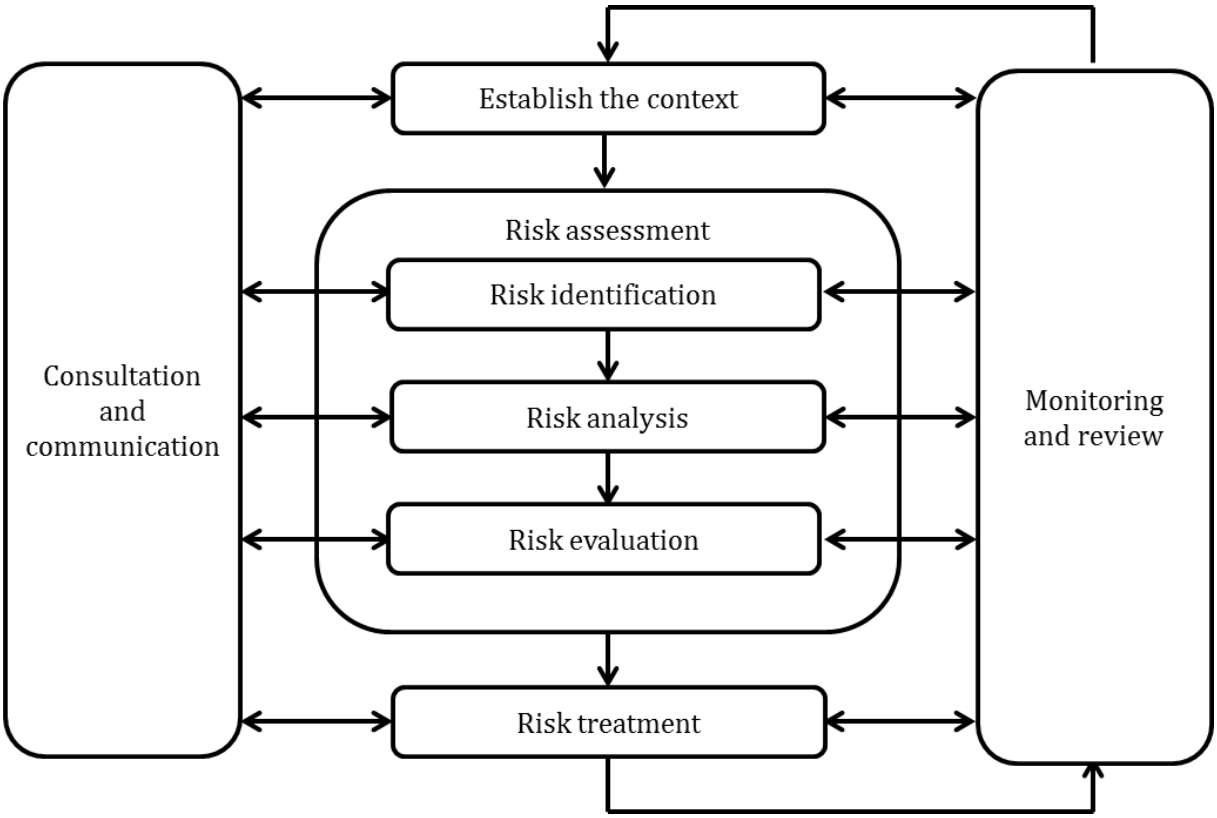

Figure 2.2. The risk management process (ISO, 2009).

A basic structure for decision-making is shown in Figure 2.3 (Aven, 2003). The structure is based on the assumption that decision-making is a process where risk and decision analyses provides input. Informal managerial judgement and review shall follow to result in a decision. The risk management process and the decision-making structure do not conflict; the former is rather an important component of the latter.

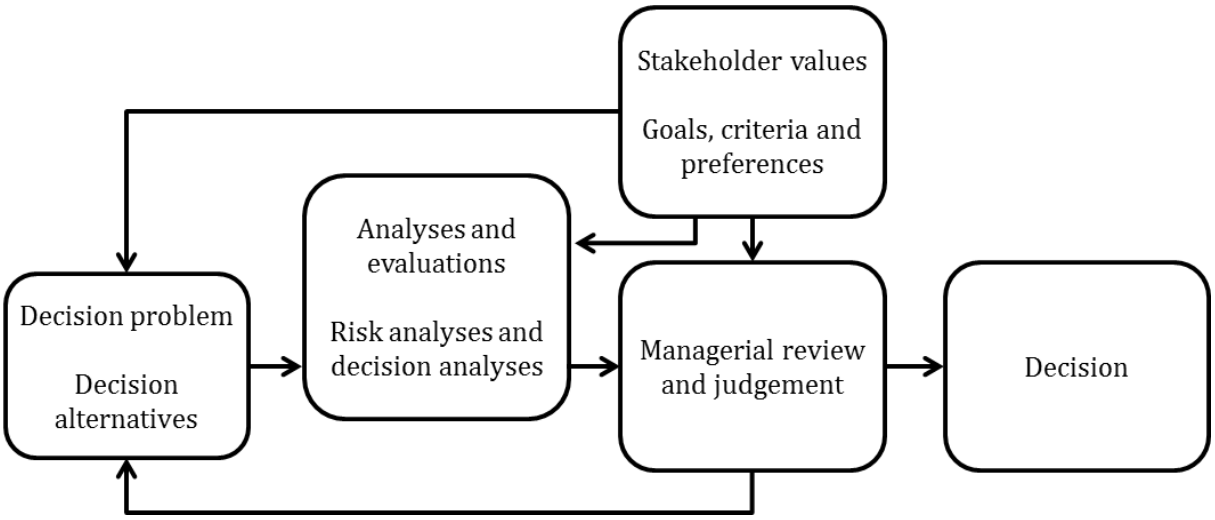

Figure 2.3. Basic structure of the decision-making process (Aven, 2003).

2.5 Experts and stakeholders

Expert judgment is almost always present in environmental risk assessment. When empirical evidence or extrapolations are not available experts can be useful. They can estimate intervals, point estimates or statistical distributions by using frequency concepts of probability without information from measurements. Subjective beliefs are another type of information that can be elicited from experts (Burgman, 2005).

However, it can be difficult choosing the right experts (Bedford and Cooke, 2001). There should be a proper selection of experts concerning the number of people and the appropriate knowledge. Any expert selected may suffer from a number of biases. Overconfidence, motivation and the political, cultural and philosophical context might imply bias on some experts. Burgman (2005) concludes that an expert needs to have proper knowledge and receive training to give unbiased estimates.

Public concern and awareness of many aspects of risk has become stronger due to the growth in communications, availability of information and scientific advances (Aven, 2003). A person or organisation that is particularly affected by the consequences of an environmental management decision is called *stakeholder* (Suter, 2007). There are also definitions containing non-human entities, such as threatened animals and plants (Burgman, 2005). The public as a whole can have an interest in environmental decisions and decisions not accepted by those affected will be politically unacceptable. The public should be differentiated from the stakeholders that have a particular concern within the decision and is a smaller group. However, it can be necessary to involve a larger group from the public in addition to stakeholders to balance the input since the stakeholders tend to be biased (Suter, 2007).

When using stakeholders as a source of information and input to decision-making it is important that their knowledge is used effectively. Implying e.g. choosing the right stakeholders for the problem at hand, elicit information rigorously and apply appropriate analysis techniques. There should be a clear statement and communication of the purpose of the assessment to the stakeholders. A clear and honest communication process throughout the assessment is necessary for an effective dialogue (Glicken, 2000).

3

Types of risk posed by shipwrecks

Shipwrecks can contain oil or other hazardous substances that can cause severe negative environmental effects if released. Furthermore, each shipwreck is unique and consideration must be taken to local environmental conditions and possible hazards.

3.1 Hazardous events that can cause damage to shipwrecks

As mentioned in the introductory chapter, there are a number of factors causing shipwrecks to deteriorate and ultimately this will lead to a release of hazardous substances such as oil. A prerequisite is of course that the wreck still contains hazardous cargo or bunker fuel for propulsion. Shipwrecks are thus a source of oil release into the marine environment. A number of hazardous events with the possibility to induce release of oil from shipwrecks have been identified through literature (Konstantinos et al., 2009; Michel et al., 2005; Schmidt Etkin et al., 2009) and brainstorming events with groups of experts. Some events are man-induced while others have natural or environmental causes. These events, described in detail below, are:

- Construction work
- Military activity
- Diving
- Ship traffic
- Trawling
- Landslides/Earth quakes
- Storms/Extreme weather
- Corrosion causing leakage

The following is a description of each of the eight identified hazardous events. The background and main assumptions regarding the events are presented.

Construction work
Minor construction work such as construction of aquaculture facilities, and research equipment and cables, are assumed to cause potential harm by anchoring of equipment or construction vessels. Supply vessels might incur damage for similar reasons. Intermediate construction work such as pipelines, offshore energy facilities and dredging might evoke the same types of hazard. Larger construction work such as the building of ports, bridges and multi-platforms for e.g. offshore energy production might cause harm to a shipwreck. Blasting works, investigational surveys, larger casting work, anchoring and supply traffic are also identified as possible hazardous events.

Military activity
Light military activity such as basic training for mariners might cause damage when anchoring in an area containing shipwrecks. Intermediate military activity such as exercises with depth charges, training in defusing mines and disarming of live mines might cause damage to shipwrecks. Releases of depth charges might go wrong and

disarming of live mines close to unknown shipwrecks can cause damage. There is also the possibility of a damage from military effort with live ammunition if e.g. a hostile vessel needs to be put out of action. At such incident, no concern is likely to be given to shipwrecks.

Diving

At the occurrence of diving at a wreck site, anchoring at or to the wreck will pose a threat of damage to the shipwreck. Some divers retrieve material from the wreck site and may by this damage the wreck. Divers might swim inside the wreck and released air from scuba-sets can get trapped inside the vessel. If frequently occurring, this may cause slight destabilization of the shipwreck.

Ship traffic

Smaller vessels such as private boats, ferry traffic, tourist vessels, research vessels, police and coastguard are assumed to have a speed of about 7-20 knots and might anchor in the area of a shipwreck. Intermediate sized vessels such as ice breakers, short sea shipping vessels, service vessels and again coast guard and police vessels are assumed to have a speed in the same range. These types of vessels might also anchor in the vicinity of a shipwreck. Large vessels are container vessels, bulk vessels, specialized shipping vessels, cruise ships and large ice breakers. The speed is assumed to be 11-23 knots. The hazard posed from ship traffic is damage due to anchoring and the squat effect. The squat effect occurs when water is pushed in front of a ship due to its movement forward. This will leave a deficit of water behind the ship and the return flow is speeded up under the ship. This causes a pressure drop and the ship drops vertically in the water (Barrass, 2004). The squat effect is assumed to potentially destabilize a shipwreck.

Trawling

Different types of fishing trawls might incur damage to shipwrecks. There are primarily two types of trawlers used in Sweden today, bottom trawls and floating trawls (Fisheries, 2011). The former is assumed to have the highest potential for causing severe damage to a shipwreck. Some of the equipment is very heavy and an impact with a shipwreck can cause an opening through which hazardous substances may be released. Shipwrecks can function as an artificial reef which fish might find as a suitable habitat, (Steimle and Zetlin, 2000). This knowledge can increase trawling in the vicinity of a wreck.

Landslide/ Earth quakes

Earth quakes, unstable sea floors, landslides and collapses can cause movement of a shipwreck. The wreck might be displaced or set to wobble. This is assumed to potentially cause damage to a shipwreck.

Storms/Extreme weather
Wind and wave action is assumed to possibly affect shipwrecks. Pressure differences and currents might cause instability to a wreck and thus harm the structure.

Corrosion causing leakage
Corrosion will affect a steel structure on the sea floor. The question is to what extent. The rate of corrosion is in general affected by e.g. dissolved oxygen, temperature, pH, salinity, current velocity, wave action, marine growth and bacteria (Kuroda et al., 2008; Sender, 2010).

There are major uncertainties associated with assessing risks of hazardous releases from shipwrecks, mainly because there are few measurements of how construction work, trawling etc. affect shipwrecks. Few measurements and available data will imply that assessments by experts are necessary, whose estimations also are uncertain. Moreover, site-specific conditions make generalizations concerning effects of hazardous release difficult. This means that handling of uncertainties is crucial to obtain useful results from a risk assessment of shipwrecks.

3.2 Oil, a driver of development and an environmental disaster

Oil (petroleum) is the primary hazardous substance of focus for this thesis. Both oil and gas are formed from plants and animals of a marine origin but the process is not fully understood. Nevertheless, the formation of petroleum is assumed to initiate with an accumulation of sediment rich in organic material. As the organic matter gets transported deeper into the anoxic sediments, heat, pressure and time (millions of years) will transform the biota into gas and liquid forms of hydrocarbons, e.g. oil. If there is a lot of oxygen in the sedimentary environment, decay will start and petroleum will not form. The oil and gas are mobile and will move upward, if existing, in porous layers of rock. If nothing stops this process, the petroleum and gas will eventually reach surface and the volatile components will evaporate. However, if a more solid layer of rock interrupts this movement, the petroleum and gas migration is halted (Tarbuck and Lutgens, 2008; Walters, 2006).

It is not possible to date the first human encounters with oil but it has been used in small amounts since antiquity. It was often used for non-energy applications such as floors and protective coatings but also for illumination. In 1837, the first commercial oil distilling factory was built in Balakhani, Azerbaijan and nine years later the first giant oil field (at least 500 million barrels of recoverable crude oil) was opened. Other countries followed and in 1860 oil was a true source of energy in Russia, Canada and the US. In 1938, large discoveries were made in Saudi Arabia and Kuwait. The demand for oil rose after the Second World War and was stimulated by e.g. car ownership and air travel. It was also cheap to transport oil by tankers (Smil, 2010).

In June 2012 the world's total use of oil was approximately 14 billion litres per day (BP, 2012). Burning of fossil fuels such as oil causes CO_2 release, and the use of fossil fuels is the primary cause of the CO_2 increase in our atmosphere. The Climate Change 2007: Synthesis Report (IPCC, 2007) states that CO_2 is the most important human induced greenhouse gas and represented 77% of the total anthropogenic greenhouse gas emissions in 2004. The largest growth of emissions stems from energy supply, industry and transport, in the long run, from our change in lifestyle due to the industrial revolution.

3.3 Fate and effects of oil in the marine environment

Each type of crude oil has a unique composition, depending on conditions during formation. The largest part is made up of hydrocarbons, which with related compounds constitute approximately 97% (NRC, 2003). It is argued that polycyclic aromatic hydrocarbons (PAH) possibly are the parts of oil that have the most severe environmental long-term effects (Martínez-Gómez et al., 2010). Other elements in oil are e.g. nitrogen, sulphur and oxygen (NRC, 2003). Crude oil and its refined products enters the marine environment through e.g. operational discharges from ships, scrapping of ships, offshore operations, shipping accidents, shipwrecks, pipelines, from coastal refineries and natural seeps. It is estimated that the total amount of oil discharge into the marine environment is 1,245,000 tonnes per year. The contribution per source is shown in Figure 3.1 (GESAMP, 2007).

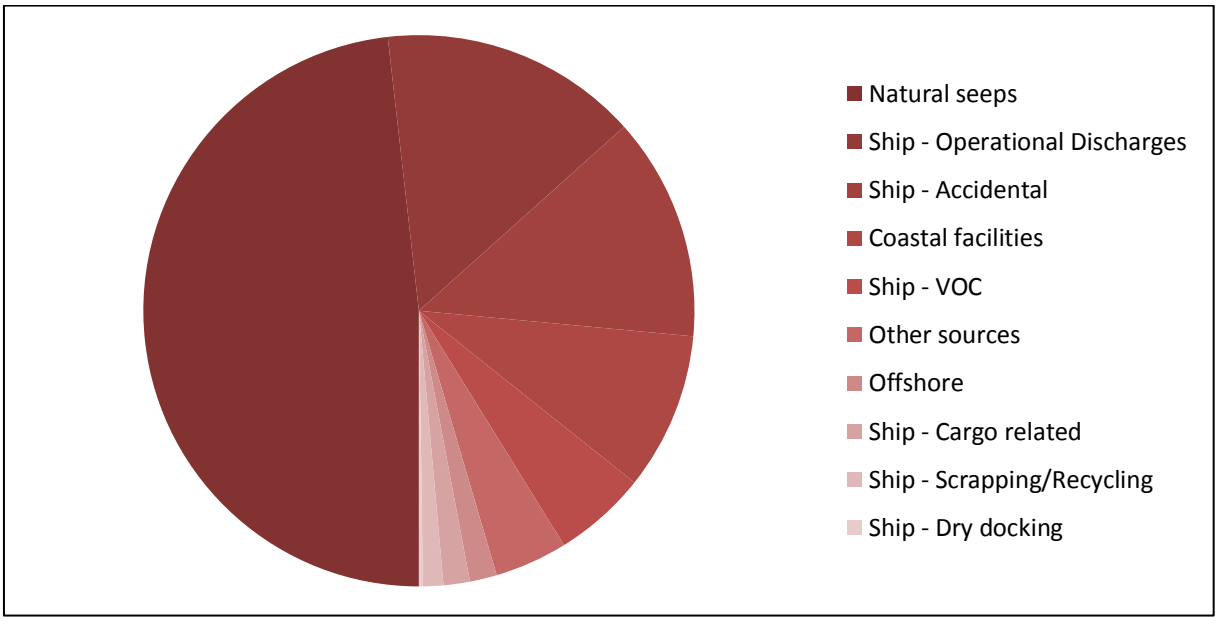

Figure 3.1. The annual contribution from shipping and other sea-based activities to oil input into the marine environment. Leakage from shipwrecks is here assumed not possible to estimate (GESAMP, 2007). The diagram shows sources of both crude oil and refined products.

Oil released into the marine environment is affected by a number of processes together called weathering (Figure 3.2). Weathering begins immediately after a discharge and chemically and physically transforms the oil. One of these processes is evaporation, an important factor in terms of mass balance, where the most volatile components in the oil evaporate to the air. Furthermore, emulsification can take place, a process where water and oil is mixed which can change the properties of the oil. A significant feature of the emulsification process is that the viscosity greatly increases which has an effect of the continuing degradation processes. Moreover, dissolution is considered an important factor even though it is assumed to contribute only to a small part of the total oil loss. Some soluble components of oil, in particular the PAHs, are more toxic to biota in a dissolved state. Oxidation is also a process affecting oil and causes altering of the mixtures of organic compounds of the oil. The products of the oxidation will be more water soluble than the hydrocarbons they are derived from. Oxidation takes place through two processes, photo oxidation and microbial oxidation. Finally, oil will be transported, both vertically and horizontally when discharged into the sea. That will induce e.g. spreading of the oil, advection, sinking, and sedimentation (NRC, 2003).

Environmental effects

Petroleum entering the marine environment has a negative effect on living organisms. Some aspects are critical to the amplitude of these effects; the physical and chemical properties of the oil, the pathways to the receptors, how receptors interact with the oil and the background exposure of environmental stressors. There are three different pathways through which oil can be exposed to receptors; direct contact or ingestion, intake of bioavailable components through water, and ingestion of prey contaminated by oil (Boehm and Page, 2007).

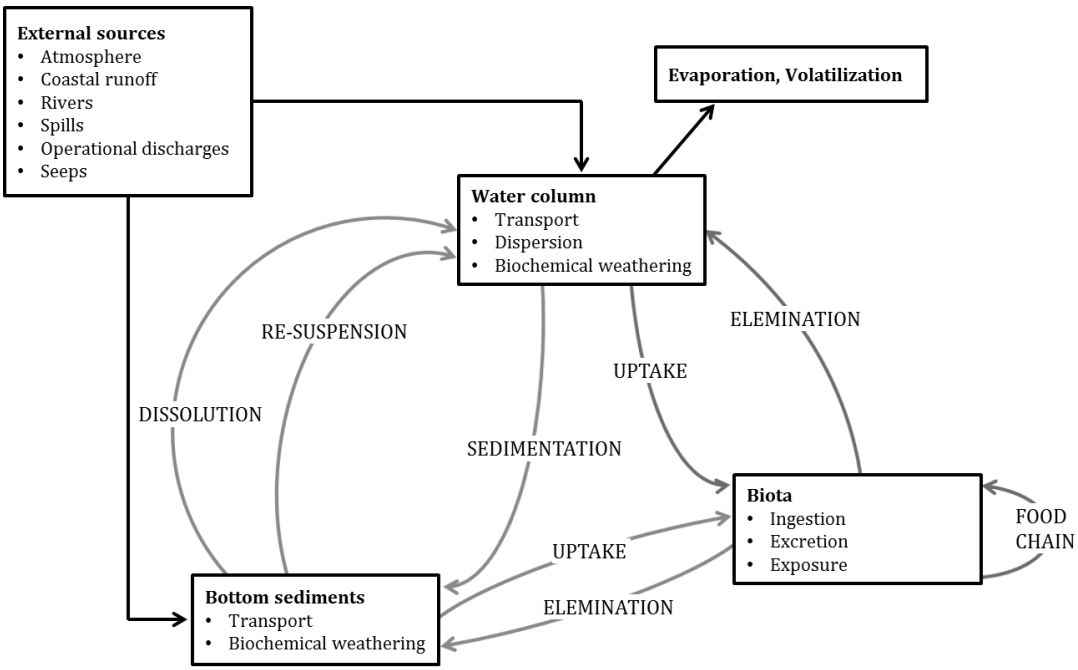

Figure 3.2. A conceptual model of fate and interactions of oil in the marine environment (NRC, 2003).

The effects of an oil spill vary between acute and chronic. Oil washed up on beaches or covering areas at sea can attract and smother seabirds. Exposure to oil can cause hypothermia in birds, due to loss of insulating capabilities, causing them to freeze to death. Adhesive oil in the water can trap smaller animals and kill them. Furthermore oil can be ingested by larger inhabitants of the sea. Animals can inhale it and the oil can get stuck on gill membranes (Jernelöv, 2012). It has been shown by e.g. Lindgren et al. (2012) that oil released into the marine environment can also effect and cause changes in community structure in meiofauna; small organisms 1000-500 to 63-44 µm in size.

Costs of an oil spill

Proper impact analysis of an oil spill requires setting a value on the harm imposed (Etkin, 2004). Such valuation might be of interest to local stakeholders, responsible parties and governments (Liu and Wirtz, 2006). The costs originating from an oil spill are large (Fejes et al., 2011). The most prominent factors affecting the cost are location of the spill, oil type and the amount spilled. Other factors contributing are e.g. clean-up strategy, timing of the spill and local and national laws (Schmidt Etkin, 1999). Furthermore, research costs can be included in the total estimate of the oil spill cost (Liu and Wirtz, 2006). The costs can be aggregated into three important areas of consequences to be taken into account: response cost, socio-economic losses and environmental damages or ecological impact (Forsman, 2007; Liu and Wirtz, 2009).
Response cost for an oil spill can be constituted of labour and equipment cost for salvage and lightering, recovery, shoreline clean-up, containment of and protection of sensitive areas, waste disposal and wildlife rehabilitation (Helton and Penn, 1999). A proactive approach of risk assessment and possible remediation of shipwrecks would reduce e.g. costs for shoreline clean-up and wildlife rehabilitation.

Socio-economic losses can consist of monetary losses of income and property damage for the fishing and tourism sector (Liu and Wirtz, 2009), which also can have indirect effects on e.g. fish consumers and restaurants serving tourists. In general consumers lose welfare from reduced quality or increased prices, or lose access to goods and services. Producers lose profit. There might also be losses of non-priced social welfare, not valued in the market. That can be ecological resources (e.g. species) or ecological services (e.g. recreational opportunities or wildlife habitats) (Fejes et al., 2011). It is also claimed that the economic sectors need time to recover from oil pollution like a contaminated natural resource (Liu and Wirtz, 2009). Socio-economic estimates of oil spills are generally difficult to perform (Kontovas and Psaraftis, 2008).

Oil spills will degrade *natural resources and eco-system services* during some time after a spill has occurred (Liu and Wirtz, 2006). Natural ecosystems can be seen as capital assets. These can, if properly managed, provide goods, services and life support over time (Daily, 1999). However, many environmental services and goods are non-market assets, and can therefore be very difficult to value economically. There are methods to estimate environmental damages (or loss of eco-system services) where economists

either indirectly link the resources (environmental goods and services) to market goods (goods that are traded at a market) or construct a hypothetical market where peoples willingness to pay for certain goods or services are estimated (Kontovas and Psaraftis, 2008). However, when it comes to ecosystems, what is valid in one part of the world might not hold true in another area (Daily et al., 2000).

It is not an easy task to determine the total cost of an oil spill (Kontovas and Psaraftis, 2008). The total actual cost cannot be properly determined until after the spill when all contributing costs have been realised and all uncertainties are eliminated (Schmidt Etkin, 2000). Moreover, each spill is a unique incident. The type of oil released might differ and the damage to the local environment might be different from spill to spill (Etkin, 2004). To conclude; it is impossible to predict the exact cost of a spill.

However, an approach to solve this problem is to estimate costs through e.g. cost-benefit analysis (CBA). By doing such valuation of potential spill consequences on beforehand, even if uncertainties are large, the benefit of reducing a risk is made clearer and it is possible to express the results in monetary units.

4

Summary of appended papers

This chapter presents and summarizes the main findings of the two appended papers: "*Evaluating the needs of risk assessment methods of potentially polluting shipwrecks*" and "*A fault tree model to assess probability of contaminant release from shipwrecks*".

4.1 Overview of the papers

The two papers appended to this thesis present: (1a) a comparison of current methods for risk assessment of shipwrecks to an international standard; (1b) a suggested framework for risk management and assessment of shipwrecks; and (2) a tool for quantitative estimation of the probability of release of hazardous substances from shipwrecks. The comparison of current methods shows where development is needed. The suggested framework provides a general structure for risk management of shipwrecks and the tool for risk estimation is a first part of a comprehensive risk assessment method for shipwrecks.

4.2 Current identified methods for environmental risk assessment of shipwrecks

By means of a literature review, six current methods for risk assessment of shipwrecks were identified. To evaluate the suitability of these methods for performing a structured risk assessment that can provide a relevant basis for managing risks from shipwrecks, comparisons to the ISO standard 31000, *Risk management – Principles and guidelines* (2009), were made (Paper I, Evaluating the needs of risk assessment methods of potentially polluting shipwrecks). The comparisons were made with respect to parameters assumed relevant for a shipwreck application. More explicitly, parts assumed to be relevant correspond to a comprehensive environmental risk assessment of shipwrecks and are presented in more detail in Table 4.1.

The methods identified were found in scientific papers and other official reports. Other material, such as the Nairobi International Convention on the Removal of Wrecks (IMO, 2007), was not included since it was not intended as a framework for risk assessment of shipwrecks. Furthermore, the IMO Guidelines for Formal Safety Assessment (FSA) (IMO, 2002) is not a wreck-specific guideline.

The identified methods were:

A. The Wreck Oil Removal Program (WORP), aimed to use a scientifically-based approach to remove oil and had a specific focus on trying to minimize costs and risk of pollution from sunken commercial vessels (NOAA, 2009).

B. Michel et al. (2005) presented a guide for risk assessment of oil release for shipwrecks. The goal was stated as to objectively analyse shipwrecks according to their potential threat of petroleum discharge and to provide guidance for addressing the issue.

Schmidt Etkin et al. (2009) presented a similar guide, however taking into account both impact of a leakage and the probability of that impact occurring, to assess the environmental risk of shipwrecks. It was a strategic modelling approach for prioritising shipwrecks as well as aiming to provide decision support to authorities.

C. DEvelopment of European guidelines for Potentially Polluting Shipwrecks (DEEPP) had the objective to provide European coastal states and national administrations with guidelines and criteria to handle the environmental threat of shipwrecks (Alcaro et al., 2007).

D. The Norwegian Pollution Control Agency (NPCA) described a wreck project in three phases: registration, priority ranking and required action. The aim was to have a complete overview of shipwrecks along the Norwegian coast (Idaas, 2005).

E. The Pacific Ocean Pollution Program (PACPOL) within the South Pacific Regional Environment Program (SPREP) was aimed at pollution of the marine environment from ship based sources. This specific strategy was aimed at e.g. preventing or minimizing negative impact from shipwrecks (SPREP and SOPAC, 2002).

F. A risk analysis strategy for shipwrecks in Greek waters was presented by Konstantinos et al. (2009). It was aimed at oil leakage and based on the IMO Formal Safety Assessment (2002).

4.2.1 Comparison to an international standard for risk management

The ISO standard for risk management (2009), illustrated in Figure 2.2 in Chapter 2, describes a commonly agreed view of the risk management process. Other similar frameworks are applied in many areas (AZ/NZS, 2004a; AZ/NZS, 2004b; IEC, 1995; The Swedish Civil Contingencies Agency, 2003). The parameters of the framework considered relevant for the comparative analysis presented here are shown in Figure 4.1 and were intended to constitute the necessary steps of a risk assessment relevant for a shipwreck application.

Establishment of the context
- Scope
- Defining risk criteria
  - *Ship selection*
  - *Geographic coverage*

Risk identification
- Sources of risks
- Areas of impact
- Events
- Causes of events

Risk analysis
- Estimation of consequences
- Estimation of likelihood/ probabilities of consequences
- Risk estimation
  - *Qualitative*
  - *Semi-quantitative*
  - *Quantitative*
- Uncertainty analysis
- Sensitivity analysis

Risk evaluation
- Comparison of risk levels to risk criteria
- Consideration of risk reduction alternatives

Figure 4.1. The parameters of the ISO standard for Risk management (2009) chosen for the comparative analysis of risk assessment methods.

Each of the methods found were graded according to a four grade scale with respect to each of the selected parameters from the ISO standard. The parameters were evaluated from “not considered at all”, “fulfilled to some extent”, “considered” to “fulfilled to a large extent”. The full comparison is presented in Paper I and the supplementary information. A summary is presented in Table 4.1.

Table 4.1. The results of the comparison of risk assessment methods for shipwrecks. A= The Wreck Oil Removal Program, B=Potentially polluting wrecks in marine waters, C=The DEEPP project, Development of European guidelines for Potentially Polluting shipwrecks, D= The Norwegian Pollution Control Authority (NPCA), E= The South Pacific Regional Environment Program (SPREP), F= The model by Konstantinos et al. (2009).

		Method					
		A	B	C	D	E	F
	○ **Establishment of the context**						
	• Scope						
	• Defining risk criteria						
	- *Ship selection*						
	- *Geographic coverage*						
Risk assessment	○ **Risk identification**						
	• Sources of risks						
	• Areas of impact						
	• Events						
	• Causes of events						
	○ **Risk analysis**						
	• Estimation of consequences						
	• Estimation of likelihood /probabilities of consequences						
	• Risk estimation						
	- *Qualitative*						
	- *Semi-quantitative*						
	- *Quantitative*						
	• Uncertainty analysis						
	• Sensitivity analysis						
	○ **Risk evaluation**						
	• Comparison of risk levels to risk criteria						
	• Consideration of risk reduction alternatives						
	Legend; Level of fulfilment						
	Fulfilled to a large extent						
	Fulfilled to some extent						
	Considered						
	Not considered						

4.3 A suggested framework for environmental risk management of shipwrecks

As described in Chapter 2, risk management is the process of risk analysis, risk evaluation and risk reduction and control. The first two parts, risk analysis and risk evaluation, together constitute risk assessment. Environmental risk management of shipwrecks is complex and should therefore be performed in a structured way. A number of general guidelines (e.g. IEC, 1995; ISO, 2009; Rosén et al., 2007) describe risk management. Based on these guidelines a generic framework for risk management of shipwrecks was suggested (Figure 4.2). The purpose was to emphasize the connection between decision-making and risk management and stress that risk assessment is an

essential support to decision-making. Some additional parts were added to the original guidelines to stress e.g. communication of results to stakeholders and the necessity of handling uncertainties.

In order to practically implement the framework it is necessary to use an adequate set of risk management tools. Largely generalized assessments are due to the complex cause-and-effect chains of risks involved with shipwrecks, not likely to provide useful results and therefore tools should be chosen with care. Development of proper tools is initiated in this thesis (Section 4.4). Uncertainties are assumed to be large and should be handled properly, e.g. by a quantitative and probabilistic approach. Furthermore, the complexity implies that a team of experts should be involved to ensure that knowledge of e.g. marine activities, the physical properties of a ship, and knowledge of the risk assessment process is properly incorporated.

Information exchange and communication is important in this type of procedure. Risk management is an iterative process and stakeholders should continuously be involved in order to update the assessment when new information becomes available. Stakeholders typically affect the boundary conditions for the risk management.

The framework advocates proactive risk management for mitigating risk of pollution from shipwrecks. However, risk assessment and management cannot be the sole source of information input to a decision. Managerial judgment and review of the decision-problem at hand is needed to ensure that aspects not contained in the risk assessment are included in the decision (Aven, 2003). Review should be done to incorporate new information and update parts of the risk management during the process if needed (ISO, 2009).

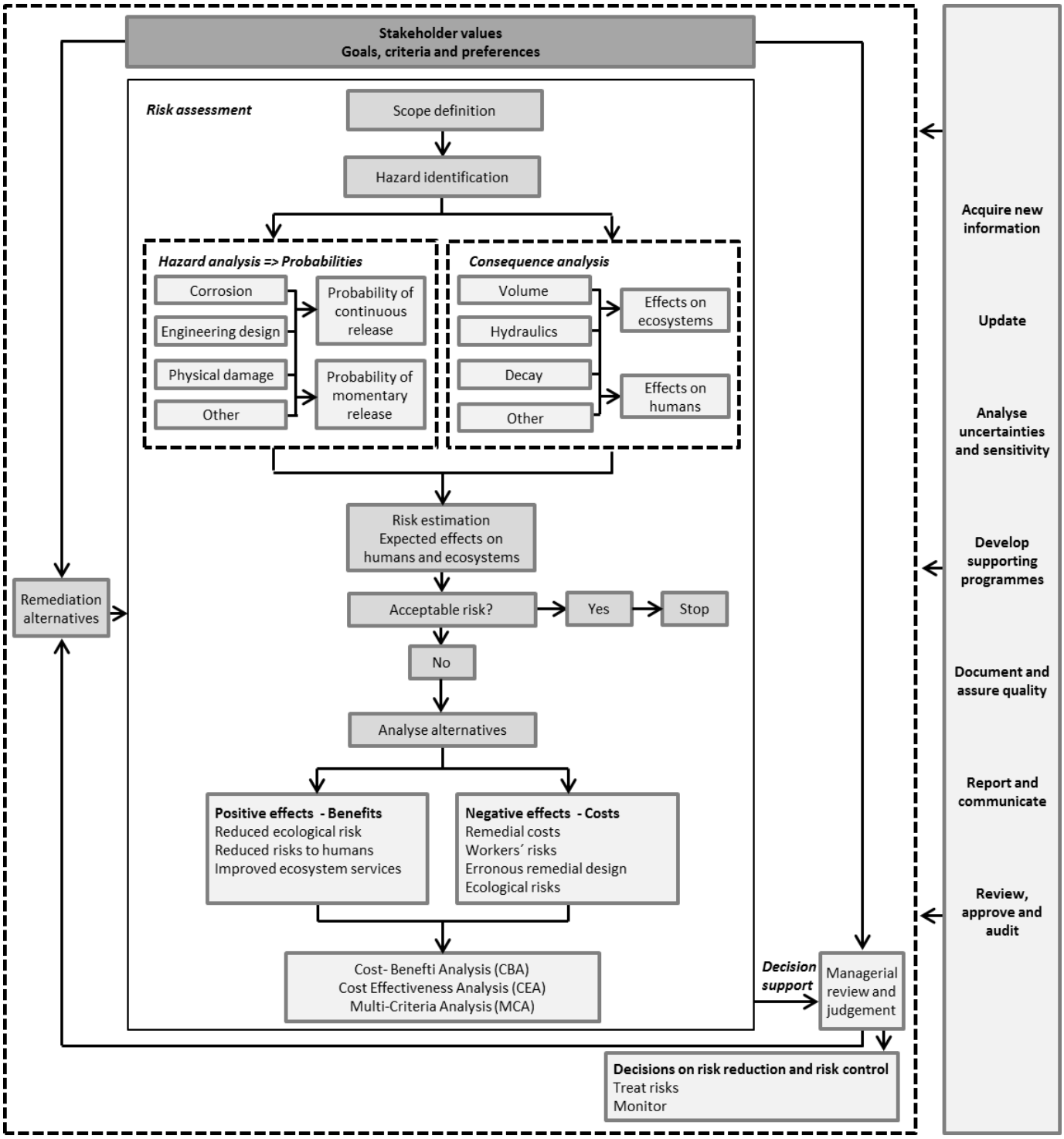

Figure 4.2. Generic framework for risk management and assessment of potentially polluting shipwrecks (Paper I, Evaluating the needs of risk assessment methods of potentially polluting shipwrecks).

4.3.1 Main conclusions of Paper I

The comparison showed that there is currently not a comprehensive method for risk assessment of shipwrecks. The main weaknesses found were that many of the methods were qualitative and in general did not suggest sensitivity or uncertainty analysis. Over

all, risk evaluation did not correspond to the level "fulfilled to a large extent". The methods found do provide some guidance but none give comprehensive support for decision-making regarding shipwrecks potentially polluting the environment or resulting in social and economic effects. This will potentially lead to inefficient allocation of resources for mitigation of such threats. The framework for risk management of shipwrecks clearly states the parts that should be included and stresses the link between risk management and decision-making.

4.4 Probability assessment of hazardous release from shipwrecks

As a contribution to the development of risk assessment of shipwrecks, based on the results of the comparison described in Section 4.3, a method for probabilistic risk assessment is suggested. The method is called VRAKA and includes risk analysis and risk evaluation (Figure 4.3).

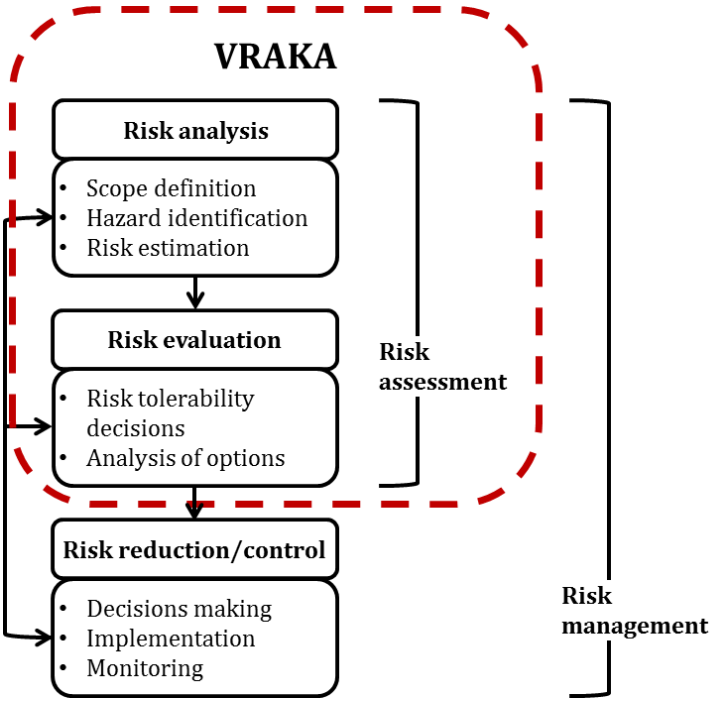

Figure 4.3. VRAKA, a risk assessment method.

However, VRAKA is under development and there is a need for tools to perform the different parts of the risk assessment. Initially, a risk estimation tool (Figure 4.4) has been developed with the purpose of estimating the probability of release of hazardous substances based on fault tree analysis. Presented here is a general outline of that basic risk estimation tool. Full risk estimation includes estimation of environmental, social and economic consequences and a risk assessment further contains risk evaluation,

including a comparison of results with tolerability criteria and analysis of options. More comprehensive risk estimation and risk evaluation will be the focus of further research.

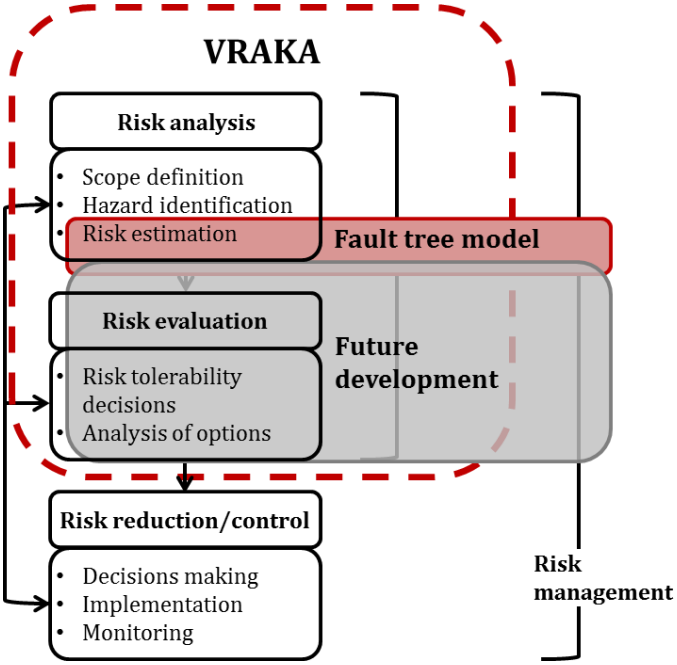

Figure 4.4. The developed basic risk estimation tool and further development needs of VRAKA.

4.4.1 Risk estimation in VRAKA – A general outline

VRAKA is a quantitative method for risk assessment of shipwrecks and is constituted of a number of parts. In the risk estimation and the part developed in this thesis, the probability of release is calculated using a fault tree model (See section 4.4.3). The results obtained are the probability of a hazardous release and a basic risk estimation of such release.

The process of the risk estimation in VRAKA (Figure 4.5) is as follows. The probability of the wreck containing a hazardous substance is estimated based on available information such as e.g. information about distance to final destination at wreckage to estimate if fuel is still contained. Eight hazardous events (see Section 3.1), e.g. trawling and military activity, are identified as possible causes of an opening through which substances can be released. A generic probability of an opening in the wreck caused by one occurrence of each identified hazardous event, is estimated by a team of experts. This probability thus reflects in generic terms, how sensitive to damage the wreck is to a specific event.

The generic probability of an opening is updated with respect to site-specific indicators reflecting the structural state of the wreck and environmental preconditions. This updated probability is then combined with the rate of occurrence for the corresponding hazardous event, to produce a site- and event-specific rate of opening. Based on the rate

of opening for each event, the probability of opening for a given time period is calculated and the overall probability of opening can be thus obtained. Finally, an estimation of the total probability of release of hazardous substances from the wreck may be calculated based on the probability of an opening for all events and the probability of the wreck containing hazardous substances.

The risk estimation in VRAKA can be performed on two levels of detail; a basic Tier 1 estimation can be performed based on the probability of release and the potential volume of hazardous substances possibly contained in the wreck. A Tier 2 estimation can be performed to obtain a more comprehensive estimation by also including the consequences of a spill. In this thesis, the Tier 1 estimation method is developed, and the Tier 2 level estimation including environmental, economic and social consequences of a spill will be developed in future work.

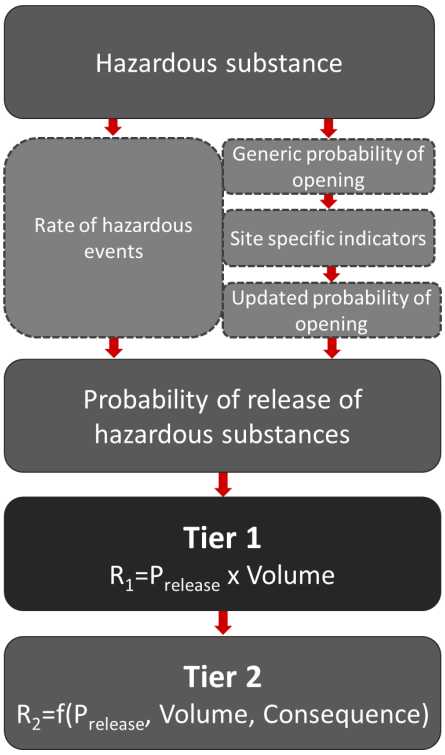

Figure 4.5. The process of risk estimation in VRAKA.

4.4.2 A fault tree approach

The process of combining the probability that hazardous substances are contained, with the probability of an opening caused by each hazardous event, and the rates of these hazardous events is made by a fault tree approach (Figure 4.6). The purpose of a fault tree is to describe the occurrence of a top-event (here, release of hazardous substances from a shipwreck) depending on the occurrence and non-occurrence of independent basic and intermediate events (Bedford and Cooke, 2001).

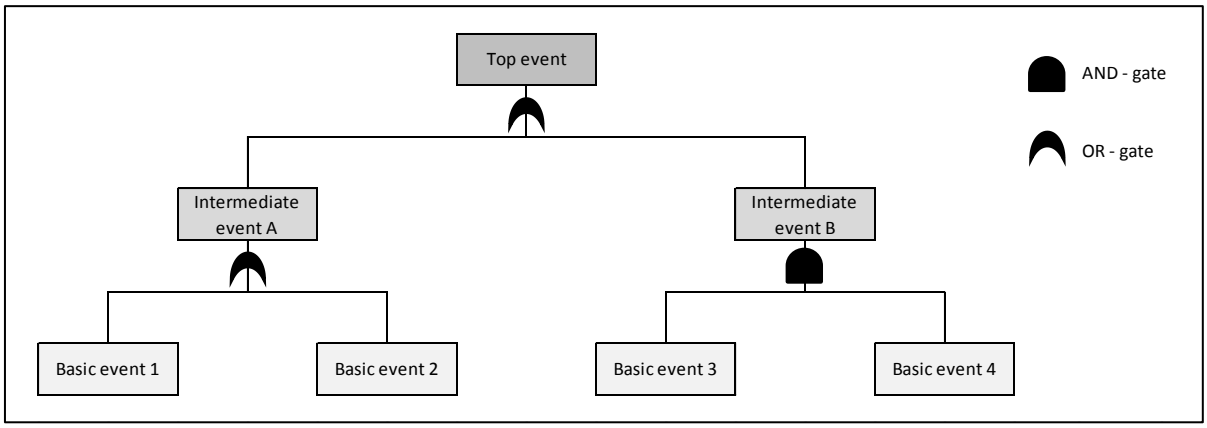

Figure 4.6. Example of fault tree (Lindhe, 2010).

The events are linked by logic gates, here AND- and OR-gates. An AND-gate describes the output of an event if all input events occur simultaneously while the OR-gate describes the output if at least one of the input events occurs. The probability of the occurrence of an output event from AND- and OR-gates is calculated as below:

$$P_{Occurence\_AND} = \prod_i P_i \qquad (4.1)$$

$$P_{Occurence\_OR} = 1 - \prod_i (1 - P_i) \qquad (4.2)$$

where P_i denotes the probability of a certain event (i) causing an opening given that the event has occurred.

The use of a fault tree can facilitate an uncertainty analysis (Bedford and Cooke, 2001). Uncertainties can be modelled e.g. by using Monte Carlo simulation where a statistical distribution is chosen to represent the uncertainty of each input variable of the model (Burgman, 2005).

4.4.3 Description of the fault tree model in VRAKA

The fault tree model in VRAKA (Figure 4.8) is constructed as follows. The top undesired event is a release of hazardous substances. This is assumed to be a function of the probability of an opening in the wreck and that oil or other hazardous substances are still contained. The hazardous substances are assumed to origin from either bunker or cargo.

As described in Section 3.1, it is assumed that an opening in a shipwreck can be caused by certain hazardous events (Table 4.2). These correspond to events in the fault tree model in VRAKA.

Table 4.2. Hazardous events included in the fault tree model.

• Construction work
• Corrosion
• Diving
• Landslides/Earth quakes
• Military activity
• Ship traffic
• Storms/ Extreme weather
• Trawling

Each event is defined by two components: a conditional probability of opening given an event, $P_{opening|event,i}$, and rate of occurrence, $\lambda_{occurrence,i}$. The generic conditional probability is pre-assessed by a team of experts and describes how likely an opening is from one occurrence of the event. The rate is estimated by the assessor and describes how likely the event is to occur during one year. The rate of opening in the shipwreck for an event is calculated as:

$$\lambda_{opening,i} = \lambda_{occurance,i} \cdot P_{opening|event,i} \tag{4.3}$$

If exponential rates are assumed, the probability of one event causing an opening in the wreck during a specific time period (t) is:

$$P_{opening,i} = 1 - e^{-\lambda_{opening,i} t} \tag{4.4}$$

Corrosion is an exception since it is viewed as an on-going process. No rate is estimated for corrosion, the probability of an opening from corrosion is derived directly from the expert assessments. The total probability for an opening from the events is calculated according to Equation 4.2.

The fault tree developed for risk estimation in VRAKA is displayed in Figure 4.8 and can be used to calculate the probability of release of hazardous substances based on the total probability of opening from the identified events and the probability that hazardous substances are contained. All input parameters are modelled by Monte Carlo simulation to facilitate an uncertainty- and sensitivity analysis.

Each shipwreck is unique in terms of pollution potential. Therefore, the generic assessments of probability of opening can be adjusted to better correspond to the wreck's physical ability to endure external forces and local environmental conditions

possibly accelerating corrosion. The adjustment is done by estimating a set of indicators (Table 4.3) derived from literature review (Konstantinos et al., 2009; Michel et al., 2005; Schmidt Etkin et al., 2009; Sender, 2010) and brainstorming sessions with experts.

Table 4.3. Site- and wreck-specific indicators.

• Bottom currents
• Construction
• Hull thickness
• Maintenance
• Oxygen concentration
• Route
• Salinity
• Sea floor properties
• Water temperature
• Water depth
• Wreck position
• Years since wreckage

The tool for Tier 1 risk estimation includes a structure to incorporate these indicators and estimate the impact on the probability of opening. The indicators are initially set to a so-called normal state. The assessor is given the possibility to adjust the indicators to decrease or increase the robustness of the wreck or set the deteriorating environment to worse or better than a normal case. The probability of opening due to certain events will increase or decrease accordingly. The magnitude of the impact of the site-specific conditions on the generic probability of opening from an event is pre-set and the assessor is guided to make these adjustments through guidance matrices (Table 4.4).

Table 4.4. Example of indicator description in VRAKA.

	Considerably better state	**Better state**	**Normal state**	**Worse state**	**Considerably worse state**
A – Hull thickness	The plate thickness was larger than 25 mm at construction.	The plate thickness was 15-24 mm at construction.	The plate thickness was 10-14 mm at construction.	The plate thickness was 5-9 mm at construction.	The plate thickness was less than 5 mm at construction.

The assessor estimates the probability that the cargo is hazardous and the probability that bunker or/and cargo is still contained. Based on that, and the total probability of opening, the probability of release of hazardous substances can now be calculated. A Tier 1 risk estimation can be obtained if combining the probability of release of hazardous substances with the possible amount of hazardous substance contained. An example of application of the tool is given in Paper II (A fault tree model to assess probability of contaminant release from shipwrecks).

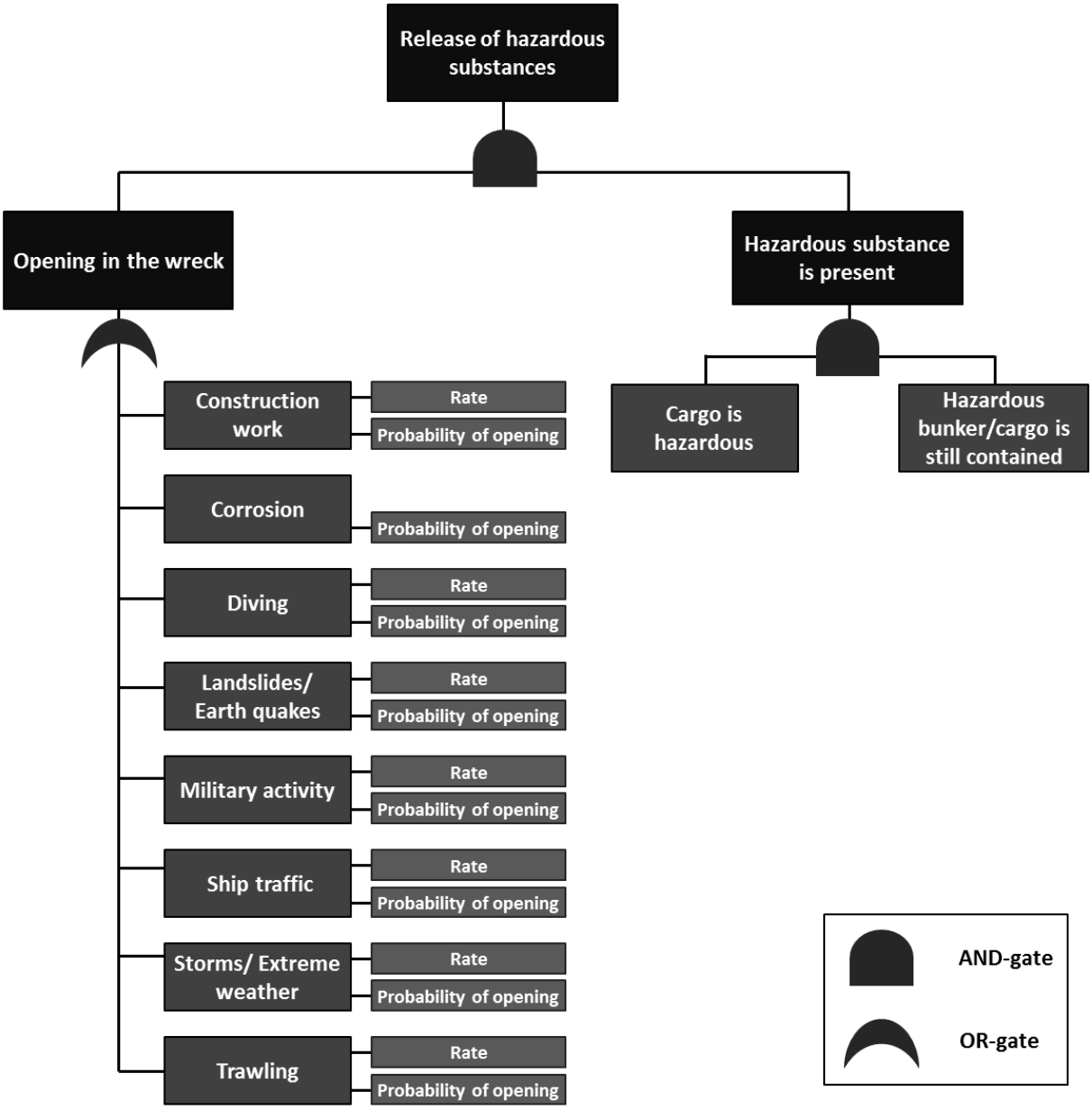

Figure 4.8. The fault tree model in VRAKA.

4.4.4 Main conclusions of Paper II

The developed tool provides a structure for estimating the probability of release of hazardous substances from shipwrecks. The quantitative approach facilitates handling of the vast amount of uncertainty present in the shipwreck context. It can also be used for a Tier 1 risk estimation where risk is expressed as the volume of the expected hazardous release. The Tier 1 risk estimation does not give any guidance regarding consequences to receptors or the rate of the release. However, it can provide input for comparing the risk from shipwrecks for prioritisation of further studies. Development is needed to validate and calibrate the tool and to include a wider consequence analysis taking economic, environmental and social aspects into account.

5

Discussion and summary

This chapter presents and discusses the main findings of the thesis. The contribution of the performed research is reflected upon and suggestions for further research are given.

5.1 Fulfilling the aim and objectives of the thesis

Shipwrecks are polluting the marine environment by release of petroleum products and actions are needed in order to mitigate the risks from these shipwrecks. However, this thesis shows that there currently exists no comprehensive guidance on risk management of shipwrecks which implies that there is an inefficient resource allocation for this problem and that shipwrecks might harm the marine environment, ecologically, socially and economically.

The overall aim of the thesis was to *develop a framework for risk management of potentially polluting shipwrecks and a tool for quantifying the probability of release of hazardous substances from such shipwrecks.*

A comparison of available methods for risk assessment to an international standard was made in order to establish the status of methods today. As a result of this comparison, a framework for risk management of potentially polluting shipwrecks was suggested. Finally, a structure and tool for probabilistic risk estimation of shipwrecks, to be used for implementing the framework, has been developed.

5.2 Comparison of current methods for risk assessment of shipwrecks

Some guidance on risk management of shipwrecks was given by the identified existing methods, but none provided a holistic risk management structure. None of the methods suggested a quantitative approach and only a few included an uncertainty analysis. Furthermore, none of the methods provided a detailed risk evaluation. This implies that there is incomplete decision-support for risk mitigation of shipwrecks and that a framework for risk management and assessment of shipwrecks is needed.

The comparison of current methods for risk assessment of shipwrecks to the international standard was performed at a certain level of detail. It might not be necessary to do a risk assessment at that level for all shipwrecks. The assessment should be adjusted to the specific wreck at hand.

5.3 The suggested framework

The framework presents a holistic risk management structure for shipwrecks and is based on well-established views of risk management. The intention of this thesis was however not to disseminate the risk management process but to apply it in a shipwreck context.

Only by applying a comprehensive framework a holistic view of the problem can be

obtained and based on this, a full risk management process and assessment can be performed. When a framework is in place, methods can be developed that is well suited for the specific purpose and fit well together. Decision support can then be obtained which contributes to a sound allocation of societal resources.

5.4 VRAKA

The VRAKA method was based on the suggested framework for risk management and assessment of shipwrecks. VRAKA as a risk assessment method consists of risk analysis and risk evaluation. Tools are needed in order to perform the different part of VRAKA and in this thesis, a tool for estimating the probability of release and a Tier 1 risk estimation is developed. More comprehensive risk estimation and risk evaluation will be the focus of further research.

5.5 The tool for probabilistic risk estimation

A tool has been developed for a first part of VRAKA, for estimating the probability of release of hazardous substances. However, estimating the consequences of such spill, is yet to be developed and risk evaluation including risk tolerability decisions and analysis of options should be included in a comprehensive risk assessment.

A fault tree model was chosen as a means to estimate the probability of hazardous releases from shipwrecks. It is an established risk assessment tool and built from hazard to consequence (Burgman, 2005; Rausand and Høyland, 2004). The fault tree represents a model of reality and is based on our understanding of that reality. It is therefore very important to have good knowledge of the system analysed in order to obtain relevant results.

The fault tree approach in combination with calculations performed using Monte Carlo simulations makes it possible to handle uncertainties of input parameters. As earlier emphasized in this thesis, uncertainties are typically large in the shipwreck context concerning both the probability of release and possible consequences of such event. In this risk estimation part of the VRAKA tool an uncertainty analysis can be performed. The purpose is both to obtain results displayed as distributions, i.e. illustrating uncertainties, and not as point values, and to analyse where more information is needed in order to reduce the uncertainties in the results.

5.6 Further development needs of the tool for probabilistic risk estimation

As a risk management process needs constant review so does the proposed framework and above all, the proposed tool for probabilistic risk estimation of shipwrecks. Firstly, the tool requires a number of input data suggested by expert groups. Applying proper expert elicitation is a time consuming activity that could be improved in e.g. terms of number of experts included and further areas of competence. The suggested tool provides a structured approach for probabilistic risk estimation of shipwrecks but does not claim to provide fully calibrated input data at this point. This is on-going research. Suggestions of calibration concerns weights of indicators to each other and extent of impact on the concerned event. Calibration should be performed during workshops involving field expert knowledge.

Another cause to review the tool is the unknown unknowns. There is some information we are uncertain about, but there is also information we do not even know at the point of developing the tool and thus is impossible to incorporate at this point (IPCC, 2007).

The tool for probabilistic risk estimation of shipwrecks should, for validation, be further tested and calibrated. There are several wrecks in Scandinavian waters suggested by the Swedish Maritime Administration (2011) to pose a threat to the marine environment. These wrecks would be suitable to use to test and validate the method since it is developed for Scandinavian waters.

5.7 The value of the findings

The holistic framework for risk management presents the necessary parts for risk management and assessment of shipwrecks and will provide guidance to more cost efficient risk mitigation of shipwrecks. This implies a more efficient resource allocation for society.

The tool for probabilistic risk estimation of shipwrecks will provide input to a decision-making process regarding risk mitigation for shipwrecks. The tool will also provide means for handling uncertainties, which are many in a shipwreck context. However, it is not the sole source of information; other information is needed to e.g. be able to fully weight costs against benefits of mitigation measures and to make an informed decision. The tool is a first part of VRAKA, a method for holistic risk assessment of shipwrecks.

5.8 Future research

The suggested framework and tool described here are under development and further research is needed. A tool for consequence analysis is crucial in order to perform a full

risk assessment. Environmental, economic and social consequences should be taken into account and guidance on how this should be done is of importance.

Consequence assessment in VRAKA should include an estimation of where the released hazardous substances end up. The intention is to integrate a tool developed by the Swedish Meteorological and Hydrological Institute, Seatrack Web (Ambjörn, 2007) where oil trajectories can be simulated based on data on currents and prevailing weather. The result obtained is amount of oil on beaches, on the water surface and in the water column.

The amount of oil possibly released is of utter importance and is in the Tier 1 risk estimation in VRAKA based on available information, rather than e.g. measurements after possible leakage during many years on the sea floor. An well founded estimation of the amount is essential both to accurately estimate the consequences and to avoid expensive unnecessary remediation operations. Both large and small oil releases occur. The ecotoxicological effects of large acute oil spills are well established while effects from small and continuous oil spills are less studied. VRAKA should include tools to also estimate the impacts from the latter type of oil spills.

The Tier 1 risk assessment does not provide any information about the rate of a possible releases. However, the probability estimations of release can be used as input for estimating both risk of momentary as well as continuous releases.

Comprehensive risk assessment of shipwrecks also requires risk evaluation. Analysis of options and decisions of what risks are tolerable should be included. The complete VRAKA tool should therefore provide a structure for risk evaluation.

Estimations of the environmental, social and economic consequences are needed for a comprehensive risk evaluation. There are tools such as e.g. cost-benefit analysis (CBA) and MCA (Multi-Criteria Analysis) to do these types of estimations of impacts from oil spills. Performing a CBA can clarify the benefit of reducing the risk by providing information on the societal profitability of risk reduction measures. Environmental impact assessments can be used to estimate the specific impacts on the environment. Moreover, an MCA can be performed to get a comprehensive evaluation of economic, social and environmental impacts.

6

Conclusions

This chapter presents a condensed summary of the thesis: the conclusions and main findings.

The main conclusions and findings of this thesis are:

- *There is a need for a risk management framework for shipwrecks.*

  Risk management should be performed in a structured manner in order to encompass all aspects and incorporate proper information. The risk from shipwrecks poses a threat to the marine environment which is unique for each wreck. A framework specific for risk management of shipwrecks is therefore needed.

- *There is a lack of quantitative risk assessment tools for shipwrecks.*

  A comparison of existing methods for risk assessment of shipwrecks was made to an international standard. The results showed that no method presented a holistic risk assessment for shipwrecks and that few methods suggested a quantitative approach taking uncertainties into consideration.

- *Uncertainty analysis is an essential part of risk assessment of shipwrecks.*

  The risk from shipwrecks depend on many and uncertain variables. Few data exist and experts are needed in order to elicit information to an assessment. Handling the uncertainties will provide means to taking the amplitude of the uncertainties into consideration when deciding on mitigation measures. An uncertainty analysis can also provide information about which variables are most uncertain and where efforts should be prioritized to decrease the uncertainty of the outcome.

- *A framework for risk management of shipwrecks is suggested.*

  This thesis presents a generic framework for risk management of shipwrecks. The suggested framework is based on a well-established view of risk management and the purpose was to emphasize the connection between risk management and decision-making.

- *A method for risk assessment of shipwrecks is suggested.*

  The VRAKA method suggested includes risk analysis and risk evaluation. It is being developed for probabilistic risk assessment of shipwrecks and uncertainties are taken into consideration. This risk assessment method will include a set of tools of which the first is developed in this thesis. Additional tools will be developed and existing tools such as CBA and MCA may be included.

- *A tool for estimating the probability of hazardous release from shipwrecks is developed.*

  By the developed tool, a structure for estimating the probability of release of hazardous substances and a means of a Tier 1 risk estimation of shipwrecks is suggested. The resulting risk of the tier 1 risk estimation is expresses as the expected volume of hazardous release. The tool is quantitative and takes the uncertainties concerning the risk of shipwrecks into consideration.

  The rate of release and consequences to exposed receptors cannot be estimated with the suggested tool. However, the Tier 1 risk estimation is assumed to provide relevant input to prioritization, based on risk, between shipwrecks in further studies.

- *Further development of the tool for estimating release of hazardous substances is needed.*

  The suggested tool provides a structure for estimating the probability of release. More expert input is needed in terms of e.g. the extent of the impact of indicators on the probability that an event causes an opening in the wreck. In addition, the tool should be tested, calibrated and validated.

- *Suggestions for future research.*

  The VRAKA method is not complete. It now incorporates a tool for estimating the probability of release of hazardous substances and Tier 1 risk estimation. Further work needs to be addressed at developing the consequence assessment, considering environmental, social and economic consequences of releases of contaminants from shipwrecks. Furthermore, a full risk assessment includes risk evaluation and the complete VRAKA method should therefore provide a structure for that.

  In general, the main focus of oil spills is on large acute spills. Small and more continuous spills are more seldom reported on. However, it has been shown by e.g. Lindgren et al. (2012) that also small amounts of oil have an effect on living organisms. The affected organisms perform ecosystem service on which the impact is not yet known. This should be considered in the future development of VRAKA.

- *The main value of the findings*

  The generic framework for risk management and assessment of shipwrecks, in a structured way presents the important steps that need to be included and how they are interconnected. It also stresses the need for

adequate assessments to facilitate proper decision support for efficient resource allocation for these types of environmental threats.

The tool for estimation of the probability of release of hazardous substances from shipwrecks provides important information about the risk posed by wrecks. It enables uncertainty analysis and is a first step towards holistic risk assessment for shipwrecks.

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