Zur Homepage der Dissertation

Developing and Testing Integrated Decision Support Models for Coastal Management

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List of Contents

List of Figures

List of Tables

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Publications

Most of results in this thesis have already been published in international journals and proceedings of international conferences.

Published/Accepted Papers:

1. **Liu, X**. and Wirtz, K.W., 2005. *Sequential negotiation in multiagent systems for oil spill response decision-making*. Marine Pollution Bulletin (50) 469-474.
2. Wirtz, K.W. and **Liu, X**., 2006. *Integrating economy, ecology and uncertainty in an oil spill mDSS: the Prestige accident in Spain, 2002*. Estuarine, Coastal and Shelf Science, in press.
3. **Liu, X**. and Wirtz, K.W., 2006. *Total oil spill costs and compensations*. Maritime Policy & Management (33) 49-60.
4. Wirtz, K.W., Baumberger, N. Adam, S. **Liu, X**. 2006. *Oil spill impact minimization under uncertainty: evaluating contingency simulations of the Prestige accident*. Ecological Economics, in press.
5. **Liu, X**. and Wirtz, K.W., 2006. *Consensus oriented, fuzzified decision support for oil spill contingency management*. Journal of Hazardous Material, (134) 27-35.
6. **Liu, X.** and Wirtz, K. W., 2006. *Decision making of oil spill contingency options with fuzzy comprehensive evaluation*. Water Resources Management, in press.
7. **Liu, X**. and Wirtz, K. W., 2006. *Consensus building in oil spill response planning using a fuzzy comprehensive evaluation*. Accepted by Coastal Management.

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8. **Liu, X**., Wirtz, K. W., 2004. *Using economic valuation methods to measure environmental damage in the coastal area*. In: D. R. Green (Ed.) Proceedings of the 7th Int. Conf. Of Delivering Sustainable Coasts: Connecting Science and Policy (Littoral 2004) Aberdeen, UK.
9. **Liu, X**. and Wirtz, K.W., 2005. *Multi-agent negotiation in the Prestige oil spill response scenario: a conflict resolution mechanism design and simulations*. The Built Environment (78) 113-121. WIT Press, UK.
10. Wirtz, K.W., Adam, S., **Liu, X**. and Baumberger, N., 2004. *Robustness against different implementations of uncertainty in a contingency DSS: the Prestige oil spill revised*. In: C. Pahl-Wostl (Ed.) Proceedings of the Int. Environmental Modelling and Software Society Conference 2004, Osnabrück.
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Abstract

Oil spill over seas are seriously environmental disasters, which cause significant, long-term impacts on the environment and socio-economic activities. For this reason, there has been a recognized need for a system modelling approach for oil spill contingency management. In order to meet the challenge of developing helping tools for decision making, a framework for integrated management for oil spill is proposed in this thesis. The overall goal of this work is to develop methods to support, relative to targeting recommendations, a consensus based selection of optimal management strategies for oil spill. In this thesis, a multi-level modular decision support model for oil spill contingency management has been developed and tested in different case studies. The system involves oil spill simulations, alternative evaluations of response measures and a virtual consensus building process among stakeholders. It is unique in that it brings together the above suite of decision support tools integrated across a whole oil spill system.

Realistic combat options are designated by using computer science such as geographic information system (GIS) and an oil spill contingency and response (OSCAR) simulation system developed by SINTEF, Norway. Through critical analysis of facilitating combat options in multiple hypothetical cases, it is summarized that the efficiency of combat strategy increases significantly with increasing spill size. For small spills, an average recovery ratio falls below 37%, while 82% on average can be achieved at larger spills.

For a proper evaluation of efficient options generated from the simulation module, the thesis focuses on the development and investigation of a set of analysis tools including multi-criteria analysis (MCA), fuzzy comprehensive evaluation (FCE) and monetary evaluation model (MEM) written in MATLAB. All three evaluation methods reflect ecosystem based thinking since they integrate major environmental issues and not simply make a profit maximization, as a private economic agent would do. Applications to two well established cases, the Prestige and the Pallas, demonstrated that the combination of simulation and evaluation module is likely to improve the quality of political decision makings. Following a closer comparison of the methods, selections of evaluation methods are summarized for development of good practice in the context of integrated coastal zone management. Among others, the outcome of

MEM together with other important criteria that fall outside the MEM framework should be included in MCA/FCE, if a large spill occurs.

Towards a sustainable management of coastal zones, therefore much attention are paid to an economic valuation of environmental damages caused by oil spills. In this study environmental goods are measured in monetary terms. Among others, a marginal value of €0.70 per household is estimated for each kilometer of beach prevented from oil pollution. Meanwhile, households with less children, higher monthly income and a membership of environmental organization are more likely to prefer a more costly but environmental friendly combat scenario. In addition, following the environmental management principle "polluter pays", the thesis estimates main categories of total oil spill costs and examines its relationship with admissible claims. In summary, it supports the view that admissible claims neither cover the overall costs of the oil spill nor be compensated in full in the case of large spills.

To increase transparency of decision making processes, compromise models which facilitate identification such as voting and negotiation are encouraged to be coupled with evaluation methods. In this sense, it provides a framework that requires decision makers to make explicitly public preferences. The thesis investigates a number of negotiation issues including protocols, trading attributes and reasoning models of the negotiating agents and proposes a hybrid negotiation protocol. It is suggested that efficient agreements are facilitated by adding compensation as one of the important negotiation issues into a multiple attribute utility function and the use of hybrid protocol and learning agents.

Summarizing, all evaluation methods adjusted and tested are in principal useful for aiding users to make a structured and robust decision in a transparent way. But they have gained different attention from policy makers across the world. MEM has been widely used by developing country governments for which a chief objective is economic efficiency and when presence of markets could provide a starting point for analysis. However, up until recently, few MEM including quantification of environmental benefits and/or costs (e.g., non-market valuation) have been reported in developing world. Reasons can be related to issues of price distortion between traded goods and non-traded goods and largely illiterate communities. While, it is generally felt that MCA and FCE have been paid much attention in developed countries since 1970s. Western countries and academia have applied these techniques on a more or less regular basis, since not only economic efficiency as a sole principal but also social and cultural considerations are concerned.

Summary

1. Motivation

1.1 The coasts in a changing world

Almost half the world's population lives within 200km of the coast (UN, 2002). The benefits provided by coastal environments to local inhabitants, but also to all of us are countless. Numerous coastal zones worldwide support regional and national economies based on commercial fisheries, boat building, agriculture or transport, but are at the same time a source of seafood, freshwater and energy. They offer diverse opportunities for research and tourism and protection against climate change-induced sea level rise and storm damage (Dahdouh-Guebas, 2002).

Coastal areas are also ecosystems of significant value supporting a rich biological diversity and frequently containing a valuable assortment of natural resources. Coastal ecosystems, such as reefs and belts of mangroves, can filter impurities, mitigate the effects of natural disasters and hold the substrate and the shoreline in place. Moreover, coastal areas embracing sandy and rocky beach, appealing vistas and blue water, provide unique beauty.

Nevertheless, many coastal areas are drastically affected by physical processes of erosion, spreading pollutants and unsustainable use of coastal resources by economic activities. Among all drives and threats, oil pollution is the highly relevant one, partly because of public attention. Over years, shipping and offshore oil activities, two main human sources of oil on the sea surface, have caused large, spectacular, accidental oil spills. There is a long list of coastal and marine habitats and ecosystems, seabirds, mammals, fisheries and people victimized by oil pollution. Oiling may lead to an increase in algae that, in turn reduce oxygen available for other life forms, often resulting in death (Marshall and Edgar, 2003; Price et al., 1993; Baalen and O'Donnell, 1984). Oil toxicities highly concentrated in biota adversely affect benthic animals higher in the food chain and may cause a decline in their populations (Carro et al., 2006; Bhattacharyya et al., 2003; Yamamoto et al., 2003). Sediments contaminated by oil may kill organisms that shelter from them and become suspended again in storms or dredging (Martins et al., 2005; Zaghden et al., 2005). Effects on plant communities include disruption of plant–water relationships, direct impacts to plant metabolism, toxicity to living cells, and reduced oxygen exchange between the atmosphere and the soil (Pezeshki et al., 2001; Ko and Day, 2004). Health risk for people involving in cleaning activities and for individuals living in communities in close proximity to spill site consists of skin irritation, dermatitis, seafood contamination and chronic lower respiratory system diseases (Baars, 2002; Suárez et al., 2005; Tatár et al., 2005).

1.2 Integrated coastal zone management (ICZM)

Undoubtedly, the inherently complex and dynamic coastal zone together with many pressures and opportunities constitutes a unique challenge for intelligent resource management and assessment. Integrated Coastal Zone Management (ICZM) aims at a feasible balance between the conservation of an abundant environment and a vibrant economic devolvement.

1.2.1 Terminology

The roots of ICZM can be found in North America where the concept was first introduced in the early 1970s as Coastal Zone management (CZM) (Kamp, 2001). The notion was consolidated in the USA in 1972, when the CZM Act was passed (Millemann, 1995). The term “Integrated” was then added in the 1980s since it became clear that the effective management of coastal areas requires an inter-sectoral approach (Cummins et al., 2004). There are many forms of integration. McGlashan (2000) suggests there are four directions of integration: spatial, temporal, vertical and horizontal. With “management”, the full cycle of information collection, planning, decision making, management and monitoring of implementation is intended (Schernewski, 2002). The inclusion of ICZM as one of the principle recommendations of the Agenda 21, at the United Nations Conference on Environment and Development (UNCED) –the Earth Summit-in Rio de Janeiro, 1992 gave the concept both international prominence and political legitimacy.

1.2.2 ICZM idea

ICZM has to be regarded as the alternative to a sector-based assessment of coastal problems (Kamp, 2001). Its basis is an in-depth understanding of the inherent linkages between human and natural elements of the total coastal environment. It will ensure that decisions that have relevance to the coast are made in a socially, economically and environmentally sustainable way. Such a management of coastal systems is vital to improve and diversify the livelihoods of coastal resource users and dwellers. It will also improve the efficiency of investments in coastal areas, encouraging a positive contribution to local livelihood development while minimizing adverse environmental impacts.

1.2.3 ICZM in Europe

EU ICZM Commission has addressed a number of problems including decline of fishing industry, erosion, pollution, poorly conceived transport networks and increasing urbanization related to the state of the coast and the coast as an entity in Europe since 1996. van Buuren (EEA, 2000) evaluated the state and progress of ICZM in altogether 181 regions in 14 European countries. Compared with advanced situation in the Netherlands and the United Kingdom where examples of fully established ICZM are available, ICZM in Spain is with little progress. Concerning the implementation of ICZM in Europe, EU Commission adopted a Recommendation guiding the Member States to develop national strategies for ICZM 2002. A survey was carried out 2005 to draw up a succinct overview of responses in the coastal Member States to the EU ICZM Recommendation. Most coastal member states reported their progress in ICZM. For example, Activities to protect landscape and prevent coastal erosion has been deployed in Spain since 2003. Their stocktaking and strategic guidelines were coordinated across sectors at national and regional levels; In Netherlands priorities were given to safety of transport and water quality; UK presented an examination of legislation, institutions and stakeholders involved in planning and management of the coastal zone.

1.2.4 ICZM in Germany

In German the idea of ICZM seems to be widely implemented after an establishment of modified National Park Act in 1999. According to this legal instrument, aiming to conserve ecosystem, all commercial activities in Wadden Sea are forbidden. To analyze current practice in planning procedures in terms of their ICZM, an interdisciplinary RETRO project was supported by the German Federal Ministry for Education and Research (BMBF) in 2004. By means of a retrospective analysis of 10 large-scale project approval and planning procedures in the German coastal zone, RETRO shows in a synopsis that the set of planning tools established in the Germany coastal region meets in part the ICZM demands for negotiation, integration and appropriate consideration of the ecological aspects of sustainability (Schuchardt et al., 2004). On the other hand, more or less existing deficits in

German cases suggest that broadening of the opportunities for participation, more intensive communication between authorities and scientists, and relative reinforcement of the ecological aspect of sustainability (Schuchardt et al., 2004; EEA, 2000).

To further promote a successful adoption of ICZM in Germany, two recently national reference projects: IKZM Oder and Coastal futures started in 2004 for the first 3 years period. Both are supported by the Federal Ministry of Education and Research Germany (BMBF). Main emphasis of these research projects is on scientific and innovative questions on ICZM as well as a vision and strategy for ICZM through a synthesis of existing approaches.

1.3 Oil spill contingency management

One major concern of an ICZM in many areas around the globe is related to the preparedness against accidental oil spills. It is estimated that tankers release up to some 4 million tonnes of oil throughout the world on a yearly basis (ITOPF) and large oil spills still occur at irregular intervals (EEA, 2000), although counter acting regulations have been strengthened. Among others, their effectiveness is constrained by several aspects. First, oil-related production and transportation have been increased dramatically. Each year, around 800 millions tonnes of oil are transported to or from ports, thereby making coastal zones most vulnerable to spills. Second, a large number of tankers transit in narrow rivers and channels (e.g. the river Elbe to Hamburg and North Sea channel to Amsterdam), creating a high risk of collision or grounding. Third, in practice to reduce greenhouse gas emission, offshore wind energy (OWE) is starting to operate in coastal oceans and seas. For example, the German government has set the substantial target of installation of 20,000 to 25,000 MW of offshore capacity by 2030. Despite many ideal characteristics of OWE, it increases the risk of oil spill due to ship collision with offshore wind farms. An oil and chemical spill and its long lived consequences can pose a major impact on sensible coastal areas, as demonstrated by the sinking of the Erika and more recently, the Prestige. The disaster of Prestige causes an immense amount of damages on the local marine environment. For example, 750 beaches along 2890 km were affected and over 200,000 birds were killed. Thus, preparing as well as responding to an emergency related to spilled oil or chemicals in an effective way turns out to be a more critical concern in the domain of ICZM than ever.

When oil is spilled onto the surface of the sea it spreads very rapidly under prevail wind condition. Moreover, such a disaster often leads to significant, long-term impacts on the environment. These require a best decision to be made at the right moment. Usually, a more risk averse management is preferred to minimize the magnitude of adverse effects of oil on coastal environment. However, it is difficult for decision makers to select an optimal option among others based on less information available (e.g. uncertainties) within a very short time window. When conclusions of an alternative are unfavorable, it is not possible to step back in time and try a different option. Obviously, evaluating combat options in a sufficient way is still an ongoing concern challenging decision makers. In addition, limited equipments or options prevent a globally satisfying combat strategy aiming to protect all coastal areas under risk. Thus, often preferences between different coastal areas or uses, respectively, have to be made in an operational way, in order not to produce an imbalanced management among stakeholders.

Ultimately, an outcome of this discussion is that social groups and science must find a place in such a decision making process. Three key principles are identified as necessary for the achievement of best practice in oil spill contingency management. They could be taken as a frame of reference for real decision processes.

I) Spatio-temporal evolution of the oil spill

Spilled oil undergoes a number of physical and chemical changes, collectively termed weathering, when it scatters on the sea (White, 2000). Predictions of probable movement, behavior and fate of oil are obviously of importance to decision making. Working together with suitable photogrammetric methods (e.g., GIS), oil fate modeling is in the ability to highlight critically affected resources including fishing grounds, tourist/recreation areas and protected zones (Keramitsoglou et al., 2003).

II) Involving relevant stakeholders

Lack of mechanisms allowing social participation and conflict resolution during the decision making for oil spill combat management often leads to undesired results including social unrest and rejections of good compromises (Kersten and Concilio, 2002; Vasseur et al., 1997; Korfmacher, 2001). However, direct participation of stakeholders is not possible within a very short time window of responding to oil. Thus, it is suggested that preferences represented by stakeholders can be *a priori* defined and tested in virtual case studies.

III) Making decision based on evaluation

To seek for an optimal solution among possible alternatives, it is necessary to utilize operational evaluation methods such as multi-criteria analysis to judge the performance of alternatives with respect to the selected criteria in a structured way. Computerized evaluation model is capable of evaluating multiple scenarios, including implausible and high risk ones, without risk to stakeholders or the environment in a matter of seconds (Veith, 2002).

2. Research objectives

The overall goal of this work is to develop methods to support, relative to targeting recommendations, a consensus based selection of optimal management strategies. While aiming at widely applicable methods, the thesis puts a focus on the field of oil spill contingency management. Seven inter-related operational objectives for oil spill contingency management initiatives are identified as follows,

I) Develop data and model driven methods to evaluate future or already applied oil combat strategies.

II) Analyze prominent case studies (Prestige, Pallas) in order to provide a practical basis for decision support in the real world.

III) Test achievable means for building a consensus among stakeholders involved in the decision making process.

IV) Determine the economic value of coastal resources, which are not traded in markets.

V) Provide supporting evidence and calculations to estimate total economic costs following an oil spill both in short and long terms.

VI) Construct a potential framework in which evaluation methods are coupled with both oil spill simulation models and consensus building mechanisms.

VII) Make recommendations for the selection of evaluation methods to practitioners and decision makers, following a closer comparison of the methods, including possible future thematic research issues.

3. Thesis outline

The thesis is written in a cumulative way in which independent parts together build a closed unity, yet can be read separately without having read preceding parts. Most of the results have already been published (see Publications). The thesis combines surveys and case studies. The surveys describe my research in perspective to integrated coastal zone management. The case studies are included to demonstrate the potential of the decision support models on realistic problems.

In short, the thesis is structured as follows: Part A and Part B integrate the multi-criteria analysis into a decision making process and applied the combined model to the Prestige accident. To account for uncertainties arising from planning, pre and post processing methods are described in these two chapters, respectively. In Part C, fuzzy comprehensive evaluation is developed and tested in the case of the Pallas accident. Part D, E, F focus on the evaluation of combat strategies in monetary terms. Five main categories of oil spill costs are identified; total oil spill costs are estimated and compared with admissible compensations in Part D. I made a pilot survey on valuation of damaged resources caused by spill in Part E. Benefit-cost analysis is used in the Pallas case to determine the cost effective combat strategy in Part F. Part G explores the potential of sequential negotiation in coastal management, which is followed by discussions on designing aspects of negotiation protocols, issues and rational agents. Finally, Part H extensively examines evaluation methods in multiple scenarios and presents a summary table to help planners evaluate which methods, if any, may be appropriate for a particular planning study.

4. Oil spill decision support system (DSS)

Major accidental oil spills still affect sensitive marine areas and shorelines around the world, constituting a challenge for operational as well as strategic contingency management. As a rationale basis for addressing both issues a Decision Support System (DSS), consisting of a combination of modelling and evaluation methods which in particular assess various impacts on habitats and local economies, is proposed. Fig. 1. outlines the framework briefly. By integrating the state-of-the-art oil spill contingency simulation system OSCAR with wind and current forecasts, environmental GIS data and evaluation techniques the DSS is able to rank different response actions to a chemical or oil spill in an operational way. Additionally, consensus building mechanisms are coupled strategically to evaluation models to automate the search for a compromise.

In the following sections the decision making problem of oil spill contingency management and the possible use of operational DSS and other consensus search techniques therein are explored.

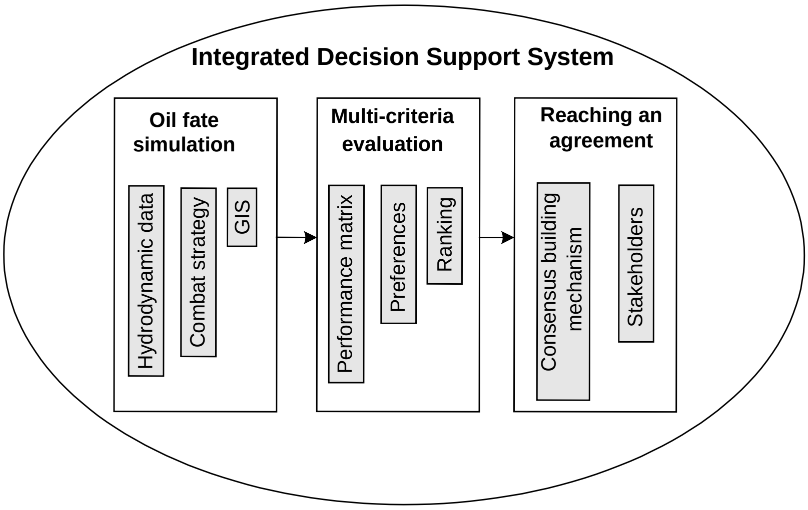

Fig. 1. A framework integrating simulation model, evaluation methods and consensus facilitating techniques into a decision support system

4.1 OSCAR contingency simulations

The spilling behaviour of each hypothetical spill is simulated using the comprehensive Oil Spill Contingency And Response simulation tool OSCAR™ developed by SINTEF, Norway. The DSS incorporates models for data based oil weathering, three-dimensional oil transport, spill combat, as well as exposure models for fish, ichthyoplankton, birds and marine mammals. OSCAR™ calculates and records the distribution of a contaminant in three physical dimensions including the residence time of a pollutant on the water surface, along a shoreline, in the water column and within sediments. A multi-agent models allows for the simulation of response activities based on adjustable containment rules such as for oil collection (priorities regarding the removal from the surface, transport and storage) or the spread of dispersant chemicals. It is more realistic in the strategic planning of combat with the aid of such a simulation, which will present people how much combat affects oil evolution compared to weathering. Another valuable contribution of OSCAR is to allow a variety of end-users for simulating operational combat situations. In this study two cases including the Prestige and the Pallas, and multiple scenarios based on the Pallas are well established by OSCAR for applications of the proposed combined methodology and examinations of evaluation methods in depth.

4.2 Evaluation methods

Decision making in response to immanent or potential oil pollution often encompasses multiple and conflicting objectives and has to face various groups of uncertainties, constituting a challenge for operational contingency management. Ideally, multiple objectives can be aggregated into a single objective function, which allows for identifying one best solution by optimisation. However, this solution strongly depends on the aggregation scheme. Here three decision making models adapted to the multi-objective optimisation problem are developed in the presence of parametric uncertainties: (1) the multi-criteria analysis (MCA), (2) fuzzy comprehensive evaluation (FCE) and (3) the monetary evaluation model (MEM). MCA is a straightforward method to aggregate a variety of ecological and socio-economic criteria, which are measured in different metrics. Since the FCE is capable to process lexical data, it provides a clear and traceable structure to integrate different stakeholders into the decision making process. A FCE further aids to determine a critical criterion by sensitivity analysis, which guides decision makers during the set-up of preferences. A MEM transfers impact intensities in various sectors to monetary values as these may more intuitively illustrate to both the public and professionals the effects of management and planning in both short and long terms. The economic approach helps to select a cost-effective pollution reduction measures in the particular case of oil spills. Focusing on the two well documented accidents mentioned above, of the Prestige and of the Pallas, the performance of their corresponding combat strategies has been investigated by using these different evaluation methods and will be compared and synthesized in Part H of the thesis.

4.2.1 Uncertainties

To some extend, a realistic decision making process will always include uncertain parameters as well as lexical knowledge representing human interactions. These facts are likely to influence the performance of evaluation models. To address the issue of sensitivity and solution robustness, analytical techniques are introduced to examine the effect of parameter variations. For example, in MCA uncertainties arising from different stages in decision making process are transformed to variability of recommended option rankings, leading to the study of large scenario ensembles instead of a singular case. Based on fuzzy logics, lexical categories are transferred into quantitative values.

4.2.2 Non-market resources

Oil spills lead to a degradation of natural resource and, consequently, to a decrease of their services in the aftermath of the incident. Given the non-market nature of environmental resources, it is necessary to measure the losses of their non-use values by employing environmental economic valuation methods, then integrate them into the decision making process of deriving an environmentally sound strategy. Here, coastal resources suffering from oil pollution are approximated in monetary units by using the method of choice experiments.

4.2.3 Building a consensus

However, the economic valuation of endangered habitats does itself not solve the conflicts between stakeholders. To find a compromise and politically balanced management, therefore additional research was addressing consensus building mechanisms such as voting systems or sequential negotiations. The thesis investigates different voting algorithms, discusses a number of negotiation issues including protocols, trading attributes and reasoning models of the negotiating agents and proposes a hybrid negotiation protocol. The designed protocol ensures several properties associated with Pareto efficiency, individual rationality or partial revelation of preferences.

5. Conclusions

In this thesis a multi-level, modular and, thus, highly adaptable decision support model for oil spill contingency management has been developed which can be run in a pre-operational mode. It can take into account both ecological and socio-economic criteria while allowing stakeholders to select and balance their conflicting preferences in the decision making process. The model includes a multi-step oil spill DSS which carries out oil spill simulations, alternative evaluations of response measures and a virtual consensus building process among stakeholders. It has immediate potential for applications on real world cases where it can be used to specific pre-operational or long-term planning issues which aims to minimize oil spill impacts minimization. In addition, the DSS may be adjusted to a variety of coastal or marine resource use conflicts. General conclusions drawn from the development as well as analysis of the model are:

I) All three evaluation methods reflect ecosystem based thinking since they integrate major environmental issues. The combination of simulation and evaluation models is regarded as an important framework, which is likely to improve the political significance of ICZM.

II) Regarding the Prestige case, both MCA and FCE group the towing direction East and North-West into the best performing cases. Meanwhile, the actual response measure taken by the Spanish government (e.g., tow the spilled vessel South-West offshore) is identified as the worst response option.

III) To fight the Pallas spill, five combat vessels including Neuwerk, Mellum, Westensee, Knechtsand and Norderhever were activated by authorities. However, using a FCE as well as a MEM, impacts could be lowered by introducing one more virtual combat vessel (i.e., Nordsee).

IV) In testing evaluation methods with multiple scenarios, spill size has been determined as a critical factor affecting ranking results. This suggests that monetary evaluation model (MEM) should be included in a MCA or FCE, if a large spill (>700 tons) occurs.

V) According to the idea of “polluter pays”, it is necessary to estimate the total oil spill costs and examine its relationship with admissible claims. Overall, we found that in general, admissible claims neither cover the overall costs of the oil spill nor be compensated in full in the case of large spills.

VI) Many goods and services produced by the coastal environment are not sold in markets. For this reason, the method of choice experiment is designated to construct a hypothetical market. The study resulted in an estimated marginal value of €0.70 per household for each kilometre of beach prevented from oil pollution.

VII) When presented with combat options, households with less children, higher monthly income and a membership of environmental organization are more likely to prefer a more costly but environmental friendly scenario.

VIII) Through an examination of multiple hypothetical cases, it is demonstrated that the oil recovery ratio increases significantly with increasing spill size. For small spills, an average recovery ratio falls below 37%, while 82% on average can be achieved at larger spills. In contrast with the recovery ratio, response costs per ton increase sharply as the spill size decreases.

IX) To provide a practical basis for negotiation support in the real world settings, a model for sequential negotiation is presented and discussed, which leads to recommendations that efficient agreements are facilitated by adding compensation as one of the important negotiation issues into a multiple attribute utility function and the use of hybrid protocol and learning agents.

Summarizing, all evaluation methods adjusted and tested are in principal useful for aiding users to make a structured and robust decision in a transparent way. But they have gained different attention from policy makers across the world. MEM has been widely used by developing country governments for which a chief objective is economic efficiency and when presence of markets could provide a starting point for analysis. However, up until recently, few MEM including quantification of environmental benefits and/or costs (e.g., non-market valuation) have been reported in developing world. Reasons can be related to issues of price distortion between traded goods and non-traded goods and largely illiterate communities. While, it is generally felt that MCA and FCE have been paid much attention in developed countries since 1970s. Western countries and academia have applied these techniques on a more or less regular basis, since not only economic efficiency as a sole criterion but also social and cultural considerations are concerned.

6. Future recommendations

Although this thesis successfully addresses oil spill contingency management using highly adaptive decision support models, several interesting topics call for further attention. These include enhancements of proposed decision support models and exploration of linkage to oil spill risk analysis.

I) Enhancements of models

Oil fate simulations should include calculations of pollution effects using a variety of spatial data. Uncertainties regarding external forcing or process descriptions should be addressed in a batch mode and a more realistic representation of weathering like burial or biodegradation might be seeked. Like many oil spill DSS the OSCAR system underestimates the effect of nutrient dynamics as well as microbial adaptation on the effective biodegradation rates.

The damage of a large spill has to be examined on many relevant resources, which are grouped for convenience in this thesis as ecological: coastal waters, birds, beaches and protected area, and economic: mariculture/fishery, tourism, port activities and cleanup. Obviously, the socio-economic impacts caused by environmental disasters such as oil spills are not limited to income losses. They may include health risks, social aware up to panic. Regarding other currently prominent problems, these criteria should be reexamined. For example, construction of offshore wind farms colloids with interests of commercial fisheries and transportation; harbor expansion limits traditional public access to the foreshore. Therefore, the set of criteria used in this research has to be modified or extended when applying the DSS to specific questions or types of oil spills occurring in other sites.

To improve credibility of evaluation model, especially techniques to link MCA/FCE with MEM should be developed where a MCA/FCE includes the outcome of the MEM and other important criteria that fall outside the MEM framework.

To enforce parties to an efficient outcome in negotiation process, their preferences should be further identified through visualization technique, such as viewing of choice cards. Such a work provides more information about parties' utility function and help to generate jointly improving compromise directions.

II) Oil spill risk analysis

To account for the economic impacts of spills occurring from transportation of oil to shores, economic estimation derived from MEM should be included in a spill risk analysis. An important first step in this analysis is to calculate the likelihood of spill occurrence (see Fig. 2). This should be done by compiling a comprehensive database of ship accidents, spill cases and, if possible, related damages. Working closely with this hazard likelihood modeling, the total oil spill costs estimated by the MEM and its power law like relationship with the spill size can be further used to address the overall economic impacts that might occur as a result of annual changes in the total amount of oil transported to regional waters. This would be crucial information for pollution control managements.

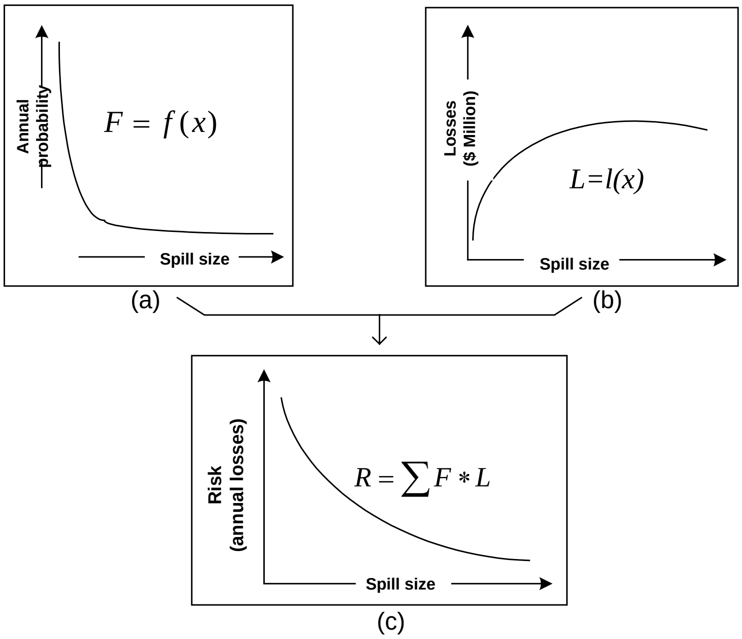

Fig. 2. A multi-step oil spill risk analysis. (a) the first part addresses the probability of oil spill occurrence; (b) in the second part the monetary losses following a spill are assessed and (c) in the third part results of the first two are combined to estimate the annual oil spill risk

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Part A: Oil spill impact minimization under uncertainty: evaluating contingency simulations of the Prestige accident*

Abstract

In order to develop a rationale for conflicts which arise in the context of oil spill contingency policies, we propose an integrated framework of simulation and valuation methods. The model system is tested for the M/T Prestige accident 270 km off the Spanish coast where it is able to assess ecological and economic oil spill impacts for a set of management options. In the Prestige case, these were given by different hypothetical towing directions. Uncertainty resulting from lacking information about the sinking probability, pollution impacts or different weighting schemes which represent specific interests of main stakeholder groups involved is taken into account by a systematic parameter variation. The results are discussed on the base of recently available data on recovery costs and sectoral economic losses. We identified clearly one worst response option and two almost equally evaluated best options. Effects of the uncertainties were relatively moderate so that the approach turned out to be suitable for an ex ante contingency response, as well as for ex post evaluations of spill abatement measures. It also supports a consensus building by making relevant information transparent to a larger group of stakeholders.

1. Introduction

Continuously improved safety measures have helped to reduce the number of small and large scale accidental oil releases into the marine environment over the past two decades (ITOPF, 2003). At the same time having greater public demand for environmental responsibility, stricter environmental laws and enforcement led to a steady increase in cleanup costs and compensation claims (Etkin, 2001; Grey, 1999). This trend is mirrored by a stepwise upgrade of the International Oil Pollution Compensation Funds (IOPC) from approximately 83 Mio. EUR in 1971 to approximately 270 Mio. EUR in November 2003 (White et al., 2003). Additional funding up to 1 Bil. EUR is in preparation. Compensation claims become

* Ecological Economics, in press.

particularly exorbitant in cases where the regional economy depends to a large extent on marine key industries such as fishery and coastal tourism and when the incident is debated at a political level.

Most intense impact studies were conducted in the aftermath of the Exxon Valdez spill. Many short- to long-term effects on local economies (Cohen, 1995; Carson et al., 2003) and in particular on the local ecosystems were detected (Peterson et al., 2003). Though those findings can not directly be applied to other coastal areas, they indicate that damages in general are multi-facetted and highly interwoven.

The heterogeneous spatial distribution of affected economic activities as well as ecological functions makes hazard management and oil spill contingency planning often a delicate task, even in coastal areas where the level of response preparedness is relatively high. A golden rule of oil spill contingency management is therefore to remove as much oil as possible from the sea surface in order to minimize onshore impacts. This pollution abatement strategy, however, works only under opportune weather conditions and when the time window for response activity is large enough to gather sufficient abatement and containment resources (Etkin, 1998). Alternatively, impacts of spillages can also be minimized by repairing or reloading the oil at sea. When conditions do not permit any of these containment strategies and the potential of breakup is imminent, vessels must be brought to a port of refuge or alternatively as far away from the coast as possible to prevent the oiling of shores. The later strategy is defended not only on economic, but also on ecological grounds, assuming ecological impacts at open sea less harmful than for sensitive coastal ecosystems such as coral reefs, estuaries, lagoon systems or mudflats. However, the abrupt changes in towing directions in the case of M/T Prestige off the Spanish Atlantic coast illustrate the practical difficulties involved in choosing an optimal towing route as well as a general lack of transparency of the decision making process.

The purpose of this paper is to demonstrate how the decision making as well as negotiation process involved in oil spill contingency management and planning can be formalised within a joint simulation-valuation framework. The central question is whether existing simulation tools together with ecological and economic data basis and evaluation procedures suffice to provide robust decision support by selecting appropriate abatement scenarios. We illustrate our approach with simulations approximating the M/T Prestige case, a tanker that was towed towards the open sea after having suffered a fracture in the side hull. M/T Prestige sank five days later on the 19. November 2002 in heavy sea about 270 km off the Galician coast (north-western Spain). The accident led to disastrous consequences along the Spanish and, with some delay, also the French coasts (Whitfield, 2003; Del Valls, 2003), while the response management was later on profoundly questioned by Spanish scientists (Serret et al., 2003).

1.1 A multi-step approach

The integration of simulation and valuation models is best described by stepping sequentially through the tasks as described in Fig. A-1. Concurrent decision support systems (DSS) for environmental management often focus on particular, mostly physical, chemical or ecological aspects tending to leave aside economic criteria. Recent developments put more emphasis on assessing the effects of the lacking or fuzzy knowledge on model based recommendations (Pahl-Wostl et al., 2004). We here propose simulation, multi-criteria evaluation and uncertainty analysis as major ingredients of an integrated approach facing selected aspects of the problem. These steps are already sketched in Fig. A-1 and later described in the next section.

2. Methodology

2.1 Contingency simulations

For each hypothetical sinking location, the spatio-temporal fate of spilled oil is simulated using the comprehensive Oil Spill Contingency And Response simulation tool OSCAR™ developed by SINTEF Norway. OSCAR incorporates models for data based oil weathering, three-dimensional oil transport, spill combat, as well as exposure models for fish, meroplankton, birds, and marine mammals. OSCAR calculates the distribution of a contaminant in three physical dimensions including the residence time of a pollutant on the water surface, along a shoreline, in the water column and within sediments. The simulation of response activities based on a multi-agent simulation component allows for the parameterisation of rule-based containment activities such as oil collection (removal from the surface, transport and storage) or the spread of dispersant chemicals (Reed et al., 1995 a/b). A series of applications at various sites around the world are documented by Daling et al. (1990), Aamo et al. (1993, 1997), Reed et al. (1995a/b) or Downing and Reed (1996).

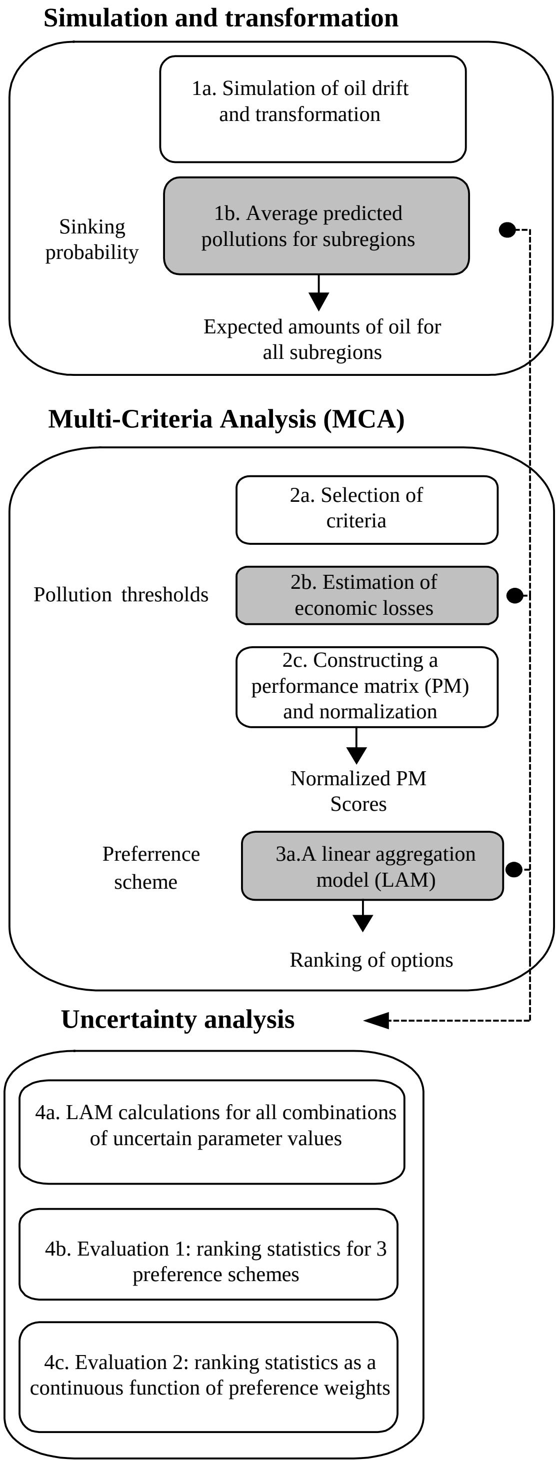


Fig. A-1. Combination of methods used in this study. Uncertainties are introduced by additional degrees of freedom (gray boxes) leading to iterated simulations and evaluations

In order to cover different possible spill scenarios given the low amount of information available at the time of the accident, hypothetical sinking locations are defined in regular intervals along each towing route (Fig. A-2). For every grounding event, a separate 20-day simulation is run with OSCAR. Since the ports in Finisterra and Coruna can be reached in shorter time, the number of hypothetical grounding locations along the eastbound and northbound routes is less than for the other directions. All 49 simulations use the same boundary conditions for the ship type (tanker), transported product (heavy Fuel Oil M-100), transported amount (77 000 tonnes), leaked amount of oil (30 000 tonnes), towage speed (32.5 km/day) and duration of oil release during final leakage (2 h). These estimates were in rough agreement with more detailed reports available in the aftermath (e.g., Del Valls, 2003).

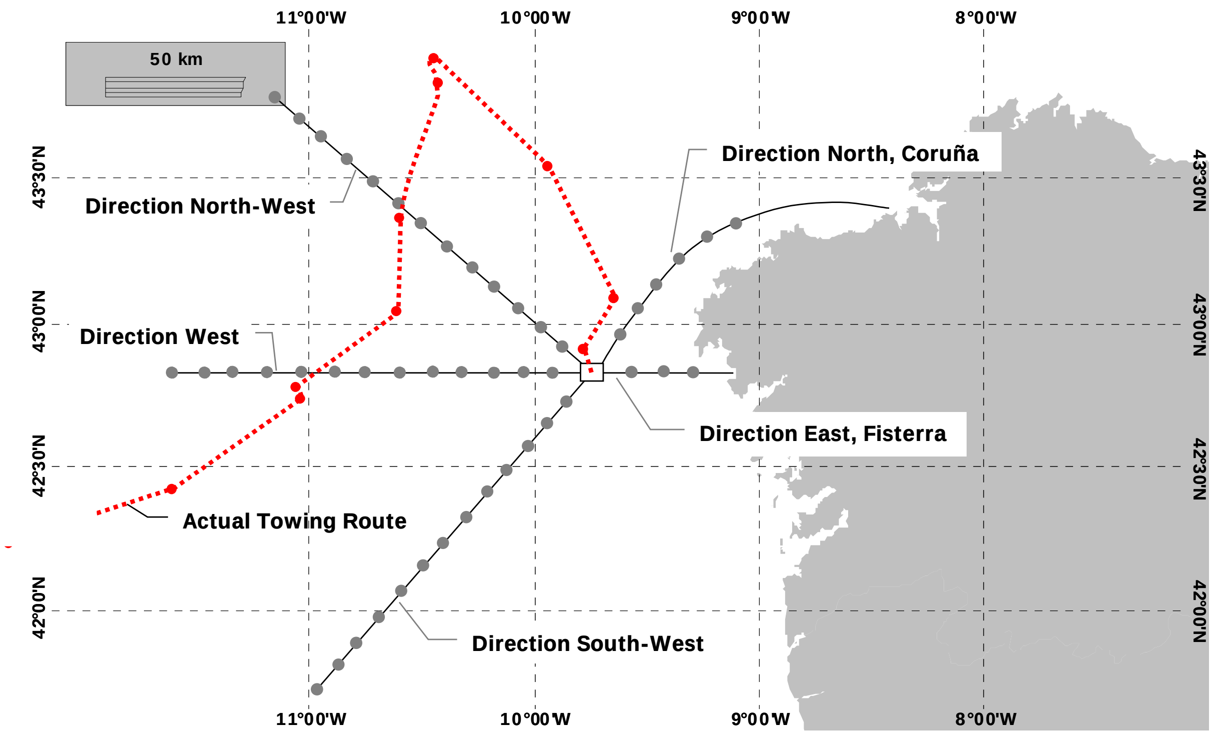


Fig. A-2. Potential towing routes and hypothetical sinking positions (gray points). It is assumed that the Prestige is towed at the rate of 32.5 km per day for all directions. For comparison, the actual route is displayed as red dotted line

Hydrographical and meteorological boundary conditions had to be assembled from various sources with different levels of resolution. As exclusively information already existing at the accident time should be used in this study, wind data are based on predictions from the operational meteorological model ARPS with a spatial resolution of 10 km. These projections showed predominant south-western winds for 11/13/2002 (MeteoGalicia, 2002). The mean current field for Nov./Dec. is based on data from the forecast service Mercator Operational Ocean (2002) at a resolution of 5-7 km. The wind and current forecasts turned out to be similar to the one reported and hindcasted by Balseiro et al. (2003) or Carracedo et al. (2006). For example, currents in November skirt the Iberian Peninsula towards the north (Portugal current), then fork round Cape Finisterra and continue along the Asturian coastline. All aspects of the response activities, e.g. the number of recovery ships, the arrival times and the equipment specifications are stated close to realistic expectations. Oil recovery strategies of individual ships are defined as a set of rules to search for the nearest, oldest and thickest oil patches within a given geographical area. The estimates for residual oil in the seawater and the cumulative landed tons of oil for the 20-day simulations are then averaged for each towing route in order to obtain a quantitative measure for the estimated impact.

2.2 Multi-criteria valuation of oil spill impacts

Large near-shore oil spills typically produce a series of environmental and socio-economic impacts and as a consequence, do affect a multitude of stakeholders with diverging interests (Edgar et al., 2003). The growing public demand for environmental responsibility and the fast rise of associated costs call for an early integration of these diverging interests in the process of emergency planning. This has, in particular, been made explicit in the Prestige case (Freire et al., 2006).

A simple mean for balancing diverging preferences in a decision context is provided by a multi-criteria analysis (MCA). The objective of MCA is to determine a rank-order of alternative options by evaluating options against a common set of criteria. For this, three main elements are required: (1) determination of criteria, (2) scoring the criteria by setting up a performance matrix and (3) normalizing and weighting scores in order to aggregate all criteria. The final step leading to a so called full MCA is only needed if no single winning option can be found in the performance matrix. More recent applications like of Brown et al. (2001) use the methodology to enhance participatory processes for coastal and marine management problems.

2.3 Selection of criteria

Both, the availability of data-bases and the specific requirements of the decision process determine the selection of criteria. For an oil spill abatement at the Spanish coast four economic and three environment related criteria were chosen. Additionally, we introduced the criteria "residual risk" quantifying non-stranded oil, which could lead with changing drift patterns to an economic or ecological harm in the future or elsewhere. All criteria and the rules to map pollution load onto these are briefly summarized in Table A-1. The set can be regarded as to a large extend generic since legal constraints and ecological or socio-economic issues related to oil pollution will be similar at other coasts.

Table A-1. Overview of all selected criteria and their quantitative

Fishery	Sum of oil in the 4 principal fishery areas
Mariculture	Sum of oil in the 10 most important areas for mariculture along the coastline of North Spain
Tourism	Sum of oil in the main recreation areas along the coastline of North Spain
Port activity	Sum of oil in the port of Coruña and Fisterra
Residual risk	Sum of oil remaining in the open sea
Reproductive capacity	Sum of oil in RAMSAR areas with special importance as spawning and breeding area
Persistency	Sum of oil in protected areas. Weighting factor depending on coastal morphology
Protection	Sum of oil in protected natural areas. The oil is multiplied with an factor depending on the number of regulations applied to an area

2.3.1 Socio-economic criteria

Economic damage is assessed on the base of income losses resulting from restricted or suspended marine resource use. These damage costs are simple opportunity costs of foregone resource use and do not include expenditures related to maintenance, avoidance or restoration, neither do they include estimates of foregone non-use ('passive use') values.

The chosen economic criteria correspond to the four directly affected economic activities: fishery, mariculture, tourism and transport (cf. Garza-Gil et al., 2006). Although their regional Value Added (V.A.) represents only about 6.7% of the total Galician regional income, this underestimates their economic importance for two reasons: a) indirect economic effects on trade, construction and public funds are neglected and b) fishery and mariculture are predominated by small scale and artisanal fishery (Garza-Gil et al., 2006), which means that a relatively large number of households depend on this activity with a relatively equal distribution of income.

In order to account for the heterogeneous spatial distribution of resource productivity along the Galician coast, subregional yearly data for tons of landed fish, cleared cargo and occupied beds are used to break down the yearly sectoral V.A. of Galicia to a subregional scale. Table A-2 represents these regionalized incomes for 2000, which we use as a proxy for the maximum potential yearly sectoral economic loss within each subregional impact area. It should be noted, however, that for a larger reference period from 1997 to 2001 Garza-Gil et al. (2006) reported a V.A. for fishery which is about on half of the value given in Table A-2 while the one provided for mariculture fits the estimate given above. This in part reflects uncertainty regarding economic data but also points to strong interannual variations in economies sensitive to variable production conditions such as fishery.

2.3.2 Economic losses

It is relatively straightforward to approximate potential maximal losses by the overall regional yearly income of the respective economic activity. Though, the relationship between oily substances on the one side and the resulting economic damage on the other side remains largely unknown. There exists, to the knowledge of the authors, no published empirical data on damage functions for specific types of oil that accounts for a range of contextual and especially environmental conditions. We therefore approximate the economic damage L_{ij} in each sector i for towing option j as a piecewise linear function of the pollution intensity P_{ij}. If the latter reaches a threshold value T_i the damage equals a maximum L_i which is given by the regionalized yearly income loss of Table A-3.

$$L_{ij} = L_i \times \begin{cases} P_{ij} / T_i & if \;\; P_{ij} < T_i \\ 1 & if \;\; P_{ij} \geq T_i \end{cases} \qquad \text{(Eq. 1)}$$

Since empirical data for evaluating T_i are lacking individual threshold magnitudes relative to thresholds for other economic activities had to be guessed. These estimates and their effects are studied in the uncertainty analysis and, in addition, compared to economic losses documented for the actual spill which roughly corresponds to intermediate spill-out locations of the northern and north-western towing routes (Fig. A-1). The parameterisation of T_i also reflects the potential adaptive responses of each specific economy, i.e. fishery, tourism, mariculture and transportation including harbour industries and can therefore be constrained by qualitative reasoning.

Table A-2. Yearly revenue of directly affected economic activities in Galicia[1]

Economic activity	Value Added for 2000 (Mio.EUR)
1. Fishery	350.00
2. Mariculture	164.00
3. Tourism	1716.75
4. Transport (ports)	32.31
Total 1-4	2263.06
Total Regional GP	33597.06

Table A-3. Estimated subregional yearly productivity [Mio. EUR] [2]

Regionalized Value Added [Mio. EUR, 2000]			
Fishery	V.A.	Port activity	V.A.
Area 1	87.5	A Coruña	14.4
Area 2	87.5	Ferrol - San Ciprián	10.5
Area 3	87.5	Marín - Pontevedra	2.0
Area 4	87.5	Vigo	4.3
		Vilagarcía	1.2
Mariculture / Aquaculture	V.A.	Tourism	V.A.
Costa de la Muerte	4.0		
Ria de Corcubion (Cee, Fisterra)	4.0	La Coruna-Muxia	345.6
Ria de Ortigueira	4.0	Carino	345.6
Rias de Ribadeo a Vivero (Lugo)	4.0	Vivero	81.1
Ria de Ferrol	12.0	Ribadeo	81.1
Ria de A Coruña	16.0	Caminha	287.8
Ria de Muros y Noia	16.0	Pontevedra-Vigo	287.8
Ria de Pontevedra	24.0	Fistera-Noia	287.8
Ria de Vigo	28.0		
Ria de Arousa (Padron)	52.0		

[1] *Sources:*
Consellería de Pesca, Marisqueo e Acuicultura: Información subministrada directamente.Datos pendentes de homologación para o ano 2000: Estadisticas de producción año 2001
IGE: Puertos del Estado. Resumen general del tráfico portuario. Diciembre 2000
IGE: Enquisa continua de ocupación hoteleira de Galicia

[2] Source:
IGE. Contas económicas. Serie 1995-2000, http://www.xunta.es/auto/ige/en/home_1.htm

There is no clear evidence available in the literature, which demonstrates ecotoxological damages to adult pelagic fish stocks. Economic damage is hence restricted to benthic resources such as oyster and mussel banks, nursery grounds or estuaries. The impact on fishery is to a large part due to costs associated with the damage of equipment (oiling of fishing gear), declining consumer demand (tainting) or fishing bans (toxicologic precaution). Fishermen most probably anticipate these costs and change their behaviour. This may include a reduction of fishing activity, a change of fishing grounds towards less polluted areas up to a general suspension of all activity (Garza-Gil et al., 2006). Following this reasoning we assume a relatively large threshold value ($T_F > 0$).

Within each subregion a large number of beaches are used for recreational activities. According simplifying considerations which, e.g., neglect media related amplifications of coastal damages we used a proportional relationship between the number of oiled beaches, respectively tonnes of oil reaching these areas and the income loss for tourism. Since the aesthetic impact of oiled shores is severe and the elasticity of demand with respect to health impacts relatively high, we assume a non-zero pollution threshold value but smaller than for fishery ($T_U < T_F$).

Given the exposure of fixed mariculture installations as well as tight ecotoxicological regulations mariculture facilities will likely be closed at the first sight of pollution traces. This corresponds to a zero-pollution threshold value ($T_M = 0$).

The marine transport sector only marginally contributes to the overall economic damage. We estimated the costs associated with a huge spill blocking a harbour as the loss of its yearly production and set the threshold value so as to impair harbour activity.

Considering the rather large additional costs associated with the oiling of equipment and installations and, above all, the huge expenditures for coastal cleaning (Liu and Wirtz, 2006; Garza-Gil et al., 2006) which is not yet covered by the approach, it is obvious that our maximum loss estimate represents only a lower boundary of all damage costs potentially incurring.

2.3.3 Ecological criteria

In complex and dynamic systems such as coastal waters it is often difficult to distinguish pollution effects from background variation, land based pollution or over-fishing (Sánchez et al., 2006). Most impact studies therefore deal with visible effects of oil pollution such as increased mortality of bird populations and short term habitat destruction.

Moe et al. (2000) have elaborated an oil spill impact indicator based on the extent and duration of damage at the level of individual populations of intertidal communities. Similarly van Bernem et al. (1994) demonstrate how an oil spill impact indicator can be constructed as a function of a series of abiotic and biotic factors and represented in the form of vulnerability maps.

Necessary data to perform a similarly detailed EIA were not available in our case and because subsequent monitoring of few key species did not reveal results which could be generalised (Sánchez et al., 2006), we adopted the idea of vulnerability mapping by using ordinal scaled impact factors for the criteria: reproductive capacity, persistence of oil and level of protection. The reproductive capacity of pelagic and benthic populations largely depends on intact spawning and nursery areas. The level of their destruction by oil can thus to be set proportional to the effects on population dynamics and for the recovery-time necessary so that we used tonnes of oil reaching estuarine areas as an indicator for the impact on spawning and nursery services.

Gundlach and Hayes (1978) find a strong relationship between the persistence of oil and the morphological characteristics of the seashore. In order to generate an impact score we multiply the amount of landed oil with a factor, which quantifies the biogeochemical effect of oil on substrates such as sand, rocks or pebbles in an aggregate way. According to Gundlach and Hayes (1978), we classify lagoons, marshes and intertidal mudflats as highly sensitive to oiling so that they are associated with an impact factor of two. Estuaries are classified as less sensitive and therefore assigned the value one.

With the level of protection as a third criteria we account for the importance that society attributes to individual coastal areas. Environmental protection is often a result of long term political engagement and lengthy evaluation procedures and may even be part of a regional development strategy involving substantial and long term public funding. The number of protective regulations for individual areas along the northwestern Atlantic coast of Spain range from one to five, including RAMSAR, EU-Natura 2000 and UNESCO Biosphere

Reserve as international regulations and five national/regional protection regulations, i.e. Natural Park/Space/Reserve and SEO/BirdLife (ETC-TE, 2002; MMA, 2003). The number of protection regulations is associated with a scoring-factor according to the following rule: One regulation gives a factor of one, two to three regulations a factor of two and four to five regulations are associated with a factor of three. Like the persistence factor, this quantity is multiplied with the amount of oil in order to generate local impact scores for protected areas.

Table A-4. Protection status and geomorphologic sensitivity of protected areas [3]

	Protection level (# of regulations)			**Vulnerability**	
Protected coastal area	Reg/Nat	EU/Int/UNESCO	index	morphology	index
Baldaio	1		1		
Corrubedo	1	1	2	lagoon	2
Costa de Muerte (Muxía - Fisterra)	1	1	2		
Costa de Vela (Pontevedra - Vigo)		1	1		
Ría del Eo o Ribadeo		2	2	estuary	1
Islas Atlánticas	3	2	3		
Islas Sisargas		1	1		
Baixo Miño		1	1		
Mundaka-Guernika		1	1	estuary	1
Ortigueira y Ladrido		2	2	estuary	1
Ría de Vigo (Islas Estrelas, Ramallosa)		1	1		
Sañtona y Noia	1	2	2	marsh	2
Umia-Grove	2	2	3	intertidal	2
Urdaibai		2	2		
Valdoviño		1	1	lagoon	2
Xarfas		1	1		

2.4 Scale transformation, weighting and aggregation

For the aggregation of the diverse impacts we use a linear additive model (LAM) in which standardized and weighted performance scores for the eight criteria are summed up resulting in a final score for each option. The underlying hierarchical ordered decision tree is displayed in Fig. A-3.

[3] Source: Ministerio de Medio Ambiente (MMA), 2003.

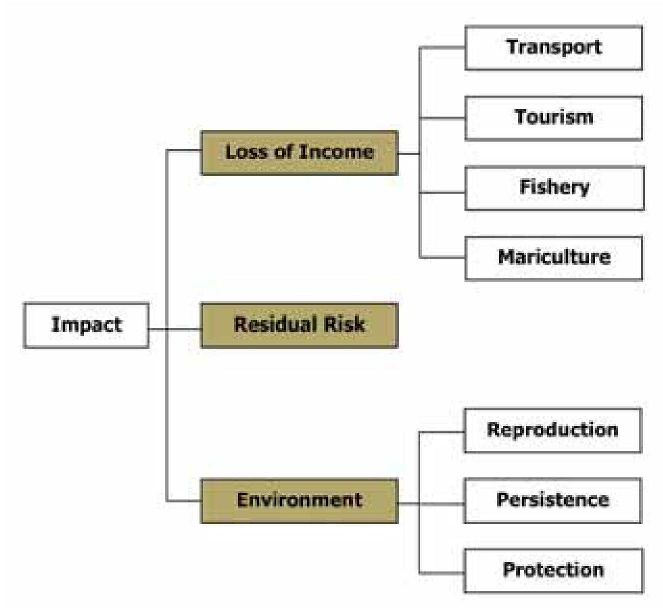


Fig. A-3. Hierarchy of targets for assessing multiple damages due to oil spills.

Table A-5. Three different weighting schemes with strong preferences in bold numbers

Scenario	1. Fishermen	2. Policy makers	3. Environmentalists
Fishery	**0.6**	0.125	0.025
Tourism	0.1	0.125	0.025
Transport	0.1	0.125	0.025
Mariculture	0.1	0.125	0.025
Resid. poll.	0.025	0.125	0.1
Reproduction	0.025	0.125	0.2
Vulnerability	0.025	0.125	**0.3**
Prot. level	0.025	0.125	**0.3**

Standardized scores are basically obtained by a scale transformation onto a ratio ranging from zero to one. Here, a negatively sloped linear transformation function is used where S_{ij} denotes the normalized score for criteria i for option j. S_{ij} decreases with an increase in ecological and economic impacts quantified by the performance scores L_{ij}. If LM_i stands for the maximal physical pollution or economic loss among all options corresponding to criteria i, one has

$$S_{ij} = 1 - L_{ij} / LM_i \qquad \text{(Eq. 2)}$$

In order to express the relative importance of a specific criteria weighting factors W_i operate as multipliers for normalized scores (e.g. Brown et al., 2001). If preferences are elucidated from decision makers, techniques such as the Analytical Hierarchical Process (AHP) can be used to identify weights in a precise and coherent way (Saaty, 1987; Lootsma, et al., 1990). Due to the missing involvement of decision makers we here we employ three different weighting schemes with which the three typical stakeholder groups involved in the coastal decision making process can be represented: fishermen, policy makers and environmentalists (Table A-5). A simple summation over all weighted standardized scores yields the final score ($\hat{S}_j$) with which options can be ranked.

$$\hat{S}_j = \sum_{i=1}^{n} W_i * S_{ij} \quad \text{(Eq. 3)}$$

Table A-6. Parameters values used for the uncertainty analysis

Symbol	Description	Variation values
T_f	Pollution threshold for fishery	[50,100,150]
T_u	Pollution threshold for tourism	[40,80,120]
T_t	Pollution threshold for transportation	[5,10,15]
L_i	Maximal economic loss for fishery, tourism, transportation and mariculture	L_F =350 Mio.EUR L_U =1716.75 Mio.EUR L_T =32.31 Mio.EUR L_M =136 Mio. EUR
P_j j = NE, NW, W, SW and E	Probability of ship sinking for the directions: j = NE, NW, W, SW and E. To western directions higher values are attributed because of larger wave heights and wind velocities in the open Atlantic.	P_{NE} =[0.002,0.004,0.006] P_{NW} =[0.0045,0.009,0.0135] P_W =[0.0045,0.009,0.0135] P_{SW} =[0.0045,0.009,0.0135] P_E =[0.001,0.002,0.003]

2.5 Uncertainty analysis

Uncertainty as a result of incomplete or imprecise information is introduced when quantifying (i) the probability of whether the ship is going to break apart when towed away from its initial location (sinking probability), and (ii) the maximum damage thresholds used to infer economic impacts from landed tons of oil. These uncertainties are incorporated by defining a value range and by carrying out a MCA for each possible combination of lower and upper boundary values as well as intermediates (Table A-6). This led to 6561 distinct calculations for each preference scenario.

3. Results

3.1 OSCAR simulations and scores

The simulations reveal significant differences in impact intensities for the potential towing directions. Prevailing winds drift the oil in direction Northeast. If the Prestige is towed to the South and West, the oil would make landfall at the northwestern coast of Galicia. The southern option would result in even larger impacted areas (Fig. A-4). According to the simulation for the westbound towing direction, a fraction of the oil would pass the cap of north Spain without stranding and flow partly submerged into the Gulf of Biscay. The northwestern towing option seems to provide the highest probability to keep the impact on Spanish coastal areas at a minimum since most of the oil drifts to the Gulf of Biscay (Fig. A-5).

The evaluation results for intermediate parameter values are listed in the performance matrix (Table A-7), which has different units for economic losses (EUR) and impacts on coastal habitats. Since the best scores are scattered over different options no dominant solution exists for our decision problem at this stage of the MCA. Option Northwest (NW) shows lowest impacts with respect to four criteria while option East (E) wins with respect to three criteria. The southwest option (SW) can be identified as worst option in 5 out of 8 cases. The performance matrix thus allows for identifying the worst case, but is ambiguous when searching for the best option. In order to rank options we had to aggregate over the scores of individual criteria.

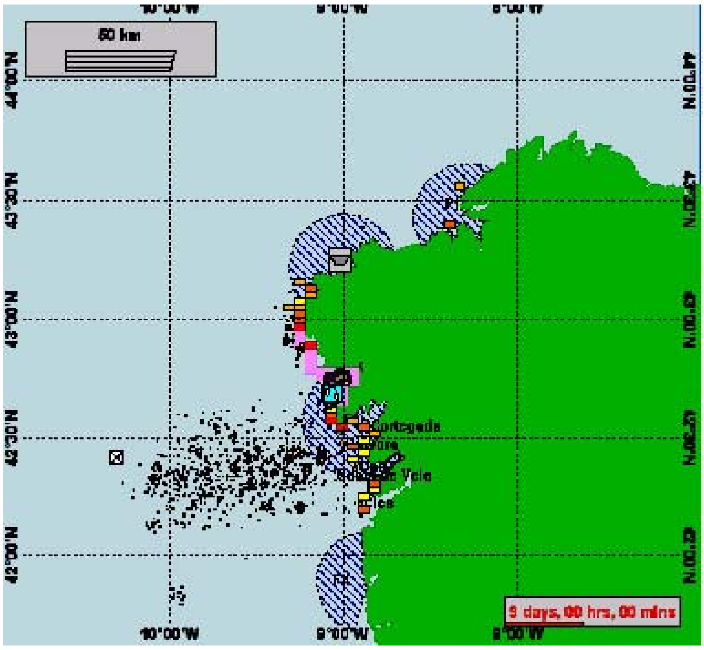


Fig. A-4. Snapshot of the OSCAR system showing the oil distribution on the surface, in the water column and ashore 9 days after the hypothetical release at the position 42°25*N*; 10°18*W* (start: 14.11.02, 14:00) what corresponds to the grounding point 5 along the southern towage route. In this scenario nearly 30% of the oil reaches the shore

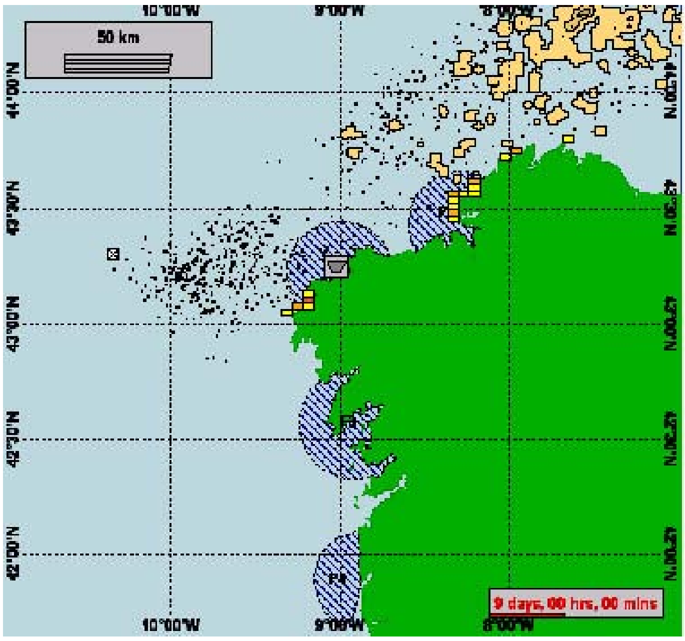


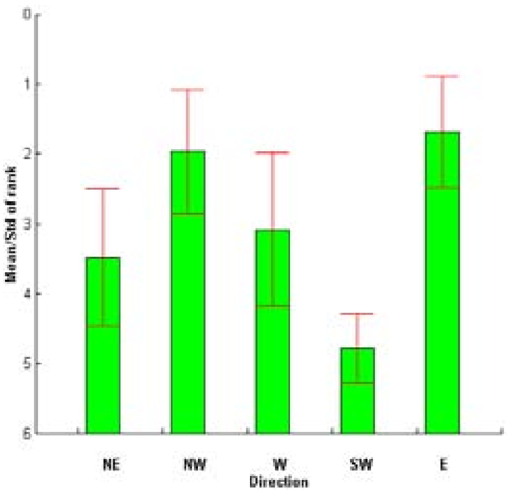
Fig. A-5. Simulated oil distribution 9 days after the hypothetical release at the position 42°25*N*; 10°18*W* (start: 14.11.02, 14:00) corresponding to the grounding point 5 along the north-western towage route. In this scenario merely 1% of the oil hits the Galician shore

3.2 Uncertainty analysis for three weighting scenarios

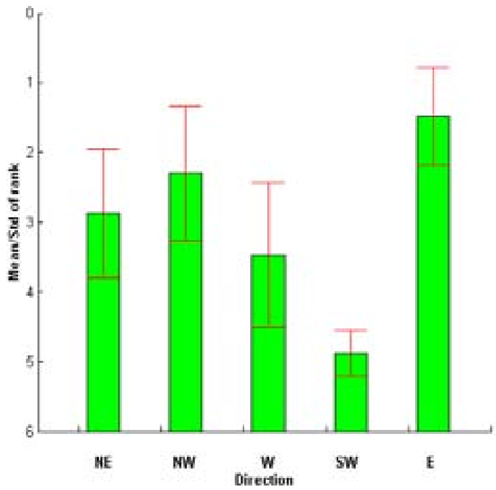
Fig. A-6. illustrates individually for each weighting scheme mean and standard deviation of option ranks, when MCAs are performed for all possible parameters combinations of sinking probability and pollution threshold. The comparison of the three ranking profiles confirms once more our first impression gained from a typical realisation of the performance matrix: Option East (E) and Northwest (NW) perform best and that only from the environmentalist' point of view, direction Northeast (NE) turned out to be a valuable second choice. Option Southwest (SW) is again identified as the least preferred. Standard deviations in general reach a magnitude of one rank order while differences between averaged ranks of the four best options are often half as large. Statistically secure distinctions in terms of the model uncertainties considered so far can thus only be made between the best and the third or between the second and the fourth best direction.

Table A-7. Performance matrix: combined representation of estimated monetary losses (Mio. EUR) for different economies and environmental impacts (tons of oil weighted by the respective ecological impact factor) using the thresholds $T_F = 100; T_U = 80; T_T = 10; T_M = 0$. Highest values (worst) are marked with an asterisk and smallest values are in bold

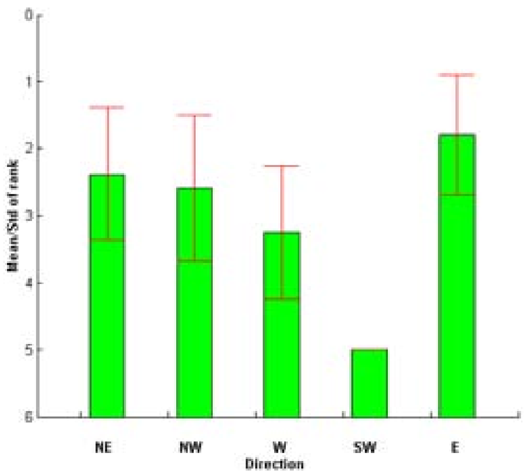
	NE	NW	W	SW	E
Fishery	120.6	**64.6**	103.4	261.3*	67.0
Tourism	588.3	**328.1**	535.1	1289.0*	339.6
Transportation	32.3*	17.0	29.7	11.3	**4.4**
Mariculture	106.0	**82.0**	136.0*	132.0	128.0
Residual risk	55.3	178.5*	168.2	114.3	**20.3**
Reproduction	**0.3**	**0.3**	0.4	4.4*	0.7
Persistence	**0.5**	0.6	1.3	5.9*	0.8
Protected area	30.1	24.0	31.0	72.9*	**18.7**



(a)



(b)



(c)

Fig. A-6. Mean ranks of towing options and their standard deviation for three different evaluation profiles given in Table A-5 representing (a) “fishermen”, (b) “policy makers” and (c) “environmentalists”

3.3 Sensitivity of rankings with respect to weights

As evident from comparing Fig. A-6(a) and (c), the ranking of options NE, NW and W depends on the weight coefficient. In order to assess the sensitivity of rank-ordering with respect to a change in preferences in a more systematic way, a sensitivity analysis was carried out for the mariculture weight (W_M). Fig. A-7 illustrates that even for a continuous variation of W_M over the whole value range [0,1] only the two options NW and E qualify best. Apparently, three intervals can be identified. For W_M below 0.25, route East performs best. In a second interval [0.25 -0.45] options E and NW oscillate around the same mean rank value while for W_M higher than 0.45 direction NW dominates. Some corollaries of the sensitivity analysis can be made for real decision problems. E.g., one can learn from Fig. A-7. to be careful when setting weight values for mariculture between 0.25 and 0.45. There, the outcome depends on slight variations of the weight and can not be regarded as a stable ranking. On the other hand, when the weight for mariculture is smaller or larger than this interval, a unique solution can be identified quite confidently.

The preference values for fishermen (0.1), for politicians (0.125) and for environmentalists (0.025, cmp. Table A-5) are all lying within the first (lower) interval where option E ranks first. In addition, their minimum difference to the lower border of the buffer zone (0.25) is around 0.125 weight units. This suggests that our ranking results, namely that E slightly outperforms NW, remains valid at least for a variation of 50 % of its standard value.

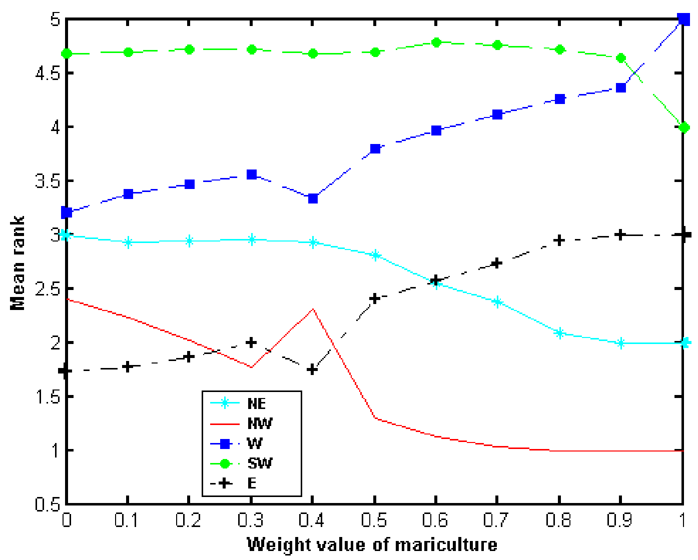


Fig. A-7. Mean ranking versus weight value WM of mariculture. Other simulation and evaluation parameters *(Li* and *Pj*) are in parallel varied according to Table A-6

4. Discussions and conclusions

4.1 Building consensus

Decision making in the context of oil spill incidents is generally driven by limited time and resources. This leaves few space for the compilation of an accurate knowledge-base, a detailed scientific impact analysis or more extensive socio-economic studies such as monetary environmental valuations.

In addition, large spills often draw a high public attention what necessitates the handling of conflicting issues in a 'politically' balanced way. The multi-step approach proposed here may ease the problem of finding a consensus between diverging interests already before the occurrence of oil spill disasters.

In environmental issues, usually very different interest groups come together, which makes the consensus building phase one of the most critical processes during the application of multi-criteria evaluation schemes (Prato, 2003). From an ideally integrated management perspective, it is necessary to base the rank-ordering on a consensual choice of relevant criteria and weights (Brown et al., 2001). Such a consensus may be achieved by bargaining, or as we favour, through a participatory process, which may trigger a dialogue between stakeholders. Especially, adding monetary compensation as one of the important issues into the negotiation process, more feasible agreements can be generated (Liu and Wirtz, 2005a; Liu and Wirtz, 2005b). Future work will therefore use the combination of tools documented in this work within participatory processes where stakeholders can bargain for changing certain preferences. This process will enhance transparent reasoning, which relates to the explicit declaration of information and data with respect to the relevant criteria. A coupled simulation-valuation model can support this critical step by confronting decision makers as well as a larger group of stakeholders with the outcome of a variety of different preference scenarios.

4.2 Uncertainty problem

By changing parameters used in intermediate valuation steps (damage-functions), the coupled approach can also be used in an experimental way. Uncertainty in the ranking of management options due to unknown simulation or valuation parameter can, if not be reduced, at least be made apparent by a simple statistical method. Formally accounting for uncertainty not only improves the model quality and contributes to a critical apprehension of the trustworthiness of valuation results. It also helps to identify risks associated with individual contingency strategies and uncertainties for a reliable emergency management. This increases the interpretability of management proposals and potentially the efficiency of decision making in politically sensitive decision making situations.

In the M/T Prestige case three quite different stakeholder profiles yield surprisingly similar ranking results. In this situation, one can confidently eliminate the worst options and concentrate on the remaining best ones, e.g. by applying a more detailed sensitivity analysis (Wirtz and Liu, 2006).

As the computational demand of systematic variations can be quite high, a compromise between accuracy, uncertainty range and computational speed is probably necessary during an *ad hoc* decision support. To work around this problem, various scenarios can be prefabricated and made accessible to decision makers in the form of lookup tables for exactly specified emergency locations and situations.

4.3 Future methodological improvements

For future versions of the coupled system, critical valuation steps involving assumptions about the functional relationships such as damage functions have to be based on findings with a larger empirical basis, which recently become available due to a series of impact assessment studies in the Prestige case (DelValls, 2003; Garza-Gil et al., 2006). In particular, complimentary methods of environmental economics are recommended to account monetary losses of injured resources in order to refine and to validate the valuation stage. Values of damaged environmental habitats firstly can be estimated by contingent valuation or travel cost methods or transferred from existing studies by the benefit transfer method (Liu and Wirtz, 2004). Their total present losses can be then aggregated with a discount rate over the impact period (Liu and Wirtz, 2006).

Although high levels of pollution were observed in exposed sandy beaches after the Prestige spill and species (e.g. crustaceans, amphipods and polychaetes) rapidly disappeared and presented a high mortality at the start of the pollution (de la Huz et al., 2005; Sanders et al., 1980; Elmgren et al., 1983; Dauvin, 1987; Negri et al., 2002). It is very questionable whether the supposed one-year impact is a realistic basic evaluation unit since the duration of impacts is not the same for all criteria. In general, the impacts will disappear after a period of time

(Wolf, 1998). For large scale oil spills, Gundlach and Hayes (1978) and Bergman (1983) predicted that on sandy beaches and flats around tidal inlets impacts my last a few months only, at the extensive tidal flats further inward the impact may last 1-4 years and only at the muddy flats near the tidal divides and the mainland coast and in the salt marshes may the damage last for many years. Also long-term studies in the Prince William Sound point to long lasting effects and the relevance of an ecosystem based toxicology (Peterson et al., 2003). One simplification made in this study, for example, was to neglect the value of benthic, near coastal habitats as nursery ground for a series of pelagic fish populations (McCay et al., 2004).

A similar complexity may in principle be reached for the economic sector. The Spanish government closed the Galician fisheries during 4 months (WWF, 2003) and approximately 1,000 miles of coastline. But the economic and environmental recovery will be partial and in the very long-term. A possible solution consists of working with smaller temporal units and sector specific duration lengths, which refers to the habitat equivalent analysis in a natural resource damage assessment (Dunford et al., 2004; McCay et al., 2004).

However, with respect of the total of all these refinements the much less sophisticated MCA technique applied here can be beneficial if not the absolute value of economic losses has to be assessed but the relative importance and balance of different interests. In addition, the use of partial and limited datasets like maps for protected areas as a proxy for the entire coastal ecosystem is legitimate for pragmatic reasons even though it does certainly not lead to conclusions in a representative way. The severe lack of data before the disaster triggered diverse monitoring programs illustrates the need of the *a priori* existence of an integrated ecological and economic knowledge base at larger spatial scales. This goal can be generalised to most coastal regions around the world where resource use conflicts or immanent damage risks call for management advice, planning and preemptive stakeholder involvement. There, existing information systems have to be joined and completed by both ecological and socio-economic data and integrated into problem adapted frameworks which account for the ecological sensitivity and economic value of coastal habitats.

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Part B: Integrating economy, ecology and uncertainty in an oil-spill DSS: the Prestige accident in Spain, 2002, revised*

Abstract

Major accidental oil spills still affect sensitive marine areas and shorelines around the world, constituting a challenge for operational as well as strategic contingency management. As a rationale basis for addressing both issues we here propose a Decision Support System (DSS) consisting of a combination of modelling and evaluation methods, which in particular assess various impacts on habitats and local economies. By integrating the state-of-the-art oil spill contingency simulation system OSCAR with wind and current forecasts, environmental GIS data and multi-criteria analysis techniques the DSS is able to rank different response actions to a chemical or oil spill. In this study, the usefulness of the approach is tested by hindcasting the Prestige accident off the coast of Spain in 2002. In particular, the short- to mid-term economic and ecological consequences of different mitigation measures are estimated. We identified clearly one worst option matching the actual decision taken by the responsible parties and one or two almost equally well performing routes. Two procedures of including uncertainty at various stages of the DSS are tested. The first method averages ensembles of outcomes between each modelling/evaluation stage, while the second one preserves the entire degree of freedom till the final ranking procedure. Results in the Prestige case turned out to be rather insensitive against both ways to account for uncertainties. The robustness as well as clarity of the DSS has the potential to enhance the efficiency of decision making even in politically sensitive situations. Limitations as well as ongoing improvements of the system are highlighted, in particular emphasizing linkages to environmental economics.

Keywords: Decision Support Systems (DSS); oil spill contingency; multi-criteria analysis; economic evaluation; uncertainty

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* Estuarine, Coastal and Shelf Science, in press.

1. Introduction

One of the major episodic threats for near-shore and coastal ecosystems and the human use of coastal areas arise from large oil or chemical spills. Once authorities are informed about an emergency call of a transport vessel or, in particular, of a tanker a contingency plan comes into action, which often carries various ambiguities. In detail, the responsible parties have to decide between alternative counter-actions such as towing towards the coast or offshore, removal of surface oil from different locations or between usage vs. non-usage of dispersants.

On the other hand, the dramatic consequences of oil or chemical spills for coastal ecosystems and economic uses make response decision a politically sensitive task. Due to the vast array of different environmental and socio-economic impacts, there also exists a multitude of stakeholder groups with diverging interests (Komatsu et al., 2003; Edgar et al., 2003; Brown et al., 2001). The growing public demand for environmental responsibility, the fast rise of associated costs and its political dimension call for an early integration of these diverging interests in the process of emergency planning. A number of oil spill simulation systems are already in existence which address the physical dimension of the problem by projecting the future distribution of spilled oil or chemicals in the marine environment (Maure et al., 1995; Skognes and Johansen, 2004; Reed et al., 2004). In this paper, we propose an extension of these approaches by means of a Decision Support Systems (DSS) in order to integrate several modelling and evaluation stages. Such a tool is ideally able not only to propagate the effects of different response solutions but also to evaluate these with respect to a few aggregated target values like important ecosystem functions. A major difficulty, however, of using DSS-based recommendations within the planning process or, more generally, for gaining acceptance of the DSS by authorities and stakeholders derives from the uncertainties related to various aspects. These range from weather forecasts, abundance of endangered seabird populations, evaluation procedures or relative weighting of different interests like of the fishing industry or of the tourist sector. If the total of inaccuracies exceeds the discrimination made by the response evaluation, the usefulness of building a DSS at the current stage of model and data availability can be doubted. Thus, it is of uppermost importance to conduct a proper and comprehensive uncertainty analysis already within an early stage of development.

1.1 Prestige spill as a case study

In late autumn 2002, the tanker Prestige carrying about 77.000 tones heavy fuel oil emitted an emergency call 150 miles off the northwestern Atlantic coast of Spain. After a 6-day cruise characterized by a series of changing strategies of the responsible authorities the ship broke apart, releasing about one half of its load which then provoked disastrous consequences along the Spanish and, with some delay, also the French coasts (Whitfield, 2003, Del Valls, 2003). In the early phase of the accident, the only feasible protection measure was to tow the ship into different directions, for example by moving the tanker into a nearby harbour at the Galician coast or to a remote ocean site. The possible break-down of the ship among other concerns seemed to impede a rationale judgment on the risks associated with different towing routes. However, the environmental and economic consequences of the actions taken together with their obvious lack of transparency led to a long-lasting political discussion on the national level (Serret et al., 2003, Freire et al., 2006). Due to this controversy, the explicit demand of developing decision support tools put forward by a large group of Spanish scientists (Freire et al., 2006) and the representative degree of uncertainties involved, we chose the Prestige accident as a test case for verifying the usefulness of the newly constructed DSS (Wirtz et al., 2006, Liu and Wirtz, 2005a).

1.2 Outline of this paper

The methodology presented here continues the work of Wirtz et al. (2006) who documented major elements of a DSS and discussed its application to the Prestige spill. Fig. B-1 displays a coarse scheme of this approach integrating environmental and economic data, simulation tools for the fate of contaminants as well as their combat by the response management and a multi-criteria evaluation module. These elements will be briefly sketched in this paper (Section 2.1-2.4) so that a particular focus can be set on the effect of including uncertainties in input data or intermediate results (Fig. B-1). Wirtz and colleagues considered constraints due to incomplete or imprecise knowledge by using simple variation algorithms. In Section 2.6 we present two different ways to process imprecise knowledge within a multi-step approach. The two methodologies lead to different rankings of preset measures, which roughly cover the space of available response options. Both rankings are compared to the decisions actually taken by the Galician and Spanish government (Section 3). Together with the identification of limitations of this approach, a short account of the ongoing and envisioned improvements is given in Section 4.1. In Section 4.2, further linkages to monetary valuation techniques from environmental economics are outlined. Section 5 concludes with some perspectives on uncertainty reduction and future applications of the DSS.

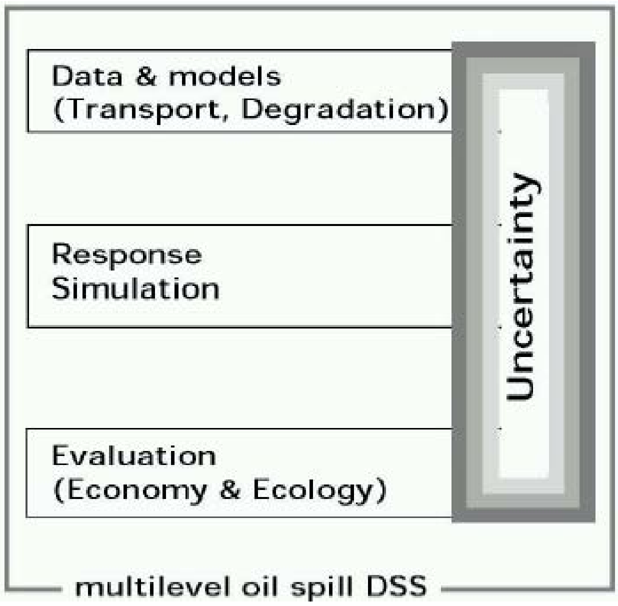

Fig. B-1. A multilevel Decision Support System for oil-spill contingency including the associated uncertainties at all stages

2. Methods

2.1 Spill simulation

From the position where the Prestige sent a SOS at 13/11/2002 off the Finisterra cape (42^o $50N$; 09^o50W), we defined five towing directions representing the above mentioned different response strategies: North-East (NE), North-West (NW), West (W), South-West (SW) and East (E). Along each towing route 3–13 potential sinking locations were distributed within a maximally three-day trawling range. The resulting 49 different sinking sites are shown in Fig. B-2.

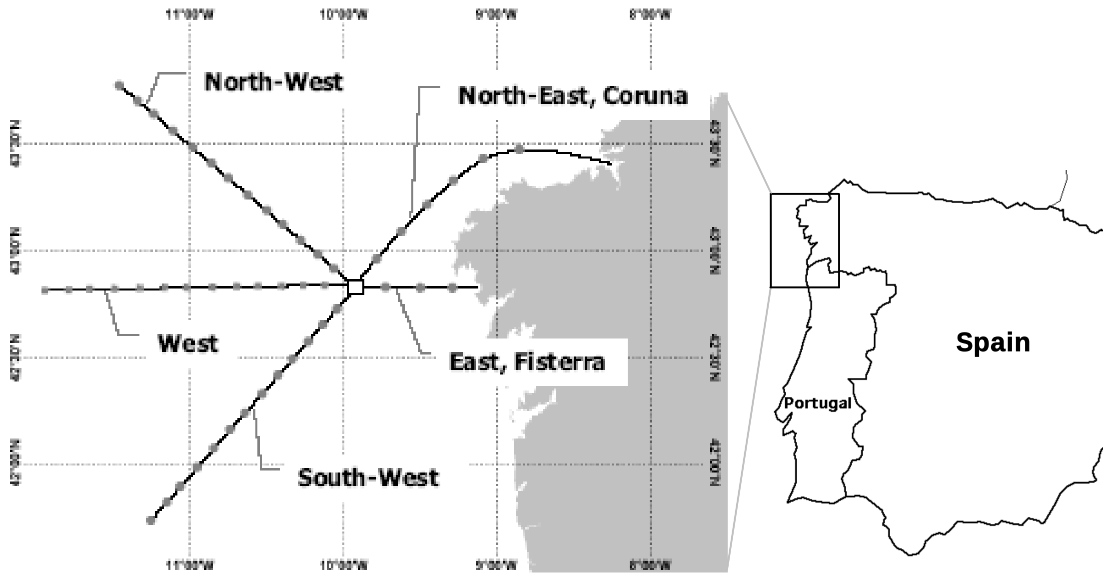

Fig. B-2. Towing routes and hypothetical sinking positions after 6-hour towing intervals (gray points). It is assumed that the Prestige is dragged at the rate of 32.5 km per day for all directions

For each of the 49 locations, the spatial–temporal evolution of spilled oil is hindcasted by the industry standard oil spill simulation and contingency tool OSCAR (Oil Spill Contingency And Response). OSCAR projects the distribution of a contaminant controlled by physical transport, chemical–physical transformation processes and by biodegradation (Daling, 1990; Aamo, 1996). As improvements of most standard oil spill models, also combat activities such as oil collecting by ships or are simulated in a realistic way using a multi-agent approach. Thus, OSCAR can be expected to produce reliable estimates of the spatial distribution of oil landings if realistic hydrographical and meteorological boundary conditions are included. For release locations close to the actual path of the Prestige, the system generates a spatial distribution of oil landings as visualized in Fig. A-4 and Fig. A-5 by Wirtz et al. (2006) which is similar to the one reported and later simulated by Balseiro et al. (2003) or Carracedo et al. (2006).

Summing over the simulated oil landings for individual spilling locations along each route, the amounts of oil P_{jk} landed at different coastal areas with index *k* for different response scenarios with index *j* (*j*=1...5) were computed. In detail, the index *j* denotes the towing option and is linked to a sub-set of simulations $S_1,...,S_{49}$ addressed by the indices n_j (e.g., $n_j = 1,2,...N_j$; for j=1: $N_j = 13$; western route). The number of sinking locations along each route j can be inferred from Fig.B-2.

2.2 Sinking probability

Each sinking scenario S_{n_j} has a specific probability $p(S_{n_j})$ which depends on the estimated time interval after which the ship is expected to break apart. Reflecting a lack of reliable predictions for an eventual sinking of the Prestige during the towing period, Fig. B-3 illustrates two different ways to construct the sinking probability. The first assumes a constant likelihood, while in the second mode $p(S_{n_j})$ becomes an uni-modal function of time. If t^* denotes the time where the likelihood of a break-up becomes maximal (p_j^*) we use

$$p(S_{n_j}) \equiv p(t(n_j), p_j^*) = p_j^* \cdot (t/t^*)^2 \cdot \exp(2 - 2t/t^*) \qquad (1)$$

where $t(n_j)$ stands for the break-up time attributed to scenario n_j. This formulation describes a lagged, non-linear increase with time of the break-up risk in an early stage and a decrease after passing the most likely sinking time t^* what results in a S-shaped cumulative probability. Though there exist no standardized equation for the risk of break-up, Eq.(1) enlarges the spectrum of scenarios with respect to constant probabilities what leads to a better representation of the uncertainty which decision makers faced at the start of the operation.

Sinking probability furthermore depends on wave heights, which increased with growing distance from the coast to the offshore directed routes. Therefore, on average a doubled break-up probability $p(S_{n_j}) = 1/N_j$ has been assigned for j=NW, W, SW with respect to $p(S_{n_j}) = 1/(2N_j)$ for j= NE. For the nearshore route j=E in the constant mode we set $p(S_{n_j}) = 0.02$.

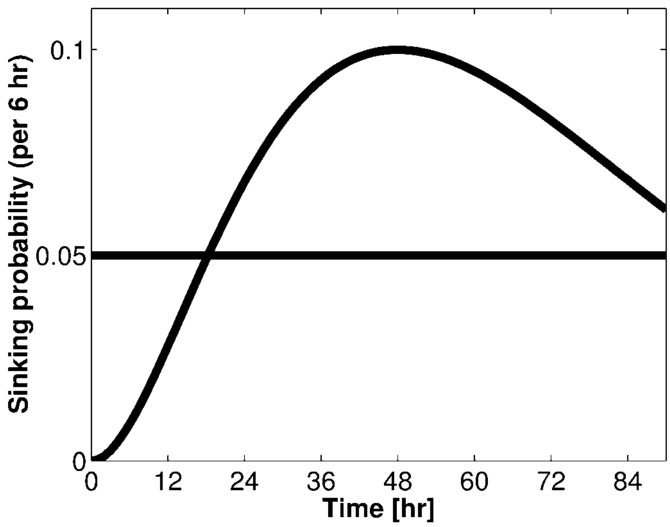

Fig. B-3. Two modes of the sinking probability, one constant (straight line) and the other as a function of time (curved line) with $t^*=48h$ and $p^*=0.1$ in Eq.(1)

2.3 Economic criteria

Many of the affected coastal areas host one of four major resource uses. In our formalism these are addressed by an index *i*: fishery (*i*=1), mariculture (*i*=2), tourism (*i*=3) and transport (*i*=4). Economic impacts are assessed on the basis of income losses which in turn are estimated using sub-regional yearly data for tons of landed fish, harvested mussels, cleared cargo and occupied beds (Liu and Wirtz, 2005b, Garza-Gil et al., 2006, Wirtz et al., 2006). These impacts are translated to an economic damage indicator L_{ij} in each sector as a piecewise linear function of the pollution intensity P_{jk}. If the latter reaches a pollution threshold value P_i^*, the damage equals the regionalized yearly income L_i as maximal loss:

$$L_{ijk} = L_i \times \min\left(1, \frac{P_{jk}}{P_i^*}\right) \qquad (2)$$

The value of P_i^* reflects both the sensitivity and adaptability of each economic activity (details in Wirtz et al., 2006). It is hardly possible to establish their exact value so that the calculation is iterated using a set of different P_i^* during the uncertainty analysis described in Section 2.6 (fishery: $P_1^* \in \{5,10,15\}$, tourism: $P_2^* \in \{4,8,12\}$, transportation: $P_3^* \in \{0.5,1,1.5\}$ and mariculture: $P_4^* \in \{0.4,0.8,1.2\}$, units: 10^3 tons of stranded oil).

2.4 Ecological criteria

Ecological impacts are differentiated with respect to three semi-quantitative indicators for the sensitivity and importance of local habitats: reproductive capacity, vulnerability and protection level. First, reproductive success of pelagic and benthic populations decreases with the extent of polluted spawning and nursery areas. The latter is assumed to be proportional to the amount of oil reaching estuarine mariculture areas as these mark relevant spawning and nursery grounds in this area. Secondly, based on vulnerability indices of Gundlach and Hayes (1978) or Moe et al. (2000), the persistence of oil is estimated using morphological characteristics of the seashore. This value multiplied with P_{jk} quantifies the aggregated effect of oil on substrates such as sand, rocks, muds or pebbles. Thirdly, a protection factor describes the importance which society attributes to individual coastal areas. In our approach, it depends on the number of protective regulations like, e.g., RAMSAR, EU-Natura 2000 or national Natural Reserves, given to an affected area. Again, this factor is transformed to a region and response specific impact score L_{ijk} by multiplication with P_{jk}. Like for economic damages, the integration of the damage scores L_{ijk} for reproduction (*i*=5), vulnerability (*i*=6) and protection (*i*=7) over all areas *k* yields three ecological impact scores L_{ij} for each towing direction *j*,

$$L_{ij} = \sum_{k=areas} L_{ijk} \tag{3}$$

To account for momentarily inaccessible damages of oil remaining on or within the water column after 20 days, the amount of residual contaminants is summed into the category ”residual risk” (*i*=8).

2.5 Multi-criteria analysis

In order to aggregate all ecological and economic impacts to a single target value of response measures we adopt a linear additive model: for each option, the standardized and weighted performance scores are added up, often along a hierarchical tree (Wolfslehner et al., 2005; Chesson et al., 1999; Maniezzo et al., 1998). A negatively sloped linear transformation function is employed in order to normalize the scores,

$$T_{ij} = 1 - L_{ij} / L_i^M \qquad (4)$$

where L_i^M denotes the maximal impact among all options and T_{ij} the normalized score for criteria *i*. After multiplication of the normalized scores T_{ij} with weights w_i expressing the relative importance of a specific criteria *i* in a defined decision context, we obtain an overall target score for each option *j*,

$$T_j = \sum_{i=criteria} w_i T_{ij} \qquad (5)$$

Due to a lack of *a priori* knowledge on preferences in our case study, we define different weighting schemes supposed to be representative for three interest groups involved in the decision making process: fishermen, policy makers and environmentalists (Table B-1).

Table B-1. Three weighting schemes (w_i) representing opposing stakeholder profiles

Index	1	2	3	4	5	6	7	8
Profile	Fishery	Tourism	Transport	Mariculture	Reproduction	Vulnerability	Protection	Residual risk
Fishermen	0.6	0.1	0.1	0.1	0.025	0.025	0.025	0.025
Policymakers	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
Environmentalists	0.025	0.025	0.025	0.025	0.2	0.3	0.3	0.1

2.6 Representations of uncertainty and final ranking

As already outlined by Wirtz et al. (2006) or Liu and Wirtz (2005c), uncertainty in input information for the DSS is described by a systematic variation of selected model parameters. By this parallel account of diverse scenarios, the algorithm operates on an ensemble of constellations rather than single realizations. For sake of simplicity only three sources of uncertainty are studied: the sinking probability $p(S_{n_j})$, the weighting schemes (w_i, see Table B-1) and the pollution thresholds (P_i^*, see Section 2.3) as these are found to have potentially a large influence on the final results.

By combining the variation of weighting schemes, thresholds and probabilities $p(S_{n_j})$ (cmp. Section 2.2) a large ensemble of possible scenarios is generated. There exists, however, some arbitrariness in the processing of such ensembles within the whole evaluation. Many standard algorithms can be divided into two classes: The first method averages model outcomes or scenario variations before the subsequent step or module, respectively, is applied ("preprocessed uncertainty"). This way, our evaluation scheme provides a single performance values for each response option (Fig. B-4).

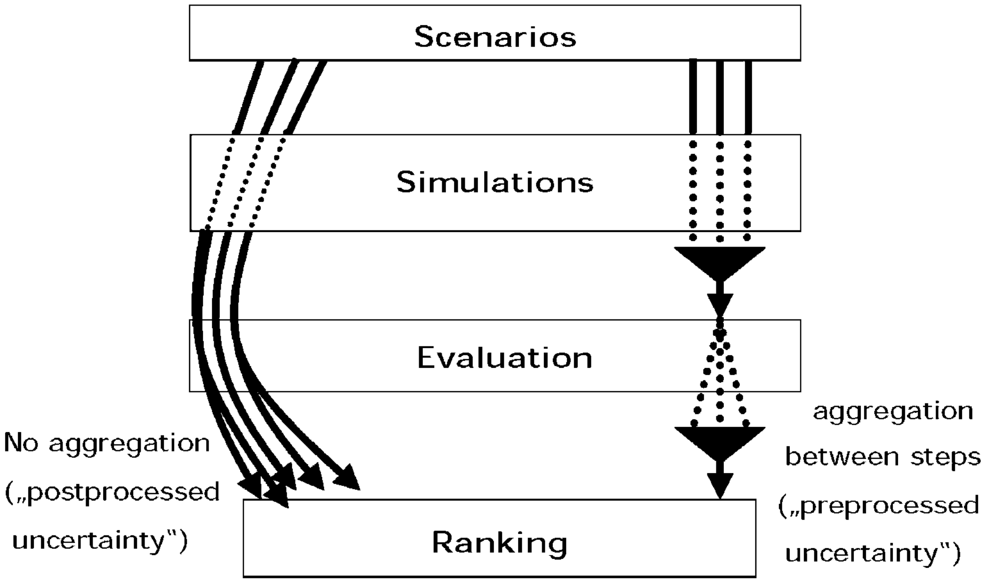

Fig. B-4. Multi–stage approach for ranking different response measures. In the "postprocessed" mode, variability deriving from parameter uncertainty is maintained or increased from stage to stage. This variability is averaged before the subsequent stage in a "preprocessed" mode

"Preprocessed uncertainty" in the case of the oil-spill DSS means that all variability originating from a non–predictable sinking time of the tanker is integrated preceding the valuation stage. Thus, before applying Eq.(2), the pollution intensities $P_{jk}(S_n)$ belonging to $S_1,...S_{49}$ are averaged over each towing route j in order to calculate an option specific expectation value for the total pollution in area k ,

$$P_{jk} = \sum_{n_j=Sink-sites} P_{jk}(S_{n_j}) \times P(S_{n_j}) \qquad (6)$$

Having specified a target value on the base of averaged pollution intensities for the five response options (Eq.(4)-Eq.(5)), the options can be rank-ordered. The ranking is repeated for each distinct combination of minimum, intermediate and maximum threshold value (P_i^* in Section 2.3) and for all three weighting schemes (see Table B-1). Different outcomes are reduced to a mean rank $\langle R_j \rangle$ and the standard deviation.

Albeit the simple usage of this algorithm one has to be aware of possible shortcomings such as an aggregation error due to the non-linear nature of the subsequent model transformations. This inaccuracy can be avoided by a second procedure at the cost of more algorithmic complexity. The idea of the second method is to maintain the entire variability until the final ranking-stage ("postprocessed uncertainty", cmp. Fig. B-4). There, all potential combinations of different settings are individually ranked. In our application, instead of 5 options 49+2 individual sinking scenarios are compared. If the ship reaches the Fisterra bight or Coruna harbour, the corresponding pollution intensities $P_{jk}(50)$ or $P_{jk}(51)$ vanish for all areas *k* except of the respective zone. Again, the ranking of 51 scenarios is repeated for different threshold values and stakeholder profiles. The mean scenario specific ranks $\left\langle R(S_{n_j})\right\rangle$ are finally summed up to an overall relative performance of each option:

$$R_j = \sum_{n_j} \left\langle R(S_{n_j})\right\rangle \cdot P(S_{n_j}) \qquad (7)$$

While in Eq.(6) pollution intensities are averaged, Eq.(7) computes option specific means of rank numbers.

In order to estimate potential error intervals following from including uncertainty in a multi-step algorithm using a different logic, the preprocessing as well as the postprocessing is performed in parallel.

3. Results

Starting from an array of hypothetical sinking locations, OSCAR simulates a variety of different spill scenarios and coastal damages. Simulation results are consistent with observations that oil stranded on the north-west coastal areas (e.g. A Coruna, Finisterra) in the form of oil patches due to both the heavy nature of the spilled oil and moderate to strong force of coastal winds (Carracedo et al., 2006; Doval et al., 2006). It should be noted, however, that OSCAR simulations were deliberately carried out in a pre-operational mode using wind and current forecasts provided by MeteoGalicia and Mercator Operational Oceanography (2002) at the time of the accident. Also accounting for the reduced information available in these days, a single point source of spilling oil was pre-set instead of a continuous release. This had an effect on the timing and exact locations of oil strandings but less on the regional distribution of the bulk mass of the pollutant.

Minimum pollution values for each criterion are scattered between different options already indicating a conflicting situation for decision makers. The final ranking of 49 sinking and 2 harbour/bight scenarios reveals that a very early rupture of the Prestige is most disadvantageous. The final outcome in terms of ranks calculated for different routes is visualized in Fig. B-5 (lower diagram (c)), corresponding to results shown in Wirtz et al. (2006). There exists an overlap of standard deviations so that a clear preference between the best and second best options E and NW is lost.

For a postprocessed uncertainty where individual sinking scenarios instead of towing routes as a whole are compared, results are shown in Fig. B-5 (a) and (b) with two alternative descriptions of the sinking probabilities (e.g. (a) varied and (b) constant). According to diagram (a), option NW slightly outranks E since here it is assumed that the maximal sinking probability is reached after 48h (see Fig. B-3). Contrary, in diagram Fig. B-5(b) options E and NE perform better than option NW since here the sinking risks along all offshore routes are assigned a value 2-4 times as high as that for inshore routes E and NE (see Section 2.2). Both methods, however, lead to a similar conclusion, i.e., dragging the ship into a harbour or a bight infers lowest overall damage scores, while for offshore scenarios the north-western route is ranked best. The latter provides the highest chance to keep the impact on Spanish coastal areas at a minimum because most of the oil drifts to the Gulf of Biscay, which is not an explicit area of interest for the evaluation procedure studied here. And clearly, direction SW turns out to be the least valuable response. This result has been proven robust against different sinking probability functions. Only extreme low or high values of p_j could change the rank behaviour in a significant way. Although the ranking of options is sensitively affected by the choice of evaluation and weight coefficients, the simultaneous use of three contrasting profiles and pollution threshold values does not delete the discriminating power of the approach. Standard deviations of ranks are in general smaller than differences between averages. Thus, statistically secure distinctions can be made between the best option E, a group of sub-optimal solutions (NW, NE, W) and the least performing SW route (Fig. B-5(b)).

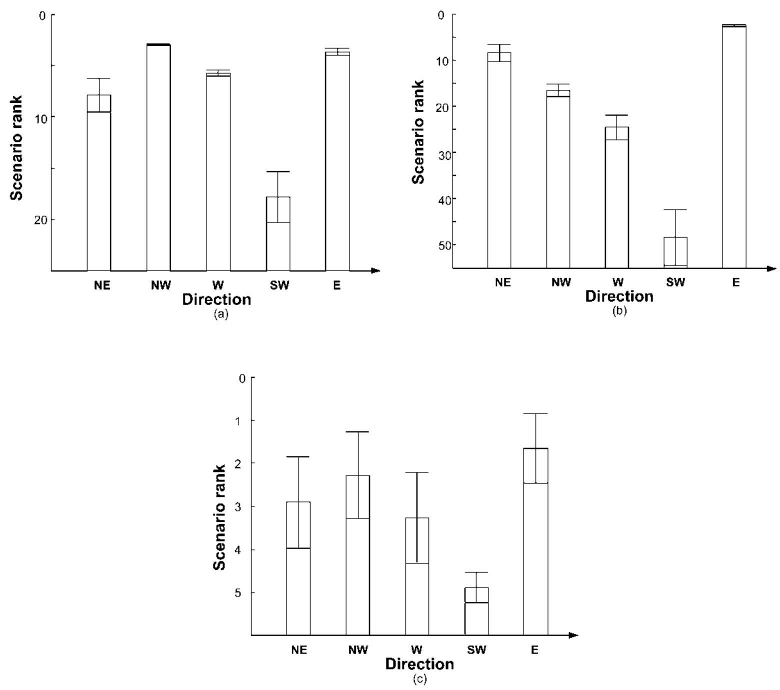

Fig. B-5. Ranking of response options in terms of towing direction of the Prestige. Standard deviations derive from variations in other insecure parameters including pollution thresholds for economic criteria. (a): Mean scenario based ranking (”postprocessing”) of different towing options using time-dependent sinking probabilities. (b): Mean scenario-based ranking (”postprocessing”) of different towing options using constant sinking risks. (c): Mean ranking of the five response measures with sinking uncertainty included according to a preprocessing mode

4. Discussions

When the Prestige attempted to reach a harbour in order to find shelter from stormy winds and high waves and to have the oil pumped off, it was turned away by Spanish ships. Many experts have criticised this decision taken by the Spanish government (Serret et al, 2003). Interestingly, both the northeastern and northwestern towing routes of the Prestige as the initial measure taken by the authorities coincides with the group of best ranked options. However, a later turn to the South with the resulting direction SW corresponds to our worst case scenario. This can be taken as an argument for the use of an operational DSS in emergency cases as it provides a rational, albeit never perfect tool for comparing alternative counter–measures. Such an instrument may strongly enforce communication channels between research and management as demanded by, e.g., Freire et al. (2006). A DSS, in addition, allows for testing different containment strategies or oil spill contingency plans in a systematic way. But quite obviously, an automatic system will hardly ever be able to cover all aspects of a complex contingency management. One example for the difficulties in particular inherent to coastal environments is the trans-border nature of many problems. Spills or oil leaking ships may very soon be drifted by currents or technical means to the territorial waters of a neighbour state. These regularly occurring scenarios are only rudimentarily addressed in our study by the notion of ”remaining risk” in the list of criteria.

The criteria as such should also be refined in future applications. Depending on data availability, ecological criteria like functioning of the pelagic ecosystem may be defined in order to account for a more realistic impact of an oil spill on the marine ecosystem which differs from the much more visible impacts at the coast (Del Valls, 2003, Sánchez et al. 2006).

4.1 Current limitations and ongoing developments of the DSS

Apart from more general problems and due to the prototype character of the presented DSS, also a number of specific shortcomings together with possible improvements have to be pinpointed.

First, the use of a single model prediction for wind as well as for currents may be legitimate if one has to focus on the first day of response management when initial actions have to be designed. But for gaining validity of subsequent applications, an online coupling with operational models is required. Also, the improvements made in operational weather and oceanographic forecasts as, e.g., integrated in the EuroGOOS frame or, more specifically for Galician waters by Balseiro et al. (2003) or Carracedo et al. (2006) can be better exploited by using an ensemble of model systems instead of a single one.

Secondly, like many oil-spill DSS the OSCAR systems underestimates the effect of nutrient dynamics as well as microbial adaptation on the effective biodegradation rates. Though this is not critical for short-term assessment, a mid- or long-term prediction of the oil amount and distribution needs information about the phosphorus and nitrogen pools in the water column (Mulkins-Phillips and Stewart, 1974; Röling et al., 2002) and of prior to spill abundances of bacteria able to oxidize long chain carbohydrates (Harayama et al., 2004; Ac-Hadhrami and Lappin-Scott, 1995). This demonstrates the necessity to extend the list of uncertain input values used in our analysis.

Both methods to account for uncertainty turn out to be difficult to handle when further sources of variability are introduced. Fuzzy techniques may provide a more effective methodology as variability directly enters into the calculation of rankings (Liu and Wirtz, 2005c, and citations therein). However, in our study the inherent non-linearity in the multi-stage transformation of pollution values to final rankings are not sufficient to distort the evaluation outcomes.

Evaluation coefficients turn out to have a higher relevance on the final ranking. The set of criteria used in this study evidently has to be extended when applying the DSS to other sites. The socio-economic impacts of environmental disasters in the coastal zone such as unemployment or loss of scenic beauty are not accounted for. Clean-up costs which often turn out to be substantial, are not addressed at all (see Section 4.2, cf. Garza-Gil et al., 2006). The selection of ecological criteria is heavily influenced by environmental regulations and laws and not by the more direct assessment of the ecosystem function and relative importance of specifically affected populations (Sánchez et al., 2006). State-of-the-art models may provide a much more detailed view on particular species groups like birds (e.g., French McCay, 2003). An appropriate index could, for example, then represent the loss of key species below a critical level where reproduction becomes entirely dependent on immigrating individuals.

4.2 Money talking

Coastal or marine pollution after an oil spill concerns several groups of economic users such as fishermen and local hotel owners, all suffering from monetary loss. Their economic losses are the discounted sum of foregone income during a recovery period (Liu and Wirtz, 2005b). A more fundamental weakness of the multi-criteria analysis originates from the too simplistic account of environmental economics. Sector specific gross economic products for the year following the Prestige accident were only indirectly entering the DSS evaluation. In particular, the weight coefficients for the four economic sectors were set with some arbitrariness even though these were subjected to the uncertainty analysis. When comparing the intervals of weights in Table B-1 with current estimates of actual monetary losses, however, discrepancies turn out to be rather moderate. A survey on different internet sources revealed cost estimates up to 750 Mill. EUR for environmental damages and between 500 and 3000 Mill. EUR for socio-economic damages. The order of magnitude of these values is supported by the 60 Mill. EUR short-term losses documented only for the coastal fishery (Garza-Gil et al, 2006). If the clean-up costs of about 600 Mill. EUR (Garza-Gil et al, 2006) to 2500 Mill. EUR (various internet sources) are predominantly attributed to restore environmental values, an approximate balance of ecological and economic costs is reached. This situation roughly matches the relative preferences used in this study. However, a replacement of neutral scores as defined in Eq.(4) and Eq.(5) by real monetary values in units $ or **€** may enhance the acceptance as well as potential use of the DSS.

Above all, the precision of the DSS could be increased by a detailed account of clean-up actions and costs by, e.g., employing simple model schemes which specify a set of clean-up methods and estimate their costs (cf. Liu and Wirtz, 2005b).

5. Conclusions

In contrast to many standard oil spill DSS, the approach presented here integrates a multi-criteria decision framework with a great variety of both monetary and non-monetary evaluation factors. As it also directly simulates response measures via the OSCAR model, the DSS can be used for optimising existing containment strategies with respect to a politically balanced target value. In ongoing applications we aim to refine the definition of the weighting scheme and the values of weight coefficients within a participatory framework (Liu and Wirtz, 2005a). By confronting regional authorities as well as representatives of interest groups with a spectrum of scenarios, the relative relevance of different impacts should be balanced in a more objective as well as interactive way.

As a major result, this study ascertained the robustness of results which a DSS may provide even when relatively few data are available. Uncertainty can be transformed to variability (of simulations and evaluations), leading to the study of large scenario ensembles instead of a singular case. But the final evaluation uncertainty as quantified by the standard deviation of ranks does not necessarily destroy a statistical discrimination of response measures, as often thought by practitioners as well as modellers. In theory, uncertainty aggregation between successive modelling stages may infer larger discrepancies with respect to a full account of possible scenarios. This effect turns out to be modest in the presented case. If this finding applies to a larger set of decision problems, the handling of uncertainty in a DSS framework can be facilitated by the ”preprocessing” approach which is much easier to use. Algorithmically more simple schemes such as fuzzy techniques might be employed as well. Both, the robustness as well as transparency of the coupled approach carries a large potential for enhancing the efficiency of decision making even in politically sensitive situations.

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Part C: Consensus Oriented, Fuzzified Decision Support for Oil Spill Contingency Management*

Abstract

Studies on multi-group multi-criteria decision making problems for oil spill contingency management are in their infancy. This paper presents a second order fuzzy comprehensive evaluation (FCE) model to resolve decision-making problems in the area of contingency management after environmental disasters such as oil spills. To assess the performance of different oil combat strategies, second order FCE allows for the utilization of lexical information, the consideration of ecological and socio-economic criteria and the involvement of a variety of stakeholders. On the other hand, the new approach can be validated by using internal and external checks, which refer to sensitivity tests regarding its internal setups and comparisons with other methods, respectively. Through a case study, the Pallas oil spill in the German Bight in 1998, it is demonstrated that this approach can help decision makers who search for an optimal strategy in multi-thread contingency problems and has a wider application potential in the field of integrated coastal zone management.

Keywords: Decision support system (DSS); Fuzzy comprehensive evaluation (FCE); Oil Spill; Combat strategy

1. Introduction

The economic productivity of the North Sea coastal region in Germany is among the highest in Germany (yearly gross value is over 125 billion Euros [1]) despite its small size (see Fig. C-1) The main economic activities at this site are transportation, recreation, tourism, fishery and to a lesser but increasing extent wind energy conversion. It is also a particularly important natural ecosystem, which supports breeding populations of seabirds, seals, dolphins and other marine species. Due to its ecological sensitivity, social, cultural, economic importance and scientific and educational purposes, a major part of Wadden Sea has been declared as Particularly Sensitive Sea Areas (PSSAs) within the framework of the International Maritime Organization (IMO). However, frequented shipping movements make this zone vulnerable to oil or chemical spills, as oil spills may lead to long lived consequences for near-shore

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ecosystems and economic uses. This has been demonstrated by the ecological disaster caused by the Pallas oil spill, a shipwreck near the German island Amrum in 1998. Therefore, responding to emergency cases in an effective way turns out to be a critical concern in the domain of integrated coastal zone management. A golden rule of oil spill contingency management, on the one hand, is to remove as much oil as possible from the sea surface in order to minimize the onshore impact; on the other hand, it aims to minimize the cleanup cost also comprising investment and maintenance of combat facilities. In this paper, we simulate a set of feasible combat strategies based on the Pallas case using available combat vessels, as shown in Fig. C-1. This creates an array of potential response measures which, in turn, can be selected after an integrated consideration of socio-economic and environmental impacts. For this, also a variety of stakeholders should be accounted, since they are directly or indirectly affected by decisions. Often their different interests cause a conflict on selecting an oil spill response strategy. Thus, we here formulate the selection of optimal combat strategy as a multi-group multi-criteria decision making problem [2]. Conventional methods of multi-criteria analysis (MCA) can be used as a Decision Support System (DSS) to generate and evaluate alternative solutions in order to gain insight into the problems and support the decision making process [3-7]. However, the multi-criteria analysis is less favored if the environmental and socio-economic impacts are non-linearly related [8]. Additionally, it is difficult to handle lexical data involving human opinions and imprecise data including uncertainties [8,9]. These and other issues of conventional multi-criteria analysis motivate seeking for alternative decision support techniques that are capable of integrating these criteria in an effective way.

Fuzzy logic techniques have represented an approach suitable for modelling imprecision and vagueness for decades [10,11]. Their use is spreading rapidly in the field of environmental management. For example, Adriaenssens et al. [12] reviewed and assessed applications of fuzzy logic for decision support in ecosystem management. As an integral part of decision support system for managing oil spill events [13], a fully automated system based on fuzzy logic was developed by Keramitsoglou et al. [14] to identify possible oil spill. Fuzzy sets were also used as instruments to evaluate sustainability in forest management and incorporate multiple objectives [15,16]. Based on a set of fuzzy rules derived from experimental observations and expert knowledge, Marsili-Libelli [17] designed a predictor for algae blooms. Gurocak and Whittlesey [18] developed a fuzzy method for fishery management. Bonvicini et al. [19] presented an application of fuzzy logic to the risk assessment of the transport of hazardous materials by road and pipelines. In a contaminated sediment management, Stansbury et al. [20] found an optimal option by using fuzzy method. In brief, fuzzy logic techniques have potential to deal with uncertain and complicated problems in operational environmental management.

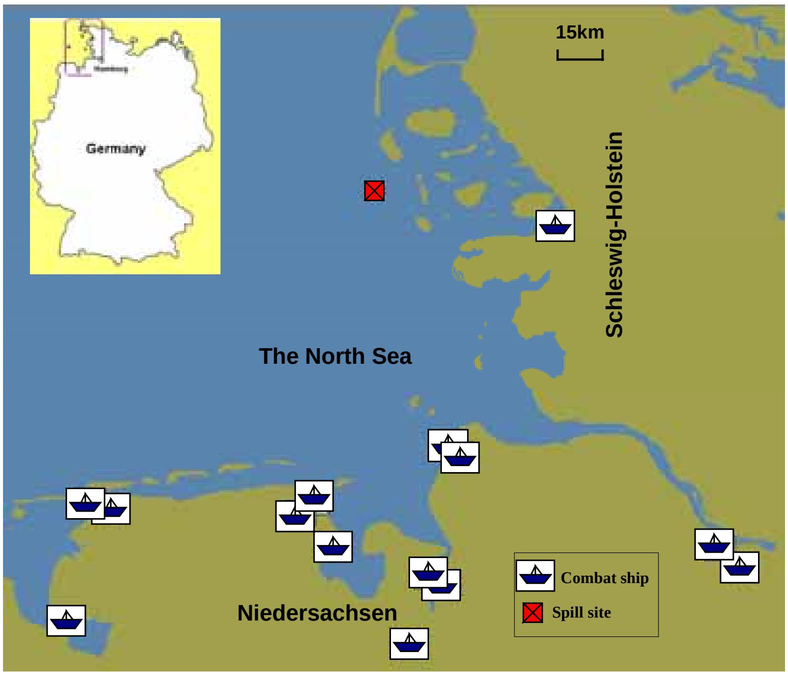

Fig. C-1. German North-Sea case study area. Both combat vessels and Pallas spill site are highlighted by different marks. Totally, there exist 14 oil combat vessels distributed in selected coastal administrative districts along the German North-Sea

In this paper, we propose a second order fuzzy comprehensive evaluation (FCE) method [21,22] in order to identify a consensus oriented solution for complex emergency cases like Pallas oil spill. The FCE consists of three principal steps: (a) A first order evaluation of performances of alternatives with respect to various criteria. (b) A second order evaluation with an involvement of weighting schemes assigned to the selected criteria by groups with different interests. (c) Making a rule based consensus, which represents a majority view of interested groups. Unlike the multi-criteria analysis which adds measures originally defined in different units, in the first step of FCE complex pollution effects can be broken down to a single fuzzy degree representing the overall environmental damage level, which allows these effects to be compatible and comparable directly. Instead of quantitative weights, stakeholders may describe the importance of criteria in a qualitative way. This way, FCE focuses on the exchange of thoughts among stakeholders and on finding a workable group consensus. The specific objectives of the paper can be formulated as follows:

- To represent systematically opposing stakeholder interests within a decision support tool for oil spill contingency management.
- To re-evaluate response measures taken in a specific contingency case (Pallas, German Bight).
- To explore potentials and limitations of the FCE for future applications in the field of integrated coastal zone management.

2. Data

Formulation of a multi-group multi-criteria decision-making problem is based on three basic components: (1) alternatives, (2) criteria and (3) stakeholders. The OSCAR (Oil Spill Contingency and Response) model system developed by SINTEF [23-25], Norway, simulated a variety of combat strategies for a 60-ton crude oil spill at the site where the accident of Pallas occurred ($54^o 32.5^{'} N$; $8^o 17.24^{'} E$). One major issue of the discussions in the aftermath of the accident was whether an appropriate number of response ship is in existence and, if so, how many of these should have been used in the Pallas case. Thus, after a preliminary evaluation of these combat alternatives, five alternatives characterized by a variable number of 4-6 combat vessels are pre-selected. Among these five alternatives, alternative 1 can be taken as a reference as it includes all five activated combat vessels: Neuwerk, Mellum, Westensee, Knechtsand and Norderhever. Based on alternative 1, in alternatives 2, 3 and 4 one more combat vessel is assumed while in the alternative 5 only four combat vessels are considered (see Table C-1). Fig. C-2 shows a 2 dimensional projections of the temporal evolution exhibited by the oil when alternative 1 as the particular combat strategy is used. Such a simulation based on the actual data for wind conditions and currents is provided by OSCAR. In accordance with observations [26], the affected area is in the simulation limited to the east part of the German North-Sea coast or, more specifically, the Schleswig-Holstein coastal area (see Fig. C-1). The five alternatives are evaluated with respect to a set of selected criteria, which can be regarded as representative for many coastal regions around the world with their specific economic uses and ecological values: the stranded oil, residual risk, oil collected, cleanup costs, fishery area, tourism area and bird area, the latter focused on the

Eider duck as a key species (details can be seen in Table C-2). They reflect existing interests as well as existing background information at the German North-Sea coast, with special regard paid to oil pollution. The performances of the alternatives in terms of these criteria contribute to one major input matrix for the model of fuzzy comprehensive evaluation (FCE). In addition, the FCE methodology requires stakeholders' preferences regarding each criterion. These weighting values can be revealed in either a quantitative or a qualitative way. In many cases, it is not realistic to ask participants who are from non-technical background to assign a numeric scale for the importance of criteria, although this kind of numeric scale response is quite straightforward for a further evaluation [9]. Thus, here we use three different importance levels only. Participants are asked to select one importance level and their preferences are directly integrated in the FCE.

Table C-1. Response strategies in terms of used combat vessels. The sixth vessel used in Alt.2, 3 and 4 is Nordsee, Eversand and Thor, respectively. These vessels are different at several aspects ranging from costs to facilities to location

Alternatives	Name of vessel	# of vessels
Alt.1	Neuwerk, Mellum, Knechtsand, Norderhever, Westensee	5
Alt.2	Neuwerk, Mellum, Knechtsand, Norderhever, Westensee, Nordsee	6
Alt.3	Neuwerk, Mellum, Knechtsand, Norderhever, Westensee, Eversand	6
Alt.4	Neuwerk, Mellum, Knechtsand, Norderhever, Westensee, Thor	6
Alt.5	Neuwerk, Mellum, Knechtsand, Norderhever	4

Table C-2. Selected criteria and their description

	Criteria	**Descriptions**
SO	stranded oil	the stranded oil (tons) in the coastal areas
RR	residual risk	summed amount of oil (tons) in the open sea
OC	oil collected	oil collected (tons) by combat vessels
CC	cleanup costs	the costs (Euro) by using the combat vessels and their equipments
F	fishery	summed amount of oil (tons) in the principal fishery areas
T	tourism	summed amount of oil (tons) in main recreation areas along the German North-Sea coastline
D	duck	summed amount of oil (tons) in important areas supporting breeding of Eider ducks

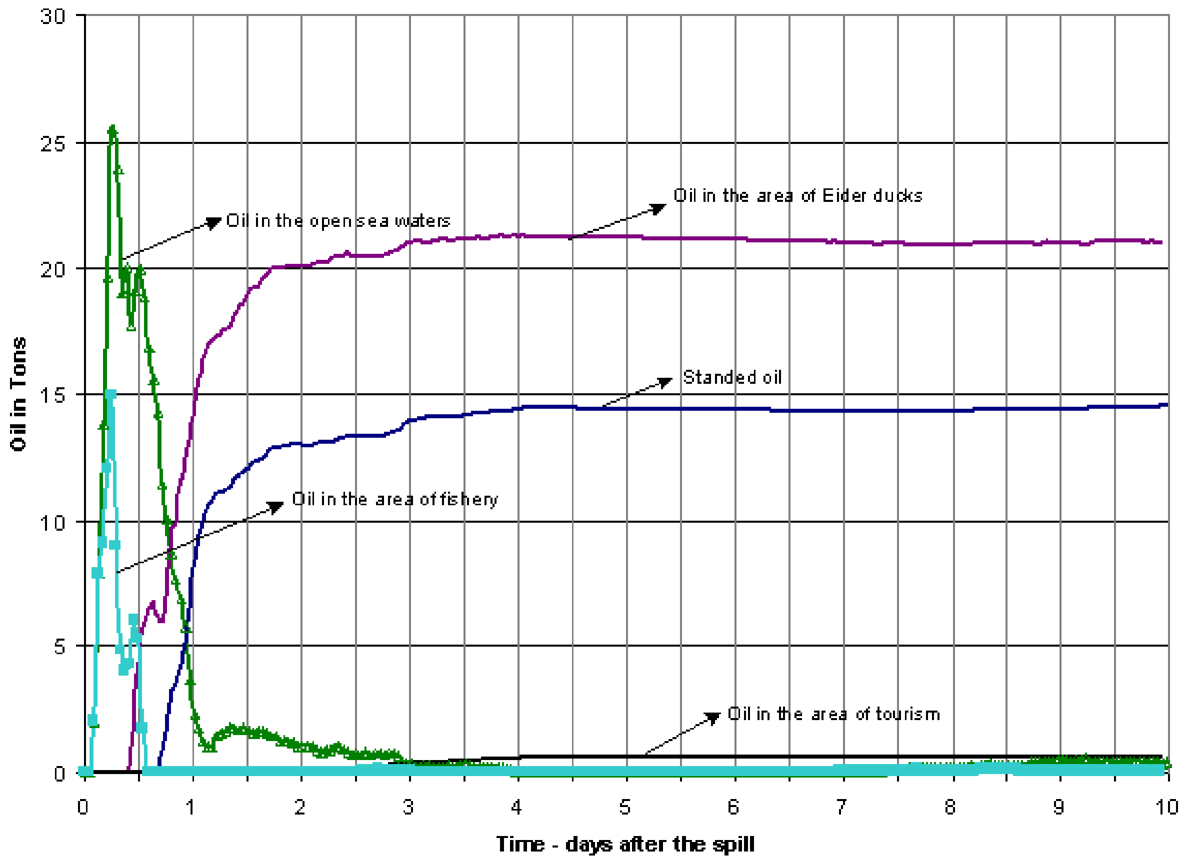

Fig. C-2. Simulated oil distribution 10 days after the use of combat strategy (e.g., Alt.1) responding to a hypothetical release (site: 54º32.5'N; 8º17.24'E; spill amount: 60 tons). Due to the small footprint in this spill scenario, the quantities of oil accumulated in different economic and ecological areas tend to stabilize after about 2-3 days following the spill

3. Fuzzy Comprehensive Evaluation

Through OSCAR simulations, consequences of using different combat alternatives in terms of selected criteria are estimated. The resulting performance matrix includes both robust information and impact uncertainties. In addition, the importance of each criterion is assumed to be presented in a qualitative way. In other words, inputs include both imprecise data and lexical knowledge as shown in Fig. C-3. In such circumstances, the method of fuzzy comprehensive evaluation (FCE) is expected to provide a high level of confidence for the selection of the optimal combat strategy by fuzzifying the performace matrix and defuzzifying the lexical weights (see Fig. C-3). The fuzzification aims to lower uncertainties in the data by using experts' experiences. Whilst, the defuzzification tries to transfer the lexical knowledge to numerical values, which are easily integrated in an evaluation process. The detailed procedure of applying FCE into the Pallas case is described in the following paragraphs.

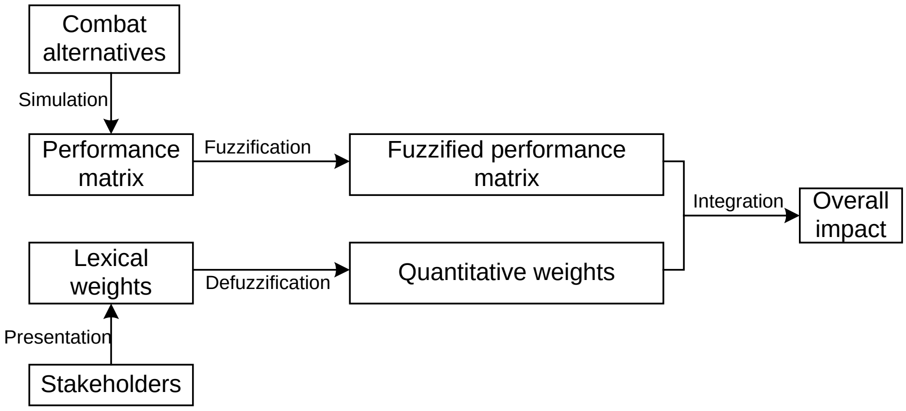

Fig. C-3. A brief methodology scheme

3.1 Fuzzy grades

Five lexically fuzzy grades are assigned to each criterion: very low impact (*VLI*), low (*LI*), middle (*MI*), fairly high (*FHI*) and high impact (*HI*). Flexibility on the design allows to set a different set of fuzzy grades, according to the resolution required for a specific problem. Thus, we get a fuzzy set that contains a series of fuzzy grades for each criterion,

$$u^i = \{VLI^i, LI^i, MI^i, FHI^i, HI^i\} \qquad (1)$$

where u^i denotes the set of lexical grades for the *i*th criterion.

3.2 Establishing Membership Degrees

Values in the performance matrix are linked to the lexical grades by using a fuzzy membership function. It is

$$\mu_{ij}^n = \max(\min(\frac{x_i^n - e_{ij}^1}{e_{ij}^2 - e_{ij}^1}, 1, \frac{e_{ij}^4 - x_i^n}{e_{ij}^4 - e_{ij}^3}), 0) \qquad (2)$$

where x_i^n is the performance value of the alternative *n* in terms of the criterion *i*; μ_{ij}^n indicates the membership degree of x_i^n regarding to the *j*th grade of the *i*th criterion and $e_{ij}^{1,\cdots,4}$ are four scalar parameters for the *j*th fuzzy grade of the *i*th criterion. A degree vector (A_i^n) is constructed below:

$$\begin{cases} A_i^n = \{a_{i1}^n, a_{i2}^n, a_{i3}^n, a_{i4}^n, a_{i5}^n\} \\ a_{ij}^n = \mu_{ij}^n \Big/ \sum_{j=1}^{5} \mu_{ij}^n \end{cases} \quad (3)$$

An intuitive example for the criterion *SO* is shown in Fig. C-4. Its fuzzy set is defined as $u^1 = \{VLI^1, LI^1, MI^1, FHI^1, HI^1\}$. Supposed that there is 28.5 tons of spilled oil stranded, then the fuzzy degree reads $A_1 = (0,0,0.5,0.5,0)$. Namely, 28.5 tons oil pollution falls into the category of *MI* and *FHI* with the fuzzy membership of 0.5, respectively.

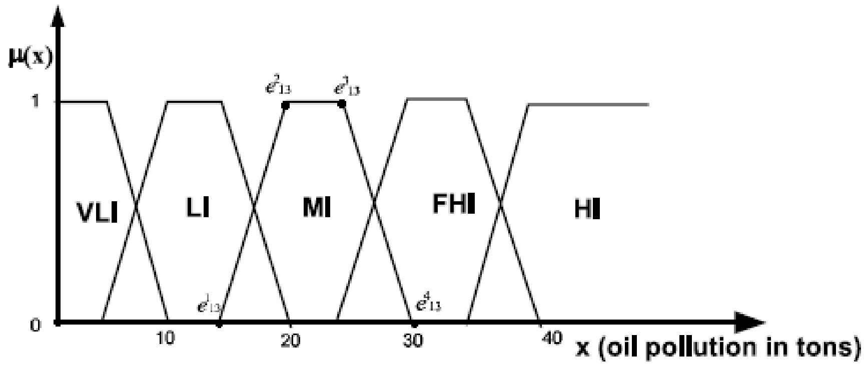

Fig. C-4. The fuzzy membership function for criterion SO (stranded oil). VLI: very low impact, LI: low impact, MI: middle impact, FHI: fairly high impact and HI: high impact

3.3 Defining Damage Levels

The coastal environment is highly vulnerable to marine pollution especially in form of spilled oil. Usually we face a practical issue: how to assist decision makers to assess the performance of different combat strategies in a quantitative way? For simplicity, equally spaced oil spill damage levels ranging from 0 to 1can be applied, it is given by

$$\varsigma = \{\varsigma_1, \varsigma_2, \cdots, \varsigma_{11}\} = \{0, 0.1, \cdots, 0.9, 1.0\} \quad (4)$$

where 0 represents no damage, while 1.0 denotes a complete damage in concerned coastal areas. Clearly an efficient strategy should lead to lower damage level.

3.4 First-Order Fuzzy Evaluation

A first-order fuzzy degree assignment matrix represents fuzzy degrees of lexical grades associated with those eleven damage levels. An example for criterion *SO* is shown in the Appendix 1. Though roughly representing existing expert knowledge and rules, the matrix coefficients are of empirical nature, so that they can be modified for a specific application. Through combining the pre-defined first order fuzzy degree assignment matrix (R_i) and the fuzzy degree vector (A_i^n), the first-order FCE set (B_i^n) for alternative *n* in terms of criterion *i* can be obtained.

$$B_i^n = A_i^n \times R_i \tag{5}$$

Following the example mentioned in Section 3.2, the first-order set (B_i) with regarding to the criterion *SO* is given by,

$$B_i=[0, 0, 0.2, 0.3, 0.4, 0.7, 0.7, 0.7, 0.7, 0.4, 0.3]$$

3.5 Second-Order Fuzzy Evaluation

It is evident that the criteria (i.e. *SO*, *RR*, *OC*, *CC*, *F*, *T*, *D*) may not be equally important from the perspective of different stakeholders who are involved in using and managing coastal resources. Hence, a parameter W^S is used to denote the weights for criteria according to the opinion of stakeholder *s*. For simplicity, three different importance levels are designed for each criterion: highly, moderate and non-important. In this paper, we supposed three different groups participating in the decision making process. Their weighting schemes are shown in Table C-3 where policy makers tend to treat these criteria equally important, while group 2 and 3 put more emphasis on efficiency of the combat strategy and environmental damages, respectively. To transform the lexical information into quantitative data, we use a weighted average defuzzification for which more details are given in [27]. By multiplying W^s by B^n, a second-order FCE set ($K^{s,n}$) for alternative *n* according to stakeholder *s* can be obtained from the following equation:

$$K^{s,n} = W^s \times \mathrm{B}^n = \kappa_1^{s,n}, \kappa_2^{s,n}, \cdots, \kappa_{11}^{s,n} \tag{6}$$

Table C-3. Weighting schemes (● highly important; ◉ moderate; ○ non-important)

	Criteria						
	SO	*RR*	*OC*	*CC*	*F*	*T*	*D*
Group 1: Policy makers	◉	◉	◉	◉	◉	◉	◉
Group 2: Combat organizations	◉	◉	●	●	○	○	○
Group 3: Environmentalists	●	○	○	○	◉	●	●
Defuzzification	●=0.95		◉=0.5		○=0.05		

3.6 Calculating the Overall Impact

The overall impact (*OI*) for a specific alternative *n* according to opinion of stakeholder *s* is determined as follows,

$$OI^{s,n} = \sum_{p=1}^{11} k_p^{s,n} \varsigma_p / \sum_{\pi=1}^{11} k_\pi^{s,n} \qquad (7)$$

A smaller value of the overall impact is preferred since it indicates less damage. To illustrate the procedure of the above method, an example to calculate the overall impact for Alt.1 is given in Appendix 2.

3.7 A Wide Consensus

The overall impact of each alternative allows for a rank-ordering. For stakeholder *s*, alternative *e* outranks alternative *f*, if $OI^{s,e} < OI^{s,f}$. Obviously, various rankings may be presented due to the different opinions of stakeholders. In order to make a consensus, which represents a majority view of stakeholders, a mean rank for each alternative is taken into account, which represents the average of ranks according to all interested groups.

4. Results and Discussions

In this study, five combat alternatives were ranked by different hypothetical interested group, respectively. As shown in Table C-4, both fishermen and policy makers take Alt.5 and Alt.2 as the top two options, while from the view of environmentalists Alt.2 significantly outranks Alt.5.

Table C-4. Ranking of combat alternatives

Stakeholder	**Ranking (1>2>3>4>5)**
Fishermen	Alt.5>Alt.2>Alt.1>Alt.3>Alt.4
Policy makers	Alt.5>Alt.2>Alt.3>Alt.1>Alt.4
Environmentalists	Alt.2>Alt.3>Alt.1>Alt.5>Alt.4

4.1 Ranking

If we compare the mean rank of five alternatives in Fig. C-5, it appears that Alt.2 is the best, followed by Alt.5, 3, 1 and 4. On the other hand, the standard deviations of ranking for each alternative indicate that Alt.4 is the leastless controversial, reflecting that all three groups take it as the worst case. Both Alt.1 and 2 are less controversial and Alt.3 and 5 are the most controversial according to different stakeholders' interests.

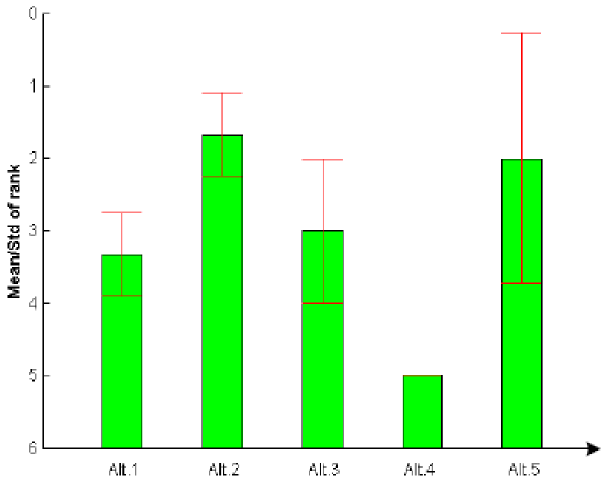

Fig. C-5. Rankings of combat alternatives based on FCE. The interval plotted in solid lines indicates the standard deviation value of ranks. The standard deviation of ranks for Alt.4 is zero because all three groups rank it indifferently

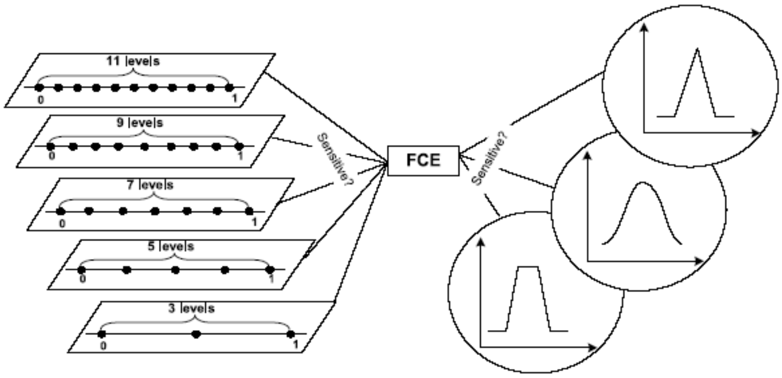

Fig. C-6. The internal check of FCE. Different setups regarding the number of damage levels and various membership functions are examined.

Although the Alt.5 outranks both Alt.1 and Alt.3 with respect to the mean rank value, the overlap among them suggests that they are very similar. Considering the mean rank and the interval of ranks comprehensively, Alt.2 is considered as the most preferred option. Alt.1, Alt.3 and 5 can be grouped into the sub-optimal class and the Alt.4 appears to be the least preferred.

4.2 Consistency and robustness checks

In order to guarantee that the evaluation using FCE is reliable to a satisfying extent, two types of examination were performed, an internal check (e.g. sensitivity test) and an external one (e.g. comparison with other methods). In the internal check the effects of model or control parameters on the result are studied. Two critical setups in FCE are the membership function and the damage level mentioned in Sections 3.2 and 3.3, respectively (see Fig. C-6). The ranking result presented in Fig. C-5 is based on a setup in which the number of damage level is 11 and the membership function is trapezoidal. In order to examine whether other possible setups could lead to different results, two tests are conducted separately. All criteria are considered to carry the same weight (e.g. the view of policy makers) in both test cases. According to the maximal extent at which the ranking of a specific alternative varies with the change of setups, the alternatives can be grouped as (i) not sensitive alternatives, (ii) relatively sensitive alternatives or (iii) highly sensitive alternatives. It is summarized as follows:

$$alt.j\ is \begin{cases} not\ \ sensitive & if\ \max(\Delta R(alt.j)) \in [0,1] \\ relatively\ \ sensitive & if\ \max(\Delta R(alt.j)) = 2 \\ highly\ \ sensitive & if\ \max(\Delta R(alt.j)) \in [3,4] \end{cases} \qquad (8)$$

where $\Delta R(alt.j)$ indicates the difference between ranks associated with the alternative j by changing the internal setups. Firstly, three different membership functions are compared: the trapezoidal shape, the triangular shape and the Gaussian curve (see Fig. C-6). The results are shown in Table C-5. Most cases are not sensitive to the change of membership functions. The rankings of Alt.2 vary significantly when the membership function is Gaussian. A possible reason is that the Gaussian curve has continuous tails, while the triangular and trapezoidal shaped functions are truncated at both sides. This leads to minimize the difference of performances of combat alternatives. Secondly, the number of damage levels is assigned as 3, 5, 7, 9 and 11 respectively (see Fig. C-6). Their effects on the rank-ordering of alternatives are presented in Table 5. Similar with the first test, all alternatives are not sensitive with the changing of such a setup according to the Eq.(8). Generally, different internal setups could result in a minor change of the ordering of alternatives. In order to minimize such effects or uncertainties introduced by different internal setups, traditional correlation analyses are useful to determine a suitable setup, which could produce a highly correlated result with those based on other setups. In case of the Pallas study in this paper, the trapezoidal shaped membership function and the number of damage levels over 7 are recommended, since they may produce results which are relatively highly correlated with those derived from other setups. Additionally, the external check is also a useful way to validate the result produced by the FCE, since it allows people to compare the result derived from FCE with the real condition or those from other methods. Alt.1 is the actual decision made by the government to response to the Pallas spill, 1998. Obviously, compared with the evaluation result shown in Fig. 5, such a decision is not predicted as the optimal but the least controversial strategy if compared with other less optimal options (e.g. Alt.1, Alt.3 and 5). Furthermore, its performance could be improved significantly if one more combat vessel (i.e. Nordsee) can be introduced. For a further validation, other methods such as monetary evaluation model and multi-criteria analysis are also applied in this oil spill case. Compared with FCE, they produce consistent outputs reinforcing the result that the best case is Alt.2, while the worst alternative is either Alt.4 or Alt.5.

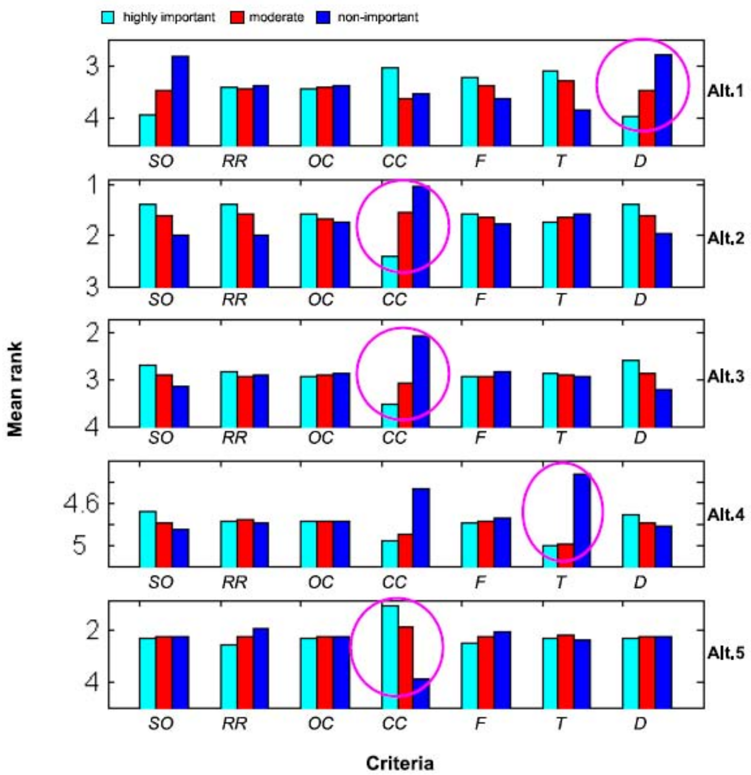

Fig. C-7. Sensitivity test for each alternative in terms of each criterion. The importance of each criterion is defined in three different levels. Their changes contribute to the variation of mean rank for each alternative. The most critical criterion for each alternative is highlighted with a circle

4.3 Critical criterion

Generally, the rank of an alternative is affected by weight profiles that are, in turn, predefined by stakeholders. In order to assess the sensitivity of rankings with respect to a changing relevance of criteria a numerical experiment is carried out for all criteria. For both simplicity and clarity, the membership function is trapezoidal shaped and the number of damage levels is specified as 3 in the experiment. As mentioned previously, the importance level of each criterion can be described in three levels: highly important, moderate and non-important. If the importance level of one criterion is fixed, the possible combination of description of other six criteria is 729 (3^6). In this case study, we collect the mean rank of 729 scenarios for each importance level of the selected criterion for each alternative. Fig. C-7 maps the change of mean rank with respect to different description of importance of each criterion for all alternatives. For example, for Alt.5, the mean rank decreases from 1.03 to 3.89, as the importance of criterion cleanup costs (e.g., *CC*) ranges from highly importance level to non-important level. For each alternative, there exists a critical criterion whose change significantly affects the mean rank of the particular alternative. As shown in Fig. C-7, criterion *CC* is highly critical for Alt.2, 3 and 5. Therefore, decision makers should be notified by the evaluation system when assigning a weight for a critical criterion.

In summary benefits of FCE are as follows (i) it is a method to deal with lexical data; (ii) it is capable of aggregating ecological and socio-economic criteria which are measured in different metrics; (iii) provides a clear and traceable structure to integrate a variety of stakeholders into the decision-making process; (iv) it is able to differentiate robustly the optimal and worst alternative groups; On the other hand one limit is that it requires knowledge of the involved parameters and a careful design of the internal setups . Thus, a re-examination of the setup is required when the FCE is applied to other case studies. In addition decision makers will in general not completely rely on the computer-based results and constrain the final decision to the order of ranking for alternatives [28]. Since decision makers are responsible for the consequences of the decision, they must maintain the freedom to deviate from a modelled solution and may inspire suggestions for new alternatives from the results and analyses [28,29]. The attractive alternatives found by FCE are not yet the compromise alternatives, although they collect a wide consensus among the majority stakeholders. However, the utilization of FCE could be the basis for further negotiation like over the combat alternatives and money payments. This may also include the compensation for stakeholders who have to make disadvantageous agreements [30].

Table C-5. Sensitivity tests regarding the internal setups of FCE. The ranks of alternatives are indicated by numerical numbers.

Tests	**Alternatives**				
1.Membership function	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5
Trapezoidal shape	4	2	3	5	1
Triangular shape	4	2	3	5	1
Gaussian curve	3	5	2	4	1
Sensitive?	not	highly	not	not	not
2. Damage levels	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5
#3	4	1	3	5	2
#5	4	2	3	5	1
#7	3	2	4	5	1
#9	4	2	3	5	1
#11	4	2	3	5	1
Sensitive?	not	not	not	not	not

5. Concluding remark

As a computer-aided decision-making tool, the fuzzy comprehensive evaluation (FCE) helps to identify an efficient combat measure for the oil spill contingency management. The generic nature of this approach is capable of dealing with lexical data, considering ecological and socio-economical criteria and integrating a variety of stakeholders simultaneously in the decision-making process. These benefits are demonstrated by the Pallas case study presented in this paper, as well as applications in other field done previously [22,23]. Additionally, in order to improve its applicability and robustness, both of the internal and external checks are highly recommended.

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Appendix 1

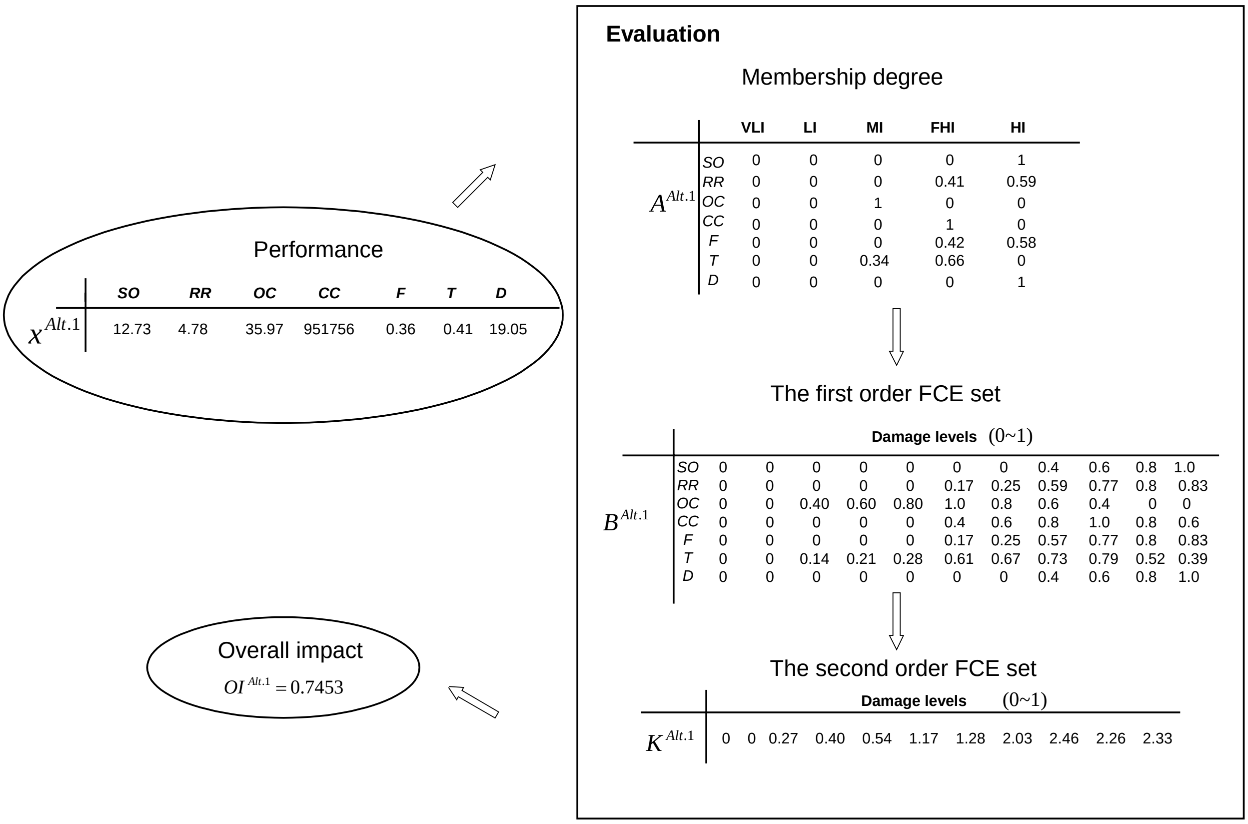
An example of the first-order fuzzy degree assignment matrix for the criterion SO (stranded oil) is as follows,

Fuzzy grades	Damage levels (#11)										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
VLI	1	0.8	0.6	0.4	0	0	0	0	0	0	0
LI	0.6	0.8	1	0.8	0.6	0.4	0	0	0	0	0
MI	0	0	0.4	0.6	0.8	1	0.8	0.6	0.4	0	0
FHI	0	0	0	0	0	0.4	0.6	0.8	1	0.8	0.6
HI	0	0	0	0	0	0	0	0.4	0.6	0.8	1

Notes: VLI: Very Low Impact; *LI*: Low Impact; *MI*: Middle Impact; *FHI*: Fairly High Impact; *HI*: High Impact.

Appendix 2

An example of calculating the overall impact for Alt.1 with the weighting schemes representing opinions of the policy makers.



Part D: Total oil spill costs and compensations*

Abstract

Although counteracting environmental programs and policies have been strengthened, large oil spills still occur at irregular intervals. The total oil spill costs and their compensations have attracted much interest from various parties such as local stakeholders, state and federal governments. This paper addresses five major cost categories whose aggregations are expected to cover the overall direct and indirect costs after the release of an oil spill. Among them, research costs should not be neglected, since they tend to be high if public attention has been drawn to the case. Through an examination of the relationship between the total oil spill costs and their admissible claims, we found that,

(i) admissible claims do not cover the overall costs of the oil spill, and
(ii) admissible claims cannot be compensated in full in the case of large spills.

Clearly, a sound oil spill contingency management aims to minimize both the environmental impacts of areas most at risk and the total oil spill costs. In this paper an economic model for measuring environmental damages following an oil spill is addressed and applied to the Prestige case, which happened to be the worst oil pollution in the history of Spain. The model indicates how an ideally *a priori* economic evaluation may intuitively help managers to make informed as well as fast decisions in contingency cases.

1. Introduction

To operationally estimate potential costs caused by oil spills is of paramount importance for contingency management and effective combat options which have to minimize environmental and economic impacts. However, relatively few studies have examined this issue in great detail [1]. In the context of the total oil spill costs, this paper presents five different categories: the environmental damages, socio-economic losses, clean-up costs, research costs and other expenditures. Among these five different cost categories, exclusively environmental damages cannot be directly assigned with monetary values in a real economic

* Maritime Policy & Management (33) 49-60.

world. Thus, this paper discusses a simple model for guiding non-economists to calculate environmental impacts of the oil spill in monetary terms. The model consists of two major steps: (i) measuring the lost services of injured natural resource; (ii) integrating the lost services with a unit value of injured natural resource, which is either measured by economic valuation methods or transferred from existing valuation studies. It can, on the one hand, act as a decision support tool for policy makers to evaluate different oil combat strategies, on the other hand it can be further used to determine the scale of restoration projects with which public demands will be compensated according to the lost use values of injured resource [2].
The final part of the paper concentrates on the relationship between the total oil spill costs and their compensations. So far, admissible claims do not fully cover the research cost which includes conducting an environmental damage assessment and the monitoring and investigation costs of the affected resources. Possible explanations are: (i) investigation and monitoring activities are less associated to small spills; (ii) relatively few environmental damage assessments have been performed in terms of historical oil spill cases [1].

2. Total oil spill costs

To have an integral cost estimate following an environmental disaster like an oil spill is of great interest for various affected parties including local stakeholders, state and federal governments and responsible parties. Five different categories of costs can generally be identified within the context of total oil spill costs and they are explained respectively in the following sub-sections. Missing or failure consideration of any of these cost categories will lead to an incomplete estimation and a false perception of the relative significance of other cost categories [1]. Among these cost categories, only environmental impacts caused by an incident cannot be measured directly in the economic world. Thus, special attention is paid to an economic model, which measures them in a monetary way.

2.1 Environmental damages

Oil spills lead to a degradation of natural resource and, consequently, to a decrease of their services in the aftermath of the incident. Fig. D-1 schematically illustrates the recovery path of a unit injured habitat over time. Year *a* is the first year following the incident and the damaged habitat is supposed to be able to provide only *f(a)*100%* of its previous services. Hence, the loss of services during the year *a* is *(1- f(a)*100%).* After that, the habitat is naturally restored till the year *b* where the injured resource is restored completely and generates a full service as ever. The lost services is the area of *L*, which can be estimated as follows,

$$L = \sum_{t=a}^{b} (1 - f(t)) \left(\frac{1}{1+d}\right)^{t-a} \qquad (1)$$

where *f(t)* is a recovery function to describe the potential services, which the injured habitats could provide during the year *t* [3]. *d* is the yearly discount rate emphasizing that the present service losses are more costly than the future ones. In NOAA [4] a value of *d*=0.03 is recommended. There exist many shapes of recovery functions like, e.g., the linear, S-shaped and logistic curve. The *S* shaped recovery path seems more realistic from an economic view since marginal services provided by the injured habitats at the first year (Year *a*) following the incident and the full restoration year (e.g. Year *b*) are expected to be close to zero. After examining the effects of different recovery functions on the estimations of lost services we found that the lost service estimations are not sensitive to the choice of recovery function, as long as the recovery time is not exceeding 10 years.

When the injury is primarily to one certain type of natural good like an animal population the above formula for the lost economic value can be simplified as,

$$L = \sum_{t=1}^{average-life} \left(\frac{1}{1+d}\right)^{t} \qquad (2)$$

where *L* counts the lost animal-years with an average life expectance of the species. The lost value (*V*) of a specific habitat/ population affected by the incident is:

$$V = M \cdot Q \cdot L \qquad (3)$$

where *M* denotes the monetary value of the injured natural good per unit resource and year; *Q* the total amount of units injured resource and *L* the lost service-years. Often, a multitude of resources is damaged by the released oil or chemical, so that the total value lost (*TV*) has to be estimated through aggregating individual losses related to each resource,

$$T = \sum_{i=1}^{n} V_i = \sum_{i=1}^{n} M_i \cdot Q_i \cdot L_i \qquad (4)$$

It is not straightforward to evaluate M_i since most of environmental goods or services are non-market. The lack of a market for them does not mean they have no value. After a thorough literature review over 100 studies in which various valuation methods, stated values and natural capital are involved, Costanza et al. [5] listed first numbers for each ecosystem and biome. For example, the total value of wetlands was estimated conservatively to be \$14,785/ha/year while the value of the entire biosphere falls in the range of \$16-54 trillion (10^{12}) per year.

Generally, there are two key ways for decision makers to get the unit value of non-market resources as described in great detail in the next paragraphs. First, one can measure it through direct or indirect economic means, or, secondly, one can transfer an estimated value from past studies.

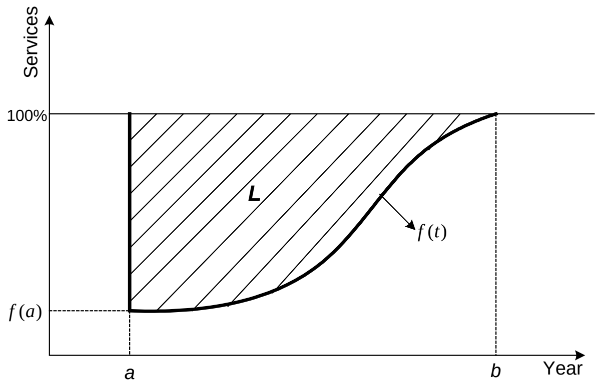


Fig. D-1. Time integral over lost services (*L*). a is the first year following the incident and b is the year when the injured habitat is fully recovered. *f(t)* is the recovery function of the injured habitat

In order to measure the value of natural resources, economists either link them indirectly to some market goods or observed economic activities or construct directly a hypothetical market in which people can be asked to pay for those resources. These valuation methods include, for example, the travel cost method, the hedonic price method or the contingent valuation method [6-9]. According to methodological differences these valuation methods can be classified into four categories [10], as shown in Fig. D-2, i.e. the constructed market valuation methods, surrogate market valuation methods, market oriented valuation methods and cost based valuation methods. The estimates derived from the first three groups emphasize losses of value based on the people's willingness to pay (WTP) in a real or hypothetical market. Here the value refers to either use value or the sum of use and non-use values. A total economic value of environmental resources should include both types of values. Although only the constructed market valuation methods allow people to measure the non-use value of environmental goods, they are criticized for being too speculative and, in some cases, for overstating damages [11]. Compared with the constructed market valuation methods, the estimations derived from the surrogate market valuation methods are more reliable, since this category of methods relate some non-market environmental services to observed economic behaviours such as the selling price of houses and the travel costs to an asset. In case of observed activities, only use values can be measured, because observed activities for non-use values are missing. The application scope of the market price method is strictly limited to a subset of environmental goods such as fish and timber having a price in the real market. In contrast to the above valuation methods, the group of cost based valuation methods focuses on the cost of restoration actions, which will generate an equivalent value to compensate the loss of use of the injured resources. Their estimated costs often refer to the lower bound of the economic value of the environmental capital. Currently, this group of methods are considered as the habitat equivalency analysis and have a higher acceptance in the NOAA's program, since their estimations rely on the physical projects rather than values generated by interviews of the public [11, 12]. Obviously, the estimates derived from each category will not be identical. A general ordering among them reads as follows,

$$Estimate^{CMVM} > Estimate^{SMVM} > Estimate^{MOVM} > Estimate^{CBVM} \quad (5)$$

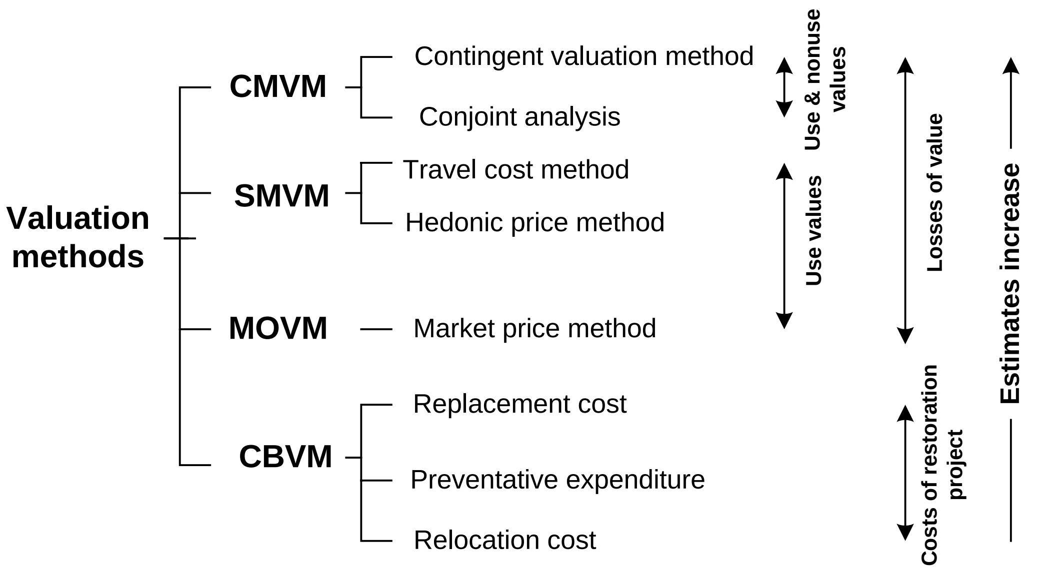


Fig. D-2. Overview over constructed market (CMVM), surrogate market (SMVM), market oriented (MOVM) and cost based valuation methods (CBVM)

However, using any valuation method costs time, money and other resources itself. Moreover, decision makers are forced to make responses immediately when facing an oil spill. In such instances, a benefit transfer method is suggested where information on the same or similar goods obtained from a previous study is used. This transformation from existing studies can then be integrated in the calculation of the lost values of affected resources (Eq. 4). Although the benefit transfer method is an efficient approach to reduce costs arising from an environmental valuation [13], one should be cautious when the unit value is transferred across sites as well as over time [14, 15].

2.2 Socio-economic losses

Coastal or marine pollution after an oil spill concerns several groups of economic users such as fishermen and hotel owners, all suffering from monetary losses. Generally, such losses consist of income losses and property damages. Both of these issues contribute to an integral part of the third party claims in an admissible compensation scheme. The income losses take damages from various economic sectors such as fishery and tourism into account. Like the injured natural resource, the affected economic sectors also need time to recover from the spill. Their economic losses (*EL*) are the sum of foregone incomes during the recovery period:

$$EL = \sum_{i=1}^{n} yr_i \cdot \sum_{m=0}^{p_i} (1 - f_i(m)) \cdot \left(\frac{1}{1+d}\right)^m \qquad (6)$$

where yr_i is the yearly revenue for economic sector ***i***, $f_i(m)$ the service in percent provided by the affected sector i at the m^{th} year following the incident, d a yearly discount rate and p_i quantifies the required period in years for a full recovery.

The property damage can be estimated simply by adding up all costs of repairing or cleaning facilities including vessels,

$$PD = \sum_{j=1}^{n} up_j \cdot Num_j \qquad (7)$$

where up_j is the unit price for property type j and Num_j the total abundance of damaged properties of type j.

2.3 Removal, research and other cost categories

Except for the above two main cost categories, the total oil spill costs still consist of clean-up costs, research costs and other costs. The clean-up costs cover the removal of oil from the sea, coastal waters and shorelines as well as the disposal of collected oil waste. A number of studies have shown that the clean-up costs are strongly influenced by the geographical spill location, clean-up method employed, spill size, oil type and shoreline oiling [16-20]. Based on these factors and an analysis of clean-up cost data in the International Oil Spill Database recording 8600 oil spills worldwide, a per-unit clean-up cost model was presented by Etkin [16] which can be directly used for a pre-estimation. Research costs include the expenditures for natural resource damage assessment, as well as the costs for the investigation and monitoring of affected areas. There is no study that takes the research costs as an independent cost category into account. However, in terms of a large oil spill such as the Exxon Valdez, it was observed that a large amount of money flowed into research activities. The ignorance of research costs is partly due to the fact that relatively few environmental damage assessments have been conducted for historical spill cases [1]. In addition, research activities are rare in case of the more regular small spills. So far only for two accidents research costs are known. For the Prestige spill off the Galician coast in 2002, an upper estimate is about €10 million [21]. This number turns out to be small compared to the $250-270 million spent after the accident of Exxon Valdez where even less oil was released [21]. As a consequence, the financial support of research in the Prestige case has been criticized by many experts as a known management error.

Additionally, as the fifth category other costs focus on sometimes rather specific circumstances such as lost combat cargo and vessels, or repairs and facility improvements for future prevention of spills [1]. According to 48 cases presented in the work by Helton and Penn [1], this category cost ranges from $147 to $16758 per ton and a mean value is estimated approximately $2058/ton.

2.4 Validation of estimated costs

One major benefit of the estimation models mentioned above is that they can be used immediately when an oil spill occurs. However, as the models are based on empirical studies and case histories, their reliability and accuracy remains always questionable. To validate their estimations, we suggest to (i) collect a wide range of claims to provide accurate information and update estimations, (ii) focus on the cost of restoring activity to offset resource loss and degradation, if possible, (ii) make a consensus on a set of key issues such as the selection of economic valuation methods and the determination of recovery periods required by injured resource among parties involved, (iv) keep estimations rather conservative and (v) to compare the results with actual measurements within a subsequent analysis.

3. Admissible claims

Responsible parties consist of the tanker owner, insurance companies and oil receivers. Only admissible claims are taken into account to be compensated, although various claims are collected and sent to the responsible parties. A detail breakdown of admissible claims can be seen in Fig. D-3, where third party claims, preventive measures and natural resources damages form the three main components. Moreover, Fig. D-3 describes the relationship between the total oil spill costs and admissible claims. Hence, other costs together with the socio-economic losses contribute to the third party claims. Clean-up costs are also incorporated in the broader pool of admissible claims. Theoretically, natural resource damages as part of admissible claims cover environmental damages as well as their assessment costs. For the historical sequence of spills, however, fewer than 1% contained natural resource damage assessment [1]. So far the monitoring and investigation costs of the affected resources are not mentioned in the context of admissible claims at all. This gap unfortunately harms the local communities' welfare, once these expenditures are relatively high.

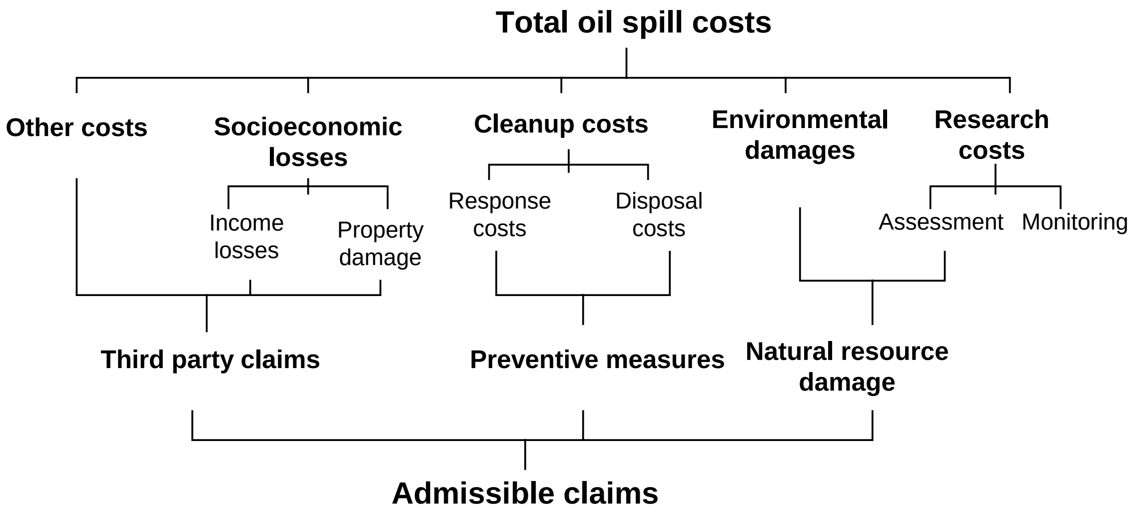


Fig. D-3. Total oil spill costs and admissible claims

In addition, admissible claims may not be paid in full since the total compensation including the amount paid by the 1992 Civil Liability Convention (CLC) is limited up to $189 million according to the 1992 Fund. Therefore, both of the 1992 Fund and CLC, although being highly effective to cover a majority of spills (e.g. small spills), fail to deal with large spills.

Similar conclusions were presented by Wren [22] following the Braer and Sea Empress oil tanker pollution incidents in UK. Here we further examine this point by a more recent case study, the Prestige spill.

4. The Prestige accident

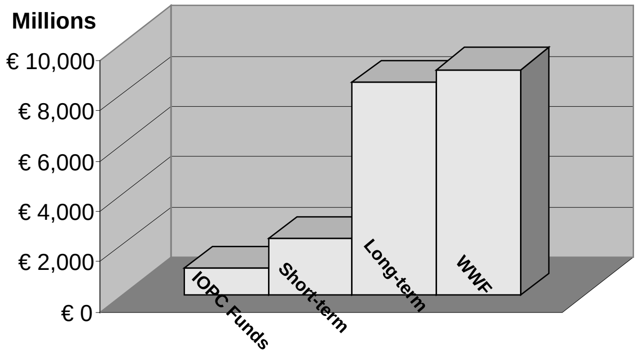
On 13 November 2002 the tanker Prestige with a load of 77000 tons of heavy fuel, broke in two off the Spanish coast. This disaster caused an immense amount of damages on the local marine environment [23]: (i) Totally 38,000 tons fuel oil were released offshore, (ii) 750 beaches along 2890 km affected, (iii) 200,000 birds and some 200 cetaceans, seals and marine turtles killed, (iv) 2000 off-shore fishing boats hit by the crisis and (v) the entire regional fishery was closed during 4 months. Other damaged economic sectors in Galicia comprise mariculture, tourism and port transportation, respectively. By using the models introduced in Section 2.1 and 2.2, it is estimated that the environmental damages cost conservatively €603.6 million and the income losses of damaged economic sectors range from €633.58 million (short-term) to €6734.4 million (long-term). The detailed calculations for these damages can be seen in Appendix. Together with the clean-up costs (€1000 million[4]), the research costs (€10 millions[5]) and €0.51 million of other costs[6], the overall costs for the Prestige is hindcasted to approximately €2250 million in short-term, and €8500 million in the long-term as shown in the left diagram of Fig. D-4. Our results are consistent with the range from a conservative estimation of €1100 million by IOPC Funds (2005) to a maximum of €9000 million given by the WWF [23]. All these amounts far exceed available payments. In the Prestige case, totally €172 millions are paid from the 1992 Fund and CLC [24] so that only 2% of the total oil spill costs are covered (see right diagram of Figure 4), with a comparison of the long-term economic effects. Society at large has, thus, to pay 98% of the estimated debit.

5. Discussions

A key parameter for calculating environmental damages is the unit value of injured services. A fundamental assumption in calculating the natural resource damages is to take this unit

[4] IOPC Funds 2005
[5] WWF 2003b
[6] A conservative approximation according to investigation from Helton and Penn (1999)

value as a constant [2] what, however, is more likely to hold for a human-made, substitutable good. Many natural resources, in contrast, are deemed to be non-substitutable so that the increased scarcity of the injured habitat will significantly increase the respective unit value [3].



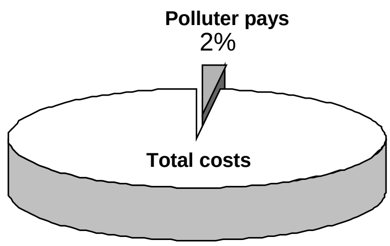


Fig. D-4. Left: Cost estimations of the Prestige oil spill. Right: Fraction of costs paid by the responsible parties in the Prestige case

Previously, responsible parties were taken granted as polluters. But local authorities' negligence may worsen the situation. For example, Spanish port authorities refused to the tanker "Prestige" an access to their port whereupon the disaster took its devastating trajectory [25]. Thus, local authorities as should in cases of serious negligence also be treated as a responsible party or indirect polluters, respectively. According to a new regulation decided by the European Parliament and the EU countries, they indeed will be charged a maximum penalty of €1.5 million besides imprisonment [25].

The research cost is suggested to be included as an independent cost category into the overall costs of an oil spill, since it tends to be costly based on observations associated with large spills. In addition, for a large and expensive spill, society at large has to bear a majority of total spill costs, due to the limitation of responsible parties or management errors made by local authorities or both. This point of view is supported again through the case of Prestige.

In the evaluation of environmental damages caused by the Prestige, only three types of injured resources are in general considered: beaches, birds and seals. However, these goods only represent a part of the affected resources. Other habitats such as deep-sea waters, continental shelf, marine vegetation and coastal waters should also be taken into account. Additionally, in the calculation of short-term estimation of socio-economic losses for the Prestige, for simplicity the averaged monthly revenue for each economic sector is used, while the seasonal effect on the monthly revenue is significant for some economic sectors such as for tourism with a much higher income in summer. Thus, an accident that takes place in winter may cause less damage for the regional economy than in summer time.

Despite the strengthening of counteracting environmental programs and policies no significant decrease in the number of accidents and oil spills can be observed in the European Atlantic [26]. Large spills like the Erika and the Prestige still occur at irregular intervals. The overall costs of those large spills not only put a big debit to the local public but also threaten viability of responsible parties. Therefore an emergency management of oil spills integrating economic and ecological sensitivities is of critical importance, in particular at coastal areas near to shipping routes which are most at risk.

Generally speaking, a suitable decision making-tool should allow an operational incorporation of environmental impacts of oil pollutions. This requires beforehand preparations including an integrated research programme linking natural resource with economic sciences. Consequences after the release of oil or chemicals into the marine environmental are not only complex, affected natural resources may also be measured with different indicators. For example, dead animals may be accounted by numbers killed or in units of polluted breading/feeding area. These indicators may not be compatible. The benefit of the environmental damage assessment model lays in breaking the array of impacts down to a single dimension, a monetary value [27]. Meanwhile, this modelling approach introduces and establishes environmental damages into decision making processes. Compared with a multi-criteria analysis, the model proposed here has two key advantages. On the one hand it provides a quantitative analysis for environmental consequences of different combat strategies for an oil spill in an intuitive way (i.e. money), which can be compared with other cost categories; on the other hand, it supports the Cost Benefit Analysis (CBA) to further identify the cost effective improvements of combat facilities. Despite these cons, this model requires high effort in compiling a *priori* information. Also sometimes, non-use values of environmental goods are quite controversial as in particular, the scarcity of injured resource increases. Therefore, we suggest that a combination of multi-criteria analysis with economic evaluation yields a practicable and more sustainable basis for oil spill contingency management.

6. Conclusions

In the context of the total costs after the release of an oil spill, five different major cost categories are addressed. As a major gap of previous analyses, here also research costs are included. The basic element of the evaluation model proposed here is to quantify the natural resource damage in monetary values. Such an economic evaluation is useful to (i) inform the public about the lost values of the destroyed habitats in an intuitive way, (ii) to help managers develop and follow an economically as well as environmentally sound combat strategy, (iii) to provide a basis for a cost benefit analysis for potential improvements, e.g. in terms of additional combat facilities. In future applications, we intend to evaluate a set of different combat options developed by using a simulation tool of OSCAR (Oil Spill Contingency and Response) for a hypothetical oil spill based on the Pallas incident 1998 Germany.

This paper also examines the relationship between the total oil spill cost and its admissible claims leading to two major findings: (i) admissible claims do not cover the overall costs of the oil spill as research costs are neglected, and (ii) admissible claims can not be fully compensated in the case of large spills.

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Appendix

Table 1. Environmental damages

		Injured habitat/animal		
		Beach	Bird	Seal
Quantity		2890km	200,000	200
Unit price		€70/m/y	€20/bird/y	€200/seal/y
Lost service by year	2003	100%	100%	100%
	2004	80%	100%	100%
	2005	60%	100%	100%
	2006	40%	100%	100%
	2007	20%	100%	100%
	2008	0%	0%	100%
	2009-2012			100%
	2013			0%
Aggregate, discount losses (€ million)		583.84	18.87	0.35
Total (€ million)		603.06		

Table 2. Short-term socio-economic losses

		Damaged economic sector			
		Fishery[8]	Mariculture	Tourism	Transportation
Monthly revenue[7] (€ million)		29.2	13.7	143.1	2.7
Lost service by month	Jan. 2003	100%	90%	90%	60%
	Feb. 2003	100%	75%	75%	50%
	Mar. 2003	100%	60%	60%	40%
	Apr. 2003	100%	45%	45%	30%
	May.2003	40%	30%	30%	20%
	Jun. 2003	20%	15%	15%	10%
	Jul. 2003	0%	0%	0%	0%
Aggregate losses (€ million)		134.17	43.05	450.71	5.65
Total (€ million)		633.58			

Table 3. Long-term socio-economic losses

		Damaged economic sector			
		Fishery	Mariculture	Tourism	Transportation
Yearly revenue[9] (€ million)		350	164	1717	32.3
Lost service by year	2003	90%	90%	90%	60%
	2004	75%	75%	75%	40%
	2005	60%	65%	60%	20%
	2006	45%	45%	45%	0%
	2007	30%	30%	30%	0%
	2008	15%	15%	15%	0%
	2009	0%	0%	0%	0%
Aggregate, discount losses (€ million)		1050.5	492.25	5153.6	38.01
Total (€ million)		6734.4			

[7] *an averaged value: yearly revenue divided by 12*
[8] *fisheries are closed during 4 months*
[9] *Sources:*
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Part E: Willingness to Pay among Households to Prevent Coastal Resources from Polluting by Oil Spills: A Pilot Survey*

Abstract

In many coastal regions, oil spills can be considered one of the most important and certainly the most noticeable forms of marine pollution. Efficient contingency management responding to oil spills on waters aiming at minimizing pollution effects on coastal resources turns out to be critically important. Such decision making highly depends on the importance attributed to different coastal economic and ecological resources. While economic uses can, in principal, be addressed by standard measures such as value added. Due to a missing of market in the real world for natural goods, they cannot be directly measured in money terms what increases the risk of being neglected in decision making. This paper evaluates these natural goods in a hypothetical market by using stated choice experiments. Oil spill management practice in German North Sea is used as an example. Results from a pilot survey show that during a combat process, beaches and eider ducks are of key concerns for households. An environmental friendly combat option has to come to a minor cost for households. Moreover, households with less children, higher monthly income and a membership of environmental organization are more likely to state they are willing to pay for combat option. Despite that choice experiments require knowledge of designing questionnaire, statistical skills to deal with discrete choices and cost time for conducting a survey, such a method can offer useful information for decision makers to find cost effective combat strategy, also has wide application potential in the field of Integrated Coastal Zone Management.

Keywords: oil spill; contingency management; choice experiments; Willingness to pay; coastal resources

1. Introduction

In practice to reduce greenhouse gas emission, offshore wind energy (OWE) has been operated in coastal oceans and seas surrounding Europe for a while time. The German

* Submitted.

government has set the substantial target of installation of 20,000 to 25,000 MW of offshore capacity by 2030. Despite many ideal characteristics of OWE, it increases the risk of oil spill due to ship collision with offshore wind farms. Oil spills can be considered one of the most important and certainly the most noticeable forms of marine pollution. Contingency management thus aims to simply keep the drifting oil away from sensible coastal areas. Due to the complex dynamics of the physical system in the coastal zone and the different ecological and economic values of coastal areas under risk, decision making during the oil spill response planning becomes a difficult task (Liu and Wirtz, 2005). A contingency management including the use of available combat vessels and facilities may create optimal conditions to prevent environmental goods from being polluted. The prevention is often taken granted as essential benefits of the particular combat strategy so that the need to assess these benefits has risen on public agendas. As an efficient combat strategy can be characterized by minimizing its response costs on seas and maximizing its benefits to society, yet little is known about how much households are willing to pay for a set of environmental goods. Due to a missing market, quantification in monetary terms is hard, implying a risk of their negligence during decision making. Often, a contingent valuation method (CVM), only part of the class of stated preference approaches, is proposed to estimate consumer's willingness to pay for non-market goods including environmental risk management. However, it is difficult to distinguish the value of each attribute of multi-attribute goods using CVM. For instance, the damage to natural resources caused by an oil spill includes a variety of effects on coastal waters, beaches, birds and so on. CVM can estimate the total value of protection from oil spills, but it cannot identify the value of avoiding each effect. Choice Experiments (CEs) as an alternative stated preference technique is capable of distinguishing the value of each attribute of multi-attribute goods. CEs is a structured technique where respondents have to choose their most preferred alternative from a set of alternatives. For environmental studies, CEs has recently been applied in forest (Horne et al., 2005; Rolfe et al., 2000; Lehtonen et al., 2003), wetland (Carlsson et al., 2003; Kuriyama, 1998), fishery (Wattage et al., 2005), waste management (Guikema, 2005; Garrod and Willis, 1998), water supply (Hanley et al., 2005; Haider and Rasid, 2002), hunting (Bullock et al., 1998; Boxall et al., 1996) and renewable energy (Álvarez-Farizo and Hanley, 2002). Although the number of CEs studies continues to increase, to our knowledge few have addressed oil spill contingency management at present.

In this paper, we use a series of stated choice experiments and random utility based Logit model to establish how much households are willing to pay for specific combat management scenario. Different levels of benefits and prices are specified in a number of experiments in order to provide a necessary variation with which the marginal utility of each benefit can be estimated.

2. Economic model

The random utility approach underlying the CE technique provides the theoretical underpinning for integrating choice behaviour with economic valuation. The random utility approach postulates that the utility of a choice alternative includes an explainable part as well as a random part. That is,

$$U_{ij} = V_{ij} + \varepsilon_{ij} \qquad (1)$$

where V_{ij} represents the measurable part of the unobserved utility (U_{ij}) of choice j held by consumer i, and ε_{ij} captures the unexplainable proportion of the utility associated with choice j and respondent i.

The observed utility, as in the following application, is formally a function of all attributes in the choice j and demographic characteristics of respondent i. A common specification of this function is linear in parameters,

$$V_{ij} = \alpha + \sum \beta_m X_{m,j} + \gamma C_j + \sum \theta_n S_{n,i} \qquad (2)$$

where α, β, γ and θ are parameters to be estimated through maximum likelihood method. $X_{m,j}$ is the m^{th} environmental attribute related to choice j, C_j denotes the cost of choice j and $S_{n,j}$ refers to the n^{th} demographic factor represented by respondent i. Selection of one choicee over another implies that the utility held by that choice is greater than the utility of the other. The probability of choosing choice j is:

$$\Pr\{j \ is \ selected\} = \Pr\{U_{ij} > U_{ik} \ \forall j \neq k\} \qquad (3)$$

In a multinomial Logit model the random part ε_{ij} is assumed to be independently and identically distributed (IID). Thus, the probability of a choice j from a choice set consisting of p choices has a closed form as follows,

$$\Pr\{j \ is \ selected\} = \frac{\exp(V_{ij})}{\sum_{k=1}^{p} \exp(V_{ik})} \qquad (4)$$

Individual *i*'s maximal willingness to pay (WTP) for option *j*, C_j^*, is defined as the payment that just makes an individual indifferent between the choice *j* and status quo. Algebraically, it can be expressed as:

$$V(X_j, C_j^*, S_i) = V(X_k, C_k, S_i) \qquad (5)$$

Hence, a marginal WTP (*mWTP*) value of a change within a single attribute *m* can be represented as a ratio of coefficients as follows,

$$mWTP_m = -\frac{\beta_m}{\gamma} \qquad (6)$$

This part-worth formula provides effectively the marginal rate of substitution between cost change and the attribute in question (Bennett and Blamey, 2001). A relative difference of willingness to pay (ΔWTP) associated with all environmental changes between two choice's profiles can be given by,

$$\Delta WTP_{j,k} = -\left(\frac{\sum \beta_m (X_{m,j} - X_{m,k})}{\gamma}\right) \qquad (7)$$

ΔWTP quantifies the environmental variation between two different choices in money terms and is here used to elicit preferences for different levels of environmental variation involved in a management option.

3. An application to oil spill combat options

To assess values that Germans might hold for coastal resources prevented from oil pollution, a questionnaire was designed and followed by a pilot survey. The questionnaire can be divided into three parts: attitudinal and behaviour, evaluation and demographic parts. Through a set of questions in the first part, respondents are warmed up and the third part will record respondents' socio-economic characteristics. The evaluation part designing CEs in a context of a hypothetical oil accident at the German Bight, 2007, consists of a number of attributes. Generally, employing combat may decrease coastal pollution and increase response costs on the other hand. To address these benefits and costs, five key attributes are employed as indicators of combat management. These attributes include three different types of natural goods, the oil collection ratio during the combat and finally, yearly payments required for the using of combat strategy. For simplicity, only coastal waters, beaches and eider ducks are concerned as main natural goods suffering from oil spills. All but one attribute (e.g. the payment) are assigned with 2 levels, respectively. The payment attribute was spilt into 4 levels. The combinations of these levels were used to build choice profiles to be presented to the respondents. Selected attributes and levels are presented in Table E-1 forming an array of 64 ($4*2^4$) possible profiles. To create choice sets in an efficient way, an experiment design process was used to select 8 out of 64 profiles. These eight profiles together with a status quo represent 8 choice sets. Each choice set consists of two combat options, the status quo together with an alternative option. For an example choice set see the Appendix. From a pretest of the questionnaire, we found, in order not to frustrate volunteers addressed by our study, firstly the length of questionnaire should be kept as short as possible; secondly, the number of profiles to be compared in each choice set should not exceed 3 and the total number of choice sets is limited up to 10; thirdly, a graphical design should help respondents understand questions at first glance.

Table E-1. Attributes and levels used in the choice experiments

Attribute	Level	
Coastal waters	200 km^2 130 km^2	avoided from oil pollution
Beaches	80km 30km	avoided from oil pollution
Eider ducks	15000 5000	birds avoided from oil pollution
Collect ratio	50% 25%	of spilled oil to be collected by combat vessels
Yearly payment	€150 €50 €20 €0	

4. Results and Discussions

For the experiment reported here, a pilot survey within Oldenburg University, Germany was conducted by the working group IMPULSE. Totally 80 people including students and staffs are randomly contacted in the campus. However, only 35 respondents completed the survey (43%). Each respondent answered 8 choice sets, giving a total of 280 observations among which costly combat option is chosen 182 times. These results may be explained that either respondents tend to exaggerate or yearly payments set in the alternative combat option are conceived as relatively low, or both. Information from attitudinal and behaviour questions indicated that while Germans were aware of oil spill issues in general, there was little to suggest that they had specific knowledge and concern about oil spill contingency management. A binary Logit model calculation in which significant demographic characteristics are included is performed by the software of Eviews®. The Logit model outcomes are presented in Table E-2. All signs of attributes in the model are expected a priori indicating whether utility has been increased or decreased. All attributes except of water are statistically significant in the model at conventional levels. The overall fit of the model as measured by McFadden's ρ^2 also meets standards for probabilistic discrete choice models (Ben-Akiva and Lerman, 1985).

Table E-2. Results for the survey with a basic binary Logit model

Variable	Coefficient	|Z| statistic
Constant	-2.56**	1.99
Water	5.36E-3	1.22
Beach	1.19E-2*	1.85
Duck	1.17E-4***	3.69
Collect	2.07E-2*	1.69
Payment	-1.69E-2***	6.33
Child[10]	-4.96E-1***	2.57
Income[11]	4.52E-1**	1.99
Member[12]	1.70***	2.75
Log L = -142.67		
$\chi^2(8)$ =77.23 (significant at 0.00000 level)		
ρ^2 =0.213		

**** Statistically significant at the 1% level;*
*** Statistically significant at the 5% level;*
** Statistically significant at 10% level.*

Table E-3. Part-worth of environmentally related attributes

Attributes	**Part-worth**
Water	$-\beta_{water}/\beta_{payment} = 0.32$
Beach	$-\beta_{beaches}/\beta_{payment} = 0.70$
Duck	$-\beta_{duck}/\beta_{payment} = 6.92\text{E-}3$
Collect	$-\beta_{oil}/\beta_{payment} = 1.22$

[10] Continuous variable indicating the number of children in a household

[11] Category variable represents the household monthly income; 1=less than €2000; 2=€2001-4000; 3=€4001-€6000; 4=€6001-8000; 5=more than €8000 euros

[12] Dummy variable set equal to 1 if respondent is a member of any environmental organization; 0 otherwise

The coefficients reveal that households with less children, higher monthly income and a membership of environmental organization are more likely to prefer the alternative, more costly combat option. As shown in Figure 1, 71% households without children are willing to pay for the combat option, while only 47% households with one or more children choose the alternative combat option. Also the percentage of households saying “yes” for the alternative option increases as monthly income increases or if the respondent is a member of any environmental organization.

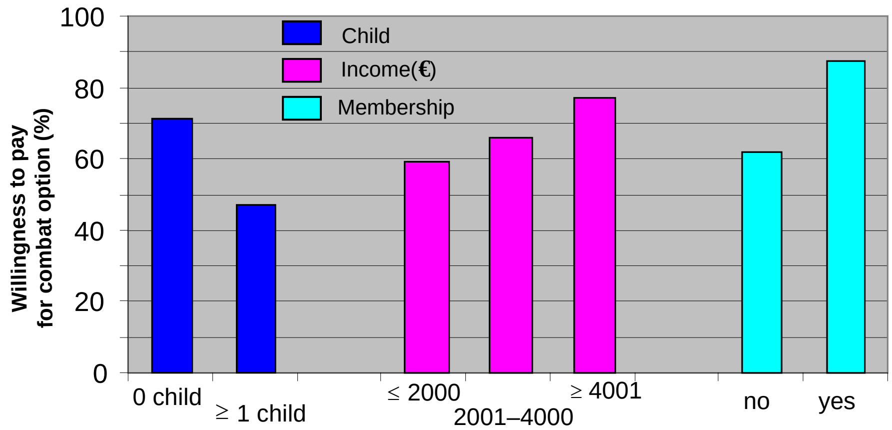


Fig. E-1. Effects of demographic characteristics of household on choice

Part-worthies can be generated for the continuous variables: waters, beaches, birds, oil collection as shown in Table E-3.

For example, the part-worth for beach reflects that each unit (1 km) increase in the length of beaches prevented from oil spill has a marginal value of €0.70 per household. The model can also be used to estimate value differences between any two profiles used in this study. For the two profiles presented in Appendix the differential WTP equals,

$$\Delta WTP = \frac{-\left[\beta_{water}\Delta water + \beta_{beach}\Delta beach + \beta_{bird}\Delta bird + \beta_{oil}\Delta oil\right]}{\beta_{payments}}$$

$$= \frac{-1}{-0.0169}\left[0.00536*(200-130) + 0.0119*(80-30) + 0.000117*(15000-5000) + 0.0207*(50-25)\right]$$

= € 157.3/household

Often, decision makers are forced to make responses immediately when facing an oil spill. In such instances, using CEs may cost time, especially when a larger sample is surveyed. Moreover, CEs require knowledge about designing of questionnaire and statistical skills to deal with discrete choices. Therefore, such a method is suggested to be conducted *ex ante* to collect possible information for future use.

It is impossible to directly ask people's WTP for one specific combat option, since they are unfamiliar with oil spill contingency management. Hence, attributes as indicators of combat management should be determined carefully to help people identify the difference between combat alternatives. Generally, they should be well known to people and their quality or quantity changes are plausible and well understood (Boxall et al., 1996).

According to a general aim of integrated coastal zone management (ICZM), environmental impacts should be introduced with a relative importance into a decision making process. Here, CEs taking economic values of environmental resources into account, break the environmental impacts in multiple dimensions down to a single dimension, a monetary value (Bräuer, 2003). The Benefit Cost Analysis (BCA) and the Multi-criteria analysis (MCA) are two widely used decision making tools in the approval of environmental management. Preferences elicited from CEs can be used in those analyses to help decision makers to find optimal combat option. For example, in the CBA they support the calculation of the Net Present Value (NPV) associated with combat management and may help to find a more cost effective combat management; they also constrain the weights of the importance between environmental resources used in the multi-criteria analysis. Undoubtedly, CEs will have wide application potential in the field of ICZM, as demonstrated by former studies (Wattage et al., 2005; Haekan and Bjoern, 2000) and the case of oil spill management in this paper.

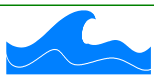
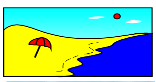
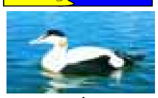
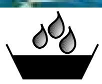
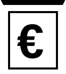
5. Conclusions

This paper describes and presents an empirical example of stated choice experiments for oil spill combat options with different levels of management attributes. It is designed to support ongoing discussions about the level of preparedness of coastal spill combat facilities, but also aims at analysing management preferences hold by the public. Future studies have to involve a broader spectrum of stakeholders what infers and even less robust statistics. Although our study is only a pilot survey involving a small number of households, which could lead to a biased result, it reveals how environmental and monetary attributes and household’s characteristics influence the support for different options. First, environmental attributes including beach, bird and oil collection ratio are proved to generate a significantly higher impact on the utility for the household than the attribute of sea water quality. Second, significant impact of the monetary attribute (e.g. the yearly extra payment) on the utility of household implies that an environmentally friendly combat option has to come to a minor cost for the household. Third, it is pointed out that households with less children, higher monthly income and a membership of environmental organization are more likely to prefer a more costly but environmental friendly scenario. The existence of such demographic trends, however, put severe constraints on the applicability of the choice experiments as one has to address a larger group of respondents than in our study in order to avoid a bias.

Overall, the coastal resources suffering from oil pollution can be measured appropriately by using the method of choice experiments. Results of the study have revealed that CEs provides essential information for evaluating combat option for oil spill management, also has wide application potential in the field of integrated coastal zone management.

Appendix

A sample choice set from the choice experiments. Pictograms represent the attributes sea water, beaches, birds (Eider ducks), oil removal and payment, respectively.

	Combat options	
Attributes	Alternative A	Alternative B
	**200km^2**	130km^2
	**80km**	30km
	**15000 birds**	5000 birds
	**50%**	25%
	**€50**	€0
I would prefer	❑	❑

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Part F: Evaluating oil spill response strategies economically: a case study of the Pallas accident in Germany*

Abstract

Oil spills are commonly considered as one of the worst forms of marine pollution. Often they constitute a challenge for an operational contingency management, since an oil spill contingency management encompasses multiple and often conflicting objectives and has to face various sources of uncertainty. Focusing on a well documented case, the Pallas oil spill in Germany, the selection of optimal strategy among others is formulated as a multi-criteria decision making problem that involves various environment, socio-economy and management related effects. These effects may not be directly comparable and compatible due to the fact that they are measured in multiple scales. To solve such a multi-criteria decision making problem, this paper proposes monetary evaluation models to assess performances of using different response strategies. Combined with the benefit cost analysis and the cost effectiveness analysis, this method enables to further determine the favored and rational strategy and the worthwhile investment of using combat facilities, respectively. Through the case of Pallas, such a proposed method is demonstrated as an important decision

1. Introduction

Oil spills are commonly considered as one of the worst forms of marine pollution, having serious impacts on coastal activities and marine life (Ventikos and Psaraftis, 2004). For instance, the oil tanker Exxon Valdez spilled an estimated 11 million gallons of crude oil across 1300 miles of coastal line in Alaska in 1989 (Williams and Olaniran, 1994), causing the damage estimated at 2,800 million Euros. In the case of Prestige, in the year of 2002, the costs in cleaning alone have amounted to 1 billion Euros. The response to an oil or chemical

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* In the proceedings of the Int. Conf. on Quantitative Methods for the Environmental Sciences (TIES), 2006. Beijing, China.

spill emergency in an effective way hence turns out to be an imminent concern in the domain of integrated coastal zone management (Douligeris et al., 1995; Galt, 1997).

The task of evaluating the response strategies is necessary but complex (Iakovou et al., 1997). Necessary because it help decision makers to select an optimal strategy which aims at lowering response costs and keeps the drifting oil away from sensible coastal areas (Liu and Wirtz, 2005). This task is also complex because it needs to consider both the environmental and socio-economic consequences following the using of proposed combat strategy for the oil spill. Conventional methods of multi-criteria analysis can be used as a decision support tool to deal with the data through a weighted linear aggregation (Almasri and Kaluarachchi, 2005). Often the environmental and socio-economic effects might not be directly comparable and compatible with each other due to the fact that they are measured in different metrics. In other words, the multi-criteria analysis is less favored if these effects are non-linearly related. Additionally, determining relative weights between effects is a subjective process and often requires a priori knowledge (Chen et al., 2004a; Brown et al., 2001). These and other issues of conventional multi-criteria analysis motivate seeking for alternative decision support techniques that are capable of integrating these effects in an effective way.

This paper proposes monetary evaluation models as a decision-making support tool for an oil spill contingency management. It focuses on the lost values of the injured environmental habitats and economic sectors affected by the accident. They integrate several stages as they are applied, one may

- select the least costly scenario by estimating the total oil spill costs which include environmental damages and socio-economic losses;
- determine the most efficient response strategy by using the benefit cost analysis;
- examine the worthiness of additional investments in the response strategies through the cost effectiveness analysis.

In particular, the political relevant question of investing into new oil combat ships will be addressed.

The paper is organized as follows: in Section 2, we simulate a hypothetical oil spill and various response strategies including the using of the combat vessels based on the Pallas accident. In Section 3, monetary evaluation method is described in great detail, in particular, its potential advantages in overcoming the above limitations of multi-criteria analysis. Finally, in Section 4, the performances of different combat strategies are evaluated by using the proposed method. Section 5 concludes the paper.

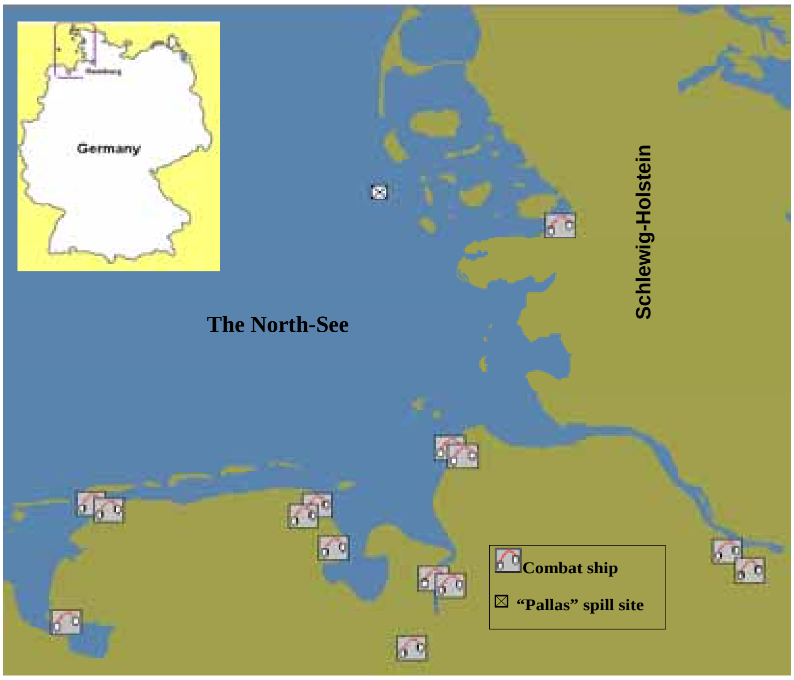

Fig. F-1. Germany North-Sea case study area. Totally, there exist 14 oil combat vessels distributed in selected coastal administrative districts along the German North-Sea area

2. The Pallas accident

On 28. Nov. 1998, the burning cargo Pallas stranded two nautical miles off the island Amrum in Schleswig-Holstein, Germany (Reineking, 1999). As a result of the Pallas, vast amounts of fuel oil through a tear in the damaged ship hull after the standing were released to the surface of the German North-Sea area, which has been declared as a major part of Wadden Sea PSSAs (Particularly Sensitive Sea Areas) within the framework of the International Maritime Organization (IMO) due to its ecological sensitivity, social, cultural, economic importance and scientific and educational purposes. For example, the PSSAs host important breeding populations of seabirds, seals, dolphins and other marine species and is also a particularly important touristic zone. Other nearby activities comprise fishery, transportation and some offshore wind farming practices. The yearly gross value of its economic productivity (over 125 billion) is among the highest in Germany, although the North-Sea coastal region in Germany shown in Fig. F-1 is small.

However, frequented shipping movements (e.g. 171.5 million tons of cargo were transferred in 1999) make this zone vulnerable to oil or chemical spills, as demonstrated by the ecological disaster caused by the Pallas oil spill. Over 20,000 birds, mainly Eider ducks are affected, which demonstrates that such an oil spill together with its long lived consequences poses one of the major episodic threats for near-shore ecosystems and the human use of the coastal areas. Approximately 7 million were used for clean-up and salvage following the accident. Referring to the Pallas case, a hypothetical oil spill, in which totally 60 tons of fuel oil is supposed to spill at the site where the Pallas occurred ($54^{o}32.5^{'}$N; $8^{o}17.24^{'}$E), is simulated by OSCAR (Oil Spill Contingency and Response), a model system developed by SINTEF, Norway (Reed et al., 1995a; Aamo et al., 1996; Reed et al., 2004; Daling et al., 1990). By using the actual information for wind and currents, OSCAR provides a 3-dimensional projections of the temporal evolution exhibited by the oil. In accordance with observations (Clausen, 2003), the affected area is in the simulation limited to the east part of the German North-Sea coast or, more specifically, the Schleswig-Holstein coastal area (see right graph in Fig. F-2). Obviously, a number of environmental resources and economic activities are threatened by an oil spill. With special attentions paid to oil pollution, six (e.g. three economic and three environmental related) criteria shown in the left diagram of Fig. F-2 are selected to be considered. They reflect existing interests as well as background information at the German North-Sea coast but may to a larger extend also reflect the situation in many other coastal regions around the world. For simplicity, the environmental damages are represented in terms of the injured beaches, polluted coastal waters and affected habitats of exemplary bird species. Here, the latter only refer to eider ducks, since November is the month with the highest number of this species (about 100,000 birds) in the Schleswig-Holstein coastal area (Reineking, 1999). The socio-economic losses include the cleanup costs (e.g. the costs for using the combat vessels and their facilities) and income losses of fishery and tourism. It is estimated that the yearly incomes for fishery and tourism amount to 160 million and 2.5 billion euros in this region, respectively (Lieberz and Ramos, 2003; Hagner, 2003). Geographical distributions of both human uses (mostly fishery and tourism) and natural breeding areas of eiders in the Schleswig-Holstein are highlighted in the right graph of Fig. F-2.

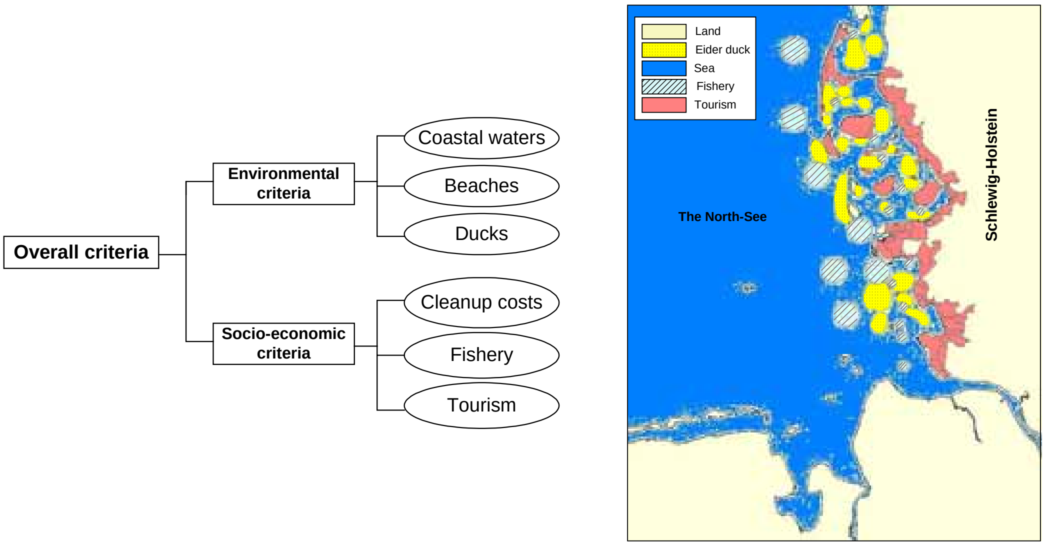

Fig. F-2. Criteria selected in the case study. Left: a hierarchy diagram of selected criteria. Right: geographic distribution of environmental habitats and human-use in the affected coastal areas

OSCAR provides a variety of scenarios and each scenario extrapolates the impacts of feasible response strategies based on available combat vessels (see Fig. F-1). Their characteristics and collection rules-of-thumb can be described by the model system in great detail. One major issue of the discussions in the aftermath of the accident was whether an appropriate number of response ship is in existence and, if yes, how many of these should have been used in the Pallas case. Thus, after a preliminary evaluation of these combat alternatives, five different combat alternatives were pre-defined such that they cover a reasonable spectrum of ship stocking. A description of the scenarios in which different combat alternatives are facilitated are summarized in Table F-1, which synthesizes the OSCAR results for each scenario in different respects (e.g. the performance matrix). In total, five combat vessels are used in the first response strategy (e.g. Alt.1). They are Neuwerk, Mellum, Westensee, Knechtsand and Norderhever. On the basis of Alt.1, the Alt.2, 3 and 4 has one more different combat vessel, respectively and the Alt.5 has only four combat vessels used in the Alt.1. Table F-2 details the five alternatives.

Table F-1. Performance matrix of scenarios of using different response strategies. Bold numbers indicate the minimal effects in terms of the specific criterion among the scenarios

	Scenarios				
	Sce.1	Sce.2	Sce.3	Sce.4	Sce.5
CC(€)	951,756(Alt.1)	1,101,615(Alt.2)	1,072,185(Alt.3)	1,047,811(Alt.4)	485,083(Alt.5)
B(km^2)	0.1074	0.0946	0.1047	0.0977	0.1205
CW(km^2)	0.1978	0.1707	0.1925	0.1815	0.2255
F(km^2)	0.0029	0.003	0.0032	0.0029	0.0036
T(km^2)	0.0034	0.0036	0.0036	0.0045	0.0043
D(birds)	156	133	148	141	174

Notes:CC(clean-up costs): the costs in Euros of using the combat vessels and their equipments; B(beaches): the covered beach area (km^2) by stranded oil; CW(coastal waters): the polluted coastal water in km^2 by oil; F(fishery): the polluted fishery area (km^2); T(tourism): the polluted tourism area (km^2) in main recreation area along the German North-see coastline; D(duck): summed amount of dead eider ducks.

Table F-2. Response strategies and their descriptions

Alternatives	#	Name of vessel
Alt.1	5	Neuwerk, Mellum, Knechtsand, Norderhever, Westensee
Alt.2	6	Neuwerk, Mellum, Knechtsand, Norderhever, Westensee, Nordsee
Alt.3	6	Neuwerk, Mellum, Knechtsand, Norderhever, Westensee, Eversand
Alt.4	6	Neuwerk, Mellum, Knechtsand, Norderhever, Westensee, Thor
Alt.5	4	Neuwerk, Mellum, Knechtsand, Norderhever

3. Estimating environmental and socio-economic damages

Conventional method of the multi-criteria analysis can be used to deal with the above performance matrix through a linearly weighted aggregation of the criteria in each scenario (wirtz et al., 2004; Wirtz et al., 2006). Due to the fact that the quantitative measurements in the performance matrix are expressed in multiple metrics, they are not easy to be directly comparable and compatible with each other. In other words, it is not suitable to integrate them through a linear aggregation, which is typically used in the multi-criteria analysis. Moreover, determining relative weights between criteria in the multi-criteria analysis is sometimes less favored, as it requires a priori estimate of relevance attributed to all the criteria. An efficient alternative is to evaluate all damages measured in non-monetary terms economically. Such a monetary evaluation, on the one hand, breaks complex pollution effects in multiple metrics down to a single value in money terms. On the other hand, it intuitively provides both the public and managers the effects of environmental problems by using money as an indicator.

3.1 Calculating environmental damages

Oil spills lead to a degradation of the nature resource since they decrease their services during the year following the incident. Fig. F-3.schematically illustrates the recovery path of a unit injured habitat over time. In the x^{th} year following the incident the damaged habitat is supposed to be able to provide only *f(x)*100%* of its previous services. Hence, the loss of services during the x^{th} year is *1-f(x)*100%*. Ultimately the habitat is completely recovered in the t^{th} year and generating again a full service. The total lost services due to the oil spill can be estimated as,

$$LS = \sum_{x=1}^{t} (1 - f(x))(\frac{1}{1+d})^{x-1} \qquad (1)$$

where *f(x)* is a time-dependent recovery function (Penn and Tomasi, 2002; French McCay and Rowe, 2003; Dunford et al., 2004) to describe the potential services, which the injured habitats could provide in the x^{th} year following the accident. The yearly discount rate d emphasizes the present service losses are more costly than the future ones. A recommended value of 0.03 is used in NOAA (1999). The lost value (*V*) of a specific habitat injured by the incident is:

$$V=M*Q*LS \qquad (2)$$

where *M* is the monetary value of one unit natural resource per year; *Q* gives the total units of an injured natural resource. When the injury is primarily to one certain type of animal, to estimate the lost economic value of dead animals, the above formula can be simplified to,

$$V_a = M_a * Q_a \qquad (3)$$

where M_a is the price per animal and Q_a is the total number of dead animals. Often a number of resources are damaged due to the oil spill, the total environmental value lost (*TEV*) is given by a simple sum,

$$TEV = \sum_{i=1}^{n} V_i = \sum_{i=1}^{n} M_i * Q_i * LS_i \qquad (4)$$

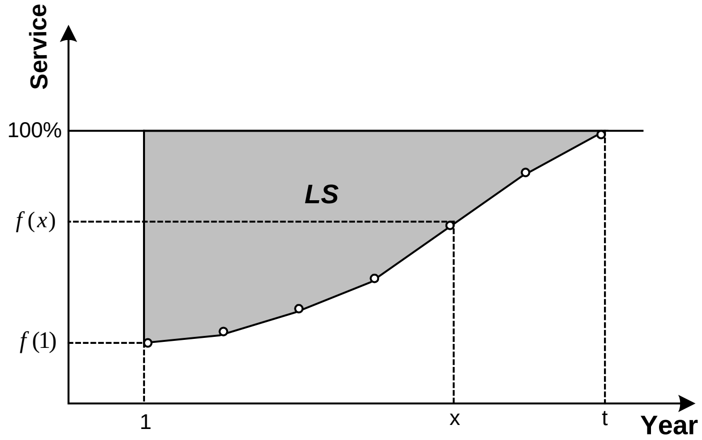

Fig. F-3. Lost services. *t* is the year when the injured habitat is fully recovered. *f(t)* is the service in percent provided by the injured habitat in the year *t*

3.2 Calculating socio-economic losses

Income losses are not avoidable when economic sectors such as the fishery and tourism are hit by the oil. Like the environmental resources, the injured economic sectors also needs time to recover. The socio-economic losses here focus on the aggregated and discounted income losses *IL* of different economic sectors over their recovery periods,

$$IL_i = YI * \frac{A_i}{TA_i} * \sum_{t=1}^{T_i} f_i(t)\left(\frac{1}{1+d}\right)^{t-1} \tag{5}$$

for a specific economic sector *i* and its yearly income *YI*, *A* and *TA* quantify the polluted area and the total area for the economic sector *i* in the affected region, respectively. $f_i(t)$ is its recovery function and T_i is the required recovery time span. The total socio-economic losses (*TIL*) is the sum of income losses from individual economic sector as follows,

$$TIL = \sum_{i=1}^{n} IL_i \tag{6}$$

An example to calculate damages due to the oil spill can be seen in Appendix.

4. Results and discussions

In this section, each scenario as the consequence of using the specific combat strategy to respond to the hypothetical accident is evaluated by the monetary evaluation method mentioned above. Two efforts are further done. One is related to investigation of the net present values for each of the combat alternatives to robustly differentiate the optimal and worst combat alternatives among others. The other aims to identify the worthiness of additional investments in the combat alternatives. In the following paragraphs, all of these will be addressed.

4.1 Total oil spill costs

In this present case study, the total oil spill costs (*TC*) consist of the environmental damages (*TEV*), economic income losses (*TIL*) and clean-up costs (*CC*),

$$TC=TEV+TIL+CC \tag{7}$$

Totally three assumptions are made when the monetary evaluation models are applied to estimate the total oil spill cost. (i) Recovery time required by both the injured habitat and economic sectors are pre-defined in three different periods: the short-term (e.g. 1 year), middle-term (e.g. 5 years) and long-term (e.g. 10 years). (ii) The unit price for beach and coastal waters is supposed to be 100/m^2/year and 30/m^2/year, respectively. With a consideration of both use and non-use values of environmental habitats, they often represent the lower bound of the economic value of those environmental capital. (iii) Value per Eider duck is varied within an interval between 30 to 300. Fig. F-4 presents an overview of clean-up costs and the total oil spill costs differentiated according to time horizon for each scenario. Generally, the total short-term costs are ranging from 7.8 million (e.g. Alt.2) to 8.8 million (e.g. Alt.5) and the long-term estimates between 62 million and 79 million. By comparing the total oil spill costs in different scenarios, it is evident that Sce.2 is the best case leading to least costly effects of the hypothetical spill. In contrast, Sce.5 with one ship lacking tends to be worse to effectively fight the oil spill under consideration as long as the effects of the spill becomes longer lived.

Obviously, the accuracy of the estimations depends highly on the assumptions made. Especially, the unit value for environmental goods remains questionable. In principle, they can be measured by economic valuation methods (Liu and Wirtz, 2004) or obtained through a transfer from previous studies in which the same or similar environmental habitat was evaluated (Ready et al., 2004; Rozan, 2004). Taking a conservative or less controversial value may guarantee the validity of the estimation results, whichever method is approached to obtain the value of environmental goods. Additionally, the cost estimation in a short-term scale in Fig. F-4 is merely somewhat sensitive to the manner in which the response strategy is defined. However, significant differences arise if more affected criteria are incorporated or a larger oil spill is given.

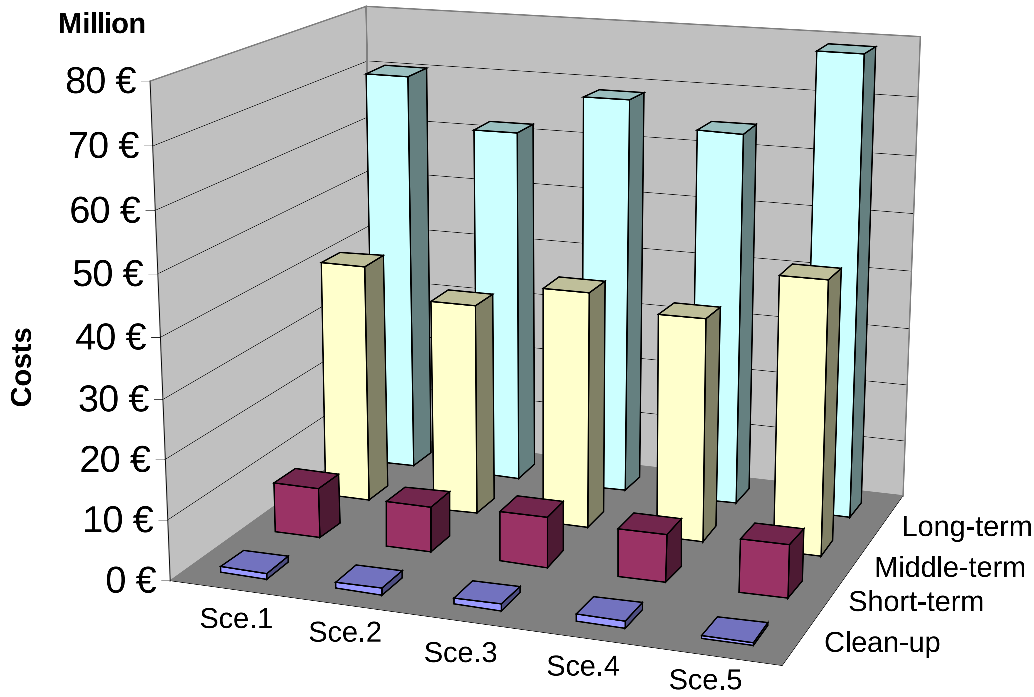

Fig. F-4. An overview of total oil spill costs in three different time terms and clean-up cost for each scenario

4.2 Benefit cost analysis

In order to determine the most effective response strategy, for each combat alternative a benefit cost analysis is applied. This analysis provides a net present value which denotes the difference between the benefit and cost of facilitating the specific combat alternative. Both benefit and cost require a frame of reference which is obtained by simulating the oil spill without any combat measures. Like the total oil spill cost estimated for each scenario in Section 4, such a reference scenario results in a different total oil spill cost TC_r for each time horizon. Therefore, the net present value of a specific combat alternative can be derived as,

$$NPV_j = TC_r - TC_j ;\ j = 1,2,\cdots,5 \qquad (8)$$

Fig. F-5 presents net present values in three different time terms for each combat alternative. The highest return in terms of net present value is revealed by the combat strategy based on the ship number given by Alt.2. Contrary, Alt.5 gives a lower net present value than other options. Such a conclusion is consistent with the rankings of scenarios mentioned in the previous subsection. Generally, benefits of facilitating response strategy are positively correlated with their costs. However, Alt.3 has lower net present values compared with Alt.4, although it induces higher clean-up costs. Thus, the application of the benefit cost analysis assists decision-makers to identify less rational strategies, which can the be further deleted from options or replaced by new strategies.

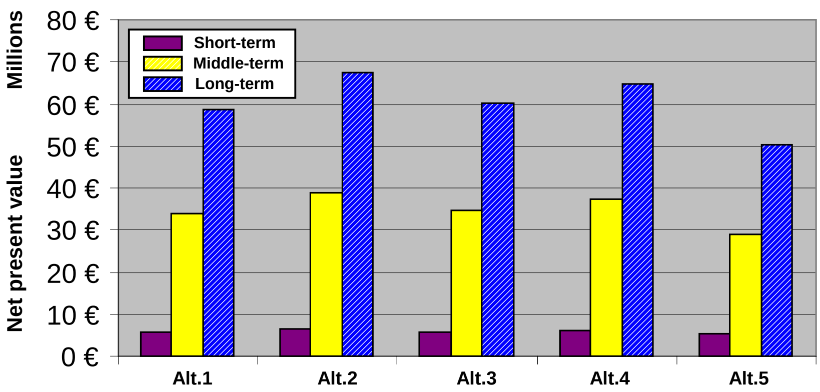

Fig. F-5. Net present values in different time terms for each combat alternative

4.3 Cost effectiveness analysis

Compared with the Alt.5, other alternatives spend different amounts of additional money for facilitating one or two more combat vessels. The worthiness of such investments can be examined by conducting the cost effectiveness analysis. One key issue in the cost effectiveness analysis is to determine the effective ratio $R_{j,k}$, which is a function of the marginal benefit $MB_{j,k}$ and cost $MC_{j,k}$ between the assessed alternative j and the target alternative k,

$$
\begin{cases}
MC_{j,k} = CC_j - CC_k \\
MB_{j,k} = NPV_j - NPV_k + MC_{j,k} \quad j \neq k \\
R_{j,k} = \dfrac{MB_{j,k}}{MC_{j,k}} = 1 + \dfrac{NPV_j - NPV_k}{CC_j - CC_k}
\end{cases}
\tag{9}
$$

In this case study Alt.5 is taken as the target alternative (e.g. k=5) so that $MB_{j,5}$ is the marginal benefit reflecting the pay-offs of additional investments into combat ships. A cost effectiveness ratio $R_{j,5}$ larger than 1 suggests that such investments are worthwhile compared with maintaining a status quo (e.g. Alt.5). As the hypothetical 60 tons of oil spilled falls into the category of small spillages, its possible effects tend to be short-term. As shown in Fig. F-6 additional investments for the combat vessels Westensee and Nordsee in Alt.2 are the most worthy, while Alt.1 and 3 (Westensee/Eversand) tend to be less effective.

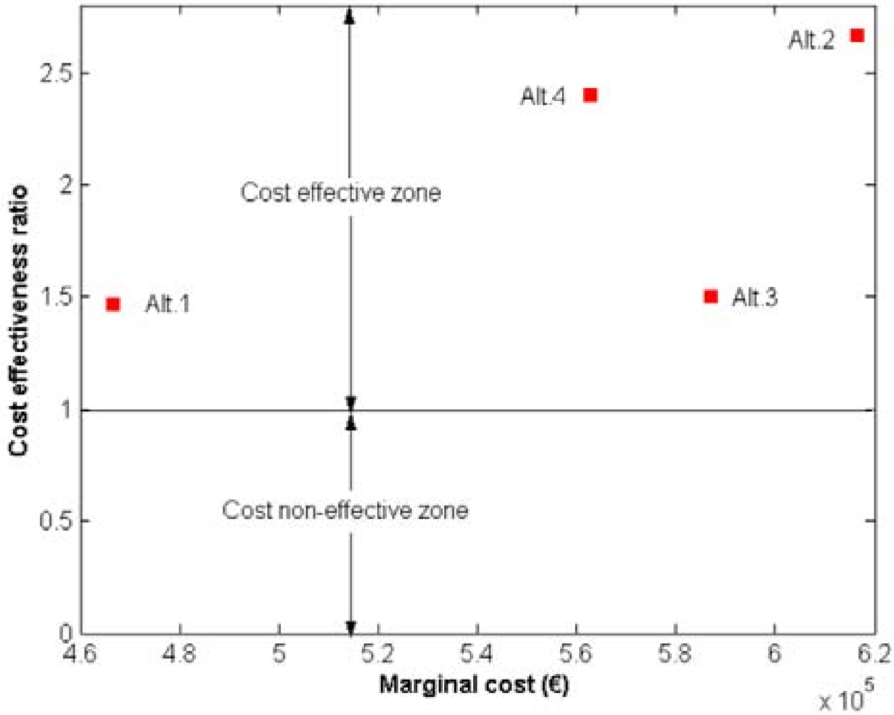

Fig. F-6. Cost effectiveness ration of Alt.1-4 in short-term based on comparisons with the target alternative (e.g., Alt.5)

This result is, of course, very case specific and has to be verified on the base of much more spill scenarios including a statistical coverage of different meteorological and hydrodynamic conditions.

5. Conclusions

Monetary evaluation model is here demonstrated here as an important decision-making support tool in the domain of coastal zone management. Five main findings of this study are outlined as follows,

- The proposed method breaks complex pollution effects in multiple metrics down to a single value in money terms, which allows the effects to be comparable and compatible directly (Braeuer, 2003).
- In contrast to the multi-criteria analysis, there is no involvement of the weights between the effects in such a monetary evaluation model.
- It intuitively provide both the public and managers the effects of environmental problems by using money as an indicator.
- Together with the benefit cost analysis, it helps decision-makers to identify the most favored and rational response strategy;
- A combination of such an approach with the cost effectiveness analysis provides possibilities to determine a worthwhile investment of using additional facilities in designing a response strategy.

Finally, the proposed evaluation method may have wider applications, in view of many multidisciplinary studies investigating environment-human interactions in the coastal zone (Chen et al., 2004b).

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Appendix

To illustrate how such monetary evaluation models might be applied practically, the environmental damages and the income losses are calculated for the scenario 1 shown in the following table in which both the injured environmental habitat and the damaged economic sectors are supposed to be linearly recovered over a period of 5 years. Due to the small footprint of the spill in the fishery and tourism areas, the income losses are estimated relatively low.

		Injured habita/animal		
		Beach	Water	Duck
Quantity		0.1074 km^2	0.1978 km^2	156 birds
Unit price		100/ m^2/y	30/ m^2/y	100/bird
Lost service by year	1999	100%	100%	
	2000	75%	75%	
	2001	50%	50%	
	2002	25%	25%	
	2003	0%	0%	
Aggregate, discount losses (€)		$26.08*10^6$	$14.41*10^6$	15,600
Total (€)			40,505,600	
		Income losses of economic sectors		
		Fishery		Tourism
Polluted area		0.0092 km^2		0.0034 km^2
Total area		377 km^2		600 km^2
Yearly income (million/y)		160		2500
Lost service by year	1999	80%		80%
	2000	60%		60%
	2001	40%		40%
	2002	20%		20%
	2003	0%		0%
Aggregate, discount losses (€)		2,989		34,399
Total (€)			37,388	

Notes: yearly discount rate is 0.03

Part G: Sequential negotiations in multi-agent system*

Abstract

Contingency management facing an imminent oil spill often is a difficult task as the long-term consequences of decisions generally affect the interests of different stakeholder groups including the broad public. We here suggest that a balanced response scheme can be achieved by integrating various interests within a virtual negotiation process. This paper compares three different negotiation protocols and designs a hybrid one where multiple issues including money compensation are traded by parties. Aiming to examine appropriate designs of this process in multi-agent systems, we simulate negotiations based on the Prestige oil spill response scenario. Experiment results show that this designed protocol may work as a robust conflict resolution mechanism for deriving a multi-agent consensus. Finally, by comparing two different rational strategies taken by agents, we add support to the view that learning techniques help agents to improve their payoffs in negotiations.

Keywords: oil spill, negotiation, multiagent system, decision making.

1. Building a win-win consensus

The most preferred alternative presented by each interested group is not yet the compromise alternative representing a consensus among stakeholders. The compromise alternatives can be searched further by a sequential negotiation in the multi-agent systems (e.g. stakeholders). For example, in Fig. G-1, the approach of negotiation in MAS can be coupled with any of the evaluation method. Firstly, by using any of evaluation methods, which occupy the angles of the triangle with a unique feature, stakeholders could select a set of alternatives as the most preferred options from all potentially possible solutions. Secondly, a sequential negotiation over multiple attributes including the response alternative and a compensation in money terms is carried out within these stakeholders. In order to persuade opponent stakeholders agree the preferred alternative, stakeholders intend to compensate opponents, which are forced make disadvantageous agreements. Finally, such a negotiation allowing the transfer of utility of stakeholders leads to individual rational and globally optimal solutions (kim et al., 2000).

* Marine Pollution Bulletin (50) 469-474.
The Built Environment (78) 113-121. WIT Press, UK.

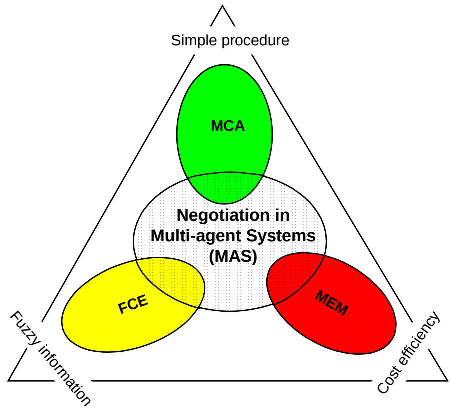

Fig. G-1. Negotiation technique and evaluation methods

In general, negotiation in MAS falls into two broad categories: competitive and cooperative bargaining, as also shown in Fig. G-2. In a competitive bargaining frame agents compete for maximizing their own local utility. Most cases in the commercial domain fit into this category, in which only one agent can win. According to different availabilities of information to the parties, competitive bargaining can be further classified into three subcategories: complete, one sided incomplete and two sided incomplete information.

Cooperative bargaining, on the other hand, is made with the objective to find a win-win condition for agents. A successful negotiation not only terminates with a deal, but also reaches a maximal combined utility of agents. A detailed review of approaches falling into this category was given in Li and Giampapa (2003).

Real disputes on environmental issues can be anticipated to evolve between competitive and cooperative negotiation. On the one hand, agents are characterized by self-interest to search for their maximal local utility and, thus, can not be coordinated simply by orders from a governmental authority; on the other hand, without cooperation agents can not finish individually a task affecting other parties like, for example, making a decision about resource allocation. Therefore, we propose that the negotiation on environmental decision making problem will be a cooperative bargaining with constraints.

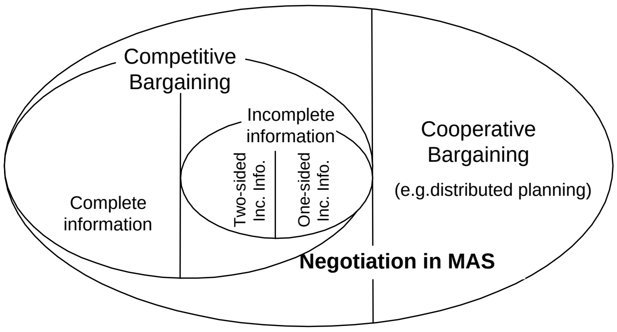

Fig. G-2. Overview of negotiation types in multiagent systems (MAS), adapted from Li and Giampapa (2003).

Continuing the work done by Wirtz et al. (2006), we here address the problem of finding a politically balanced relevance scheme with a multi-agent negotiation technique. The underlying idea is that a computerized negotiation technique will also stimulate social participation and lead to a better account of their interests by responsible authorities during and already before accidents. In the case study used here we focus on the problem of choosing an appropriate towing direction. When technically building an autonomous agent, which is capable of representing a realistic argumentation behavior in a negotiation process, the main components that should be considered comprise: (i) negotiation issues (ii), a negotiation protocol and (iii) a reasoning model of the trading agents (Mueller, 1996).

2. Negotiation issues

A central element of the approach we adopted is a negotiation over two attributes that was described as the multi-issue negotiation by Kurbel and Loutchko (2001). Negotiation issues can be a number of quantitative and qualitative items. In our work, one response action, i.e. the option of towing the spilling vessel into one of five predefined directions and a compensation in money terms are considered. Both issues contribute to the utility of agents. Kim et al. (2000) argued that allowing the transfer of utility for compensation lead to individual rational and globally optimal solutions. In order to persuade opponent agents agree the suggested proposal, agents intend to compensate opponents, which are forced to make disadvantageous agreement. In our case study of oil spill abatement, different towing directions result in different amount of oil stranded on coastal sub-areas with their specific ecological and/or economic value. Thus, each agent prefers a response action, which induces a minimal impact to the coastal area of his or her interest.

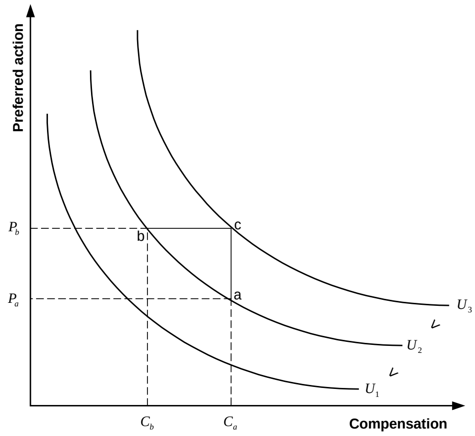

Fig. G-3. Multi-attribute utilities including the trade-off between action preference and compensation

Compensation provides an important means for the negotiating process. It facilitates the finding of compromises by making losses in the utility function more acceptable. Consequently, the combined utility for agents will increase without treating some other party worse. Fig. G-3 shows the relationship between negotiation issues and the utility. For example, let us suppose that the utility of agent B is U_2. Given that two different amounts of oil spilled in its interested area due to different towing options and P_b corresponds to a scenario with less pollution, P_b is preferred by agent B. In order to restore its previous utility of U_2, the agent will ask a compensation of C_b as the minimum willingness to accept (WTA) to tolerate such an amount of oil pollution. A second agent A may be more in favour of saving other coastal areas as feasible by option P_a. If the agent B agrees to select the option of P_a as the response of the oil spill, C_a would be the minimum WTA to keep its previous utility of U_2. Hence, the difference between C_a and C_b is the monetary compensation, which agent B asks to agent A in order to agree with action P_a. Let each attribute of the traded problem be quantified by the value a_j ranging from $\min_j$ to $\max_j$. For each agent the function $V_j(a_j) \in [0,1]$ describes the utility value of attribute *j*. Following Teuteberg and Kurbel (2002), the utility function which evaluates a specific negotiation issues is here defined as:

$$u_j(a_j) = \left[\frac{a_j - \min_j}{\max_j - \min_j} \right]^{\alpha} \qquad (1)$$

The parameter α determines the convexity of the utility function. A linear model is defined as $\alpha = 1$. Since simple psychological considerations agree with a decreasing trend of $\Delta u / \Delta a_j$ as a_j increases, a utility function convexity smaller than one ($\alpha < 1$) is likely. Moreover, it is realistic to assume that different agents may choose different convexity of their utility function. Table G-1 gives parameter values used in the following simulated experiments. The convexity reflects the importance of the negotiation issue for an agent's utility since a change of negotiation issue j has a more pronounced effect on the agent characterized by a higher value of α. The total utility over all issues is calculated through a weighted sum:

$$U_A = \sum_{j=1}^{2} w_j^A u_j^A \qquad (2)$$

where w_j^A describes the relative importance that agent A assigns to issue a_j (with $\sum_{j=1}^{2} w_j^A = 1$).

Table G-1. Parameter values in the negotiation process simulated in this study

Negotiation issue a_j	Utility function and parameters	
	Agent A	Agent B
Preferred towing action	$\alpha = 0.5$	$\alpha = 0.3$
Compensation	$\alpha = 0.7$	$\alpha = 0.5$

Each agent evaluates the five towing options and assigns a maximum willingness to pay ($M_{ax}WTP$) and a minimum willingness to accept ($M_{in}WTA$) in money terms for its most and least preferred towing option, respectively. Therefore, an agent's reserved utility base line is constructed on the basis of these items:

$$\begin{cases} base_A = w_1^A u_1^A (TO_{most}) + w_2^A u_2^A (-M_{ax}WTP) \\ base_A = w_1^A u_1^A (TO_{least}) + w_2^A u_2^A (+M_{in}WTA) \end{cases} \qquad (3)$$

where the most preferred towing option (TO_{most}) together with its $-M_{ax}WTP$ contributes to agent A's utility base line $base_A$, and the same definition is applied to the least preferred towing direction and its $M_{in}WTA$. There exists an agreement zone, if one agent's $M_{ax}WTP$ for a specific towing option (TO_j) is not less than its opponent's $M_{in}WTA$ (e.g.

$M_{ax}WTP_{TO_j}^{ag.A} \geq M_{in}WTA_{TO_j}^{ag.B}$ or $M_{ax}WTP_{TO_j}^{ag.B} \geq M_{in}WTA_{TO_j}^{ag.A}$). Otherwise, the agreement zone does not exist and a consensus can not be reached during the course of play, which leads to a failure of negotiation.

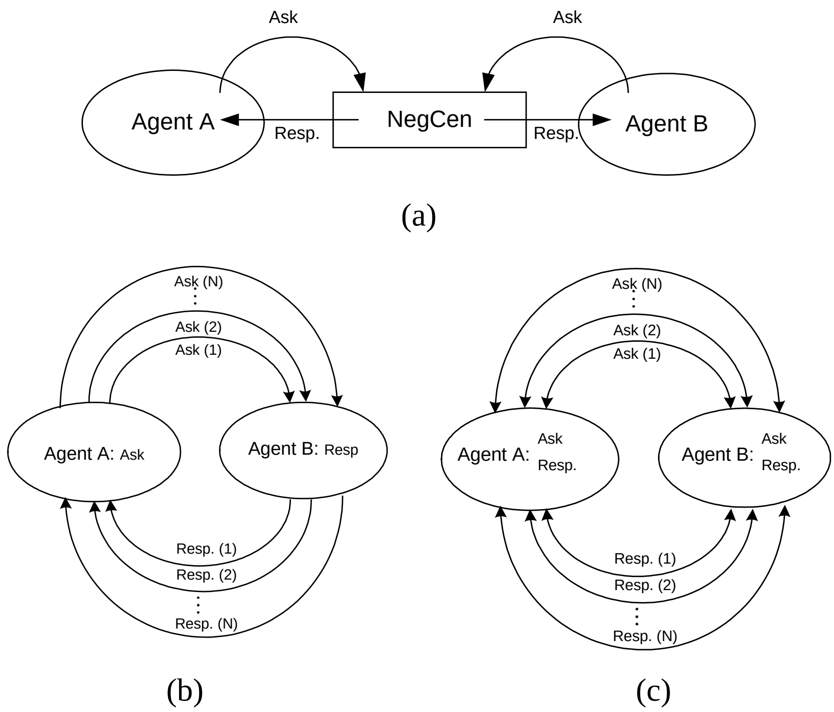

Fig. G-4. The three negotiation protocols used in this work. (a) Scheme of the one shot game. (b) The ultimatum game. (c) The alternating offers game protocol

3. Conventional protocols

Three widely used negotiation protocols are presented in Fig. G-4. Fig. G-4(a) schematically shows the protocol of one-shot negotiation, in which a negotiation center (NegCen) as a neutral organization helps to achieve a successful outcome. The two agents A and B simultaneously present their proposal to the NegCen without any knowledge of the opponent’s demand. If their proposals are compatible, the NegCen equally distributes the payoff to the agents. Otherwise, the process ends with disagreement and both agents receive nothing. In Fig. G-4(b) the ultimatum negotiation falling into the category of asymmetry negotiation is sketched. Only agent A sends a proposal to agent B who may accept or reject. The negotiation process is repeated under a time limit. An extension of the ultimatum is the alternating offers protocol in Fig. G-4(c), which belongs to the class of symmetrical negotiation. Here, agent A starts by offering a proposal to B. After evaluating the incoming offer, agent B may accept it or reject it with a counter proposal. This process is repeated until the negotiation is ended with an agreement or until the time limit is met.

By using three protocols, we let the two parties, fishermen and environmentalists, run negotiations for a suitable response to an imminent oil spill. There are two issues considered: the towing direction of the spilling vessel and the compensation. Totally, 243 oil spill scenarios are presented to the parties. In each scenario, the damages are differently distributed into coastal sub areas as calculated by a model system. This system uses realistic boundary conditions and five different options for the towing direction (Wirtz et al., 2006; Wirtz et al., 2004). If the alternating offer negotiation protocol is used, for each of these scenarios firstly both parties evaluate and rank the towing directions. Secondly one party proposes an offer including its preferred action and minimum willingness to pay (MWTP) for such an action. Finally the offer is accepted or a counter offer with a different preferred action and the MWTP is sent by the opponent party.

Three different measures for estimating the negotiation success are employed. Following Zhang et al. (2000), we collect data for each scenario test and summarize these data with respect to the different protocols:

1) Outcome/number of succeeded negotiation (NSN): A negotiation is successful if it ends with an agreement that increases the global utility for agents;
2) Global utility gain (GU): the sum of the utility gain for each agent for successful negotiations;
3) Number of negotiation steps (ANNS): the length of negotiation rounds for each scenario if there is a time constrain.

As can be seen from Table G-2, significant differences between protocols arise. Out of 243 scenario tests, the one-shot protocol succeeds in 192 cases, the ultimatum and the alternating offers do so in 216 and 230 cases, respectively. Due to the presence of a counter-proposal from the opponent agent, the alternating offers protocol helps both agents to find more successful cases. Additionally, through the comparison of different protocols as shown in Table G-2, the alternating offers is the most elegant negotiation model, which promotes both parties to reach more beneficial solutions. Thus, it produces the highest average global utility over all scenario cases, although its average number of negotiation steps is larger than that of the one-shot protocol.

Table G-2. Efficacy of different protocols (NSN: the number of successful negotiations out of 243 scenario tests. AGU: the average global utility over all the scenario cases. ANNS: the average number of the negotiation steps over all the successful cases.)

Negotiation Protocol	NSN	AGU	ANNS
The one-shot	192	0.3966	1
The ultimatum	216	0.4480	1.25
The alternating-offers	230	0.4725	1.2384

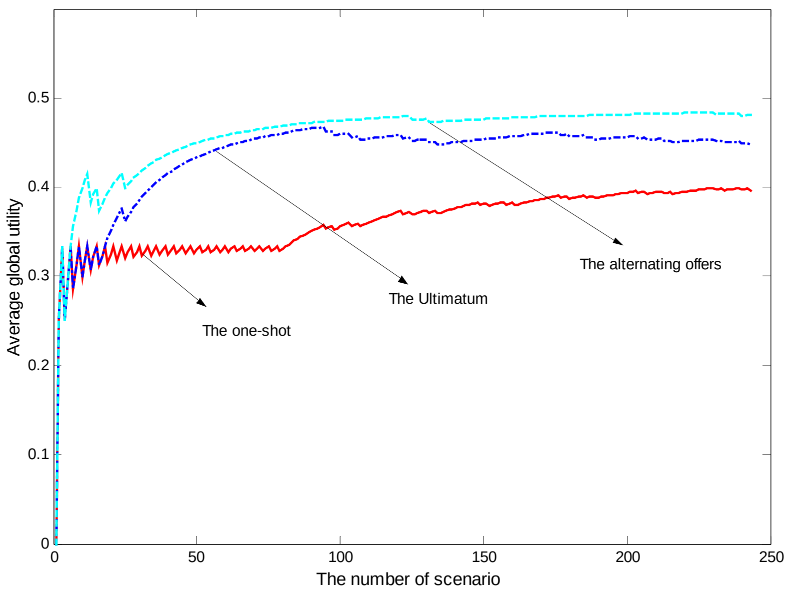

Fig. G-5. Comparison of average utility outcomes for three protocols which are sequentially applied to 243 oil spill scenarios

The development of the average global utility for three different negotiation protocols is presented in Fig. G-5. Among the first 10 scenario tests, in which both agents' proposals for the oil spill response (e.g. the selection of the towing direction) are not significantly different, the protocols perform equally. The one-shot protocol consumes less time and acts fair to both agents, since the payoff is equally divided by the NegCen. However, the straightforward mechanism of the one-shot can fail if proposals are completely conflicting: agents have no knowledge about their opponent agent's demands and are self-interested so that their initial proposal is completely driven by the belief of maximizing their local utility. In the one-shot protocol, the negotiation is terminated whatever the outcome is, once the initial proposals by both agents are given. Contrary, in the ultimatum as well as the alternating offers protocol, agents may change their demanding proposals in the next negotiation round through reflecting proposals presented at previous negotiation rounds. This flexibility facilitates a positive outcome of the trading process.

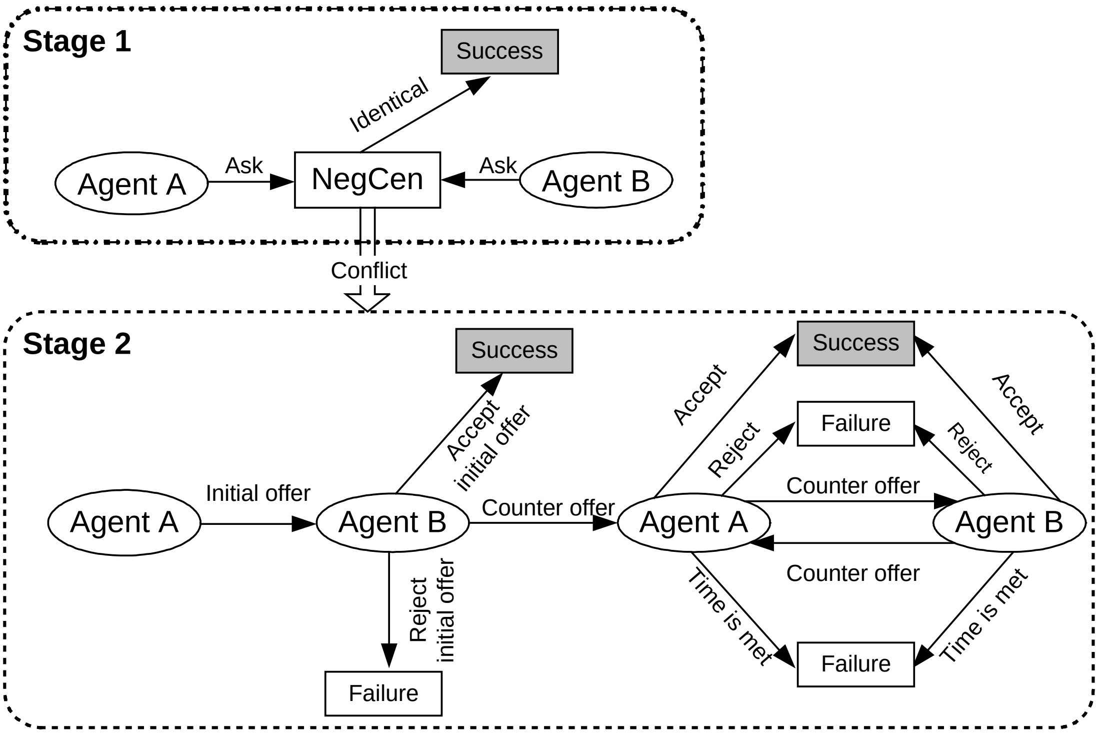

Fig. G-6. A detailed scheme of the hybrid negotiation protocol

4. A Hybrid protocol

A hybrid negotiation protocol is created by combining the one-shot and the alternating offer, consisting of two principal stages as shown in Fig. G-6. The first stage is the oneshot like mechanism where a negotiation center (NegCen) as a neutral organization helps to identify both agents' preferences. The two agents *A* and *B* simultaneously sent their preferences (e.g. the towing direction) to NegCen without any knowledge of the opponent's demand. If their preferences are identical, the negotiation is ended successfully with equally distributed payoffs to the agents. Otherwise, the negotiation comes to the second stage, which includes several negotiation rounds. Firstly, one of the agents is randomly selected as a starter to send an initial proposal to the opponent. After evaluating the incoming offer, the opponent may accept or reject it with a counter proposal. This process is repeated until the negotiation is ended with an agreement or a time limit is met. Agents will receive nothing if the negotiation is not ended with an agreement. The designed protocol ensures pareto efficiency, individual rationality, maximal social welfare, fairness, telling truth and partial revelation of preferences.

Pareto efficiency: all potential solutions build up an agreement space of agents (see Fig. G-7 left). During a negotiation, it enables agents to compare alternative solutions and find an optimal solution as close to the pareto optimal frontier as possible. The pareto optimal solutions are efficient in the sense that no other solution exists where some individuals are better off and no individual worse off.

Individual rationality: negotiating agents are rational at several principal aspects. Firstly, by participating the agent’s payoff increased with respect to a non-participation. Secondly, they prefer making an agreement, if the suggested proposal has a better utility payoff than its utility base line. Thirdly, their actions such as presenting an initial offer, evaluating an incoming offer and proposing a counter offer are based on a personal multi-attribute utility function and conservative utility.

Maximal social welfare: if the social welfare is defined as a set of indifference curves shown in the right diagram of Fig. G-7, the pareto optimal choice which reaches the local maximal social welfare indifference curve *S*3 at a single point *G* defines the best solution. Here the social welfare focuses on the combined product of all individual utilities as described in Wei et al. (2003). Thus, solution *G* presents an equity for both of agents. In a real negotiation, agents intend to avoid an agreement which benefits one agent too much and make the other suffer a big loss. Such a case like choice *H*, although it is at pareto optimal frontier, is prevented by using the utility base line as a constraint.

Fairness: all agents are treated equally important during the whole negotiation. No dominant or superior agent exists and equal opportunities to start a negotiation are shared.

Telling truth: the negotiation centre is neutral. Both agents have no information about the preferences of the opponent before the start of negotiation. Thus, telling the truth is a dominant strategy for both agents.

Partial revelation of preferences: Not all preferences of agents are revealed in the process of negotiation. For example, their reserved utility base line remains a completely private information.

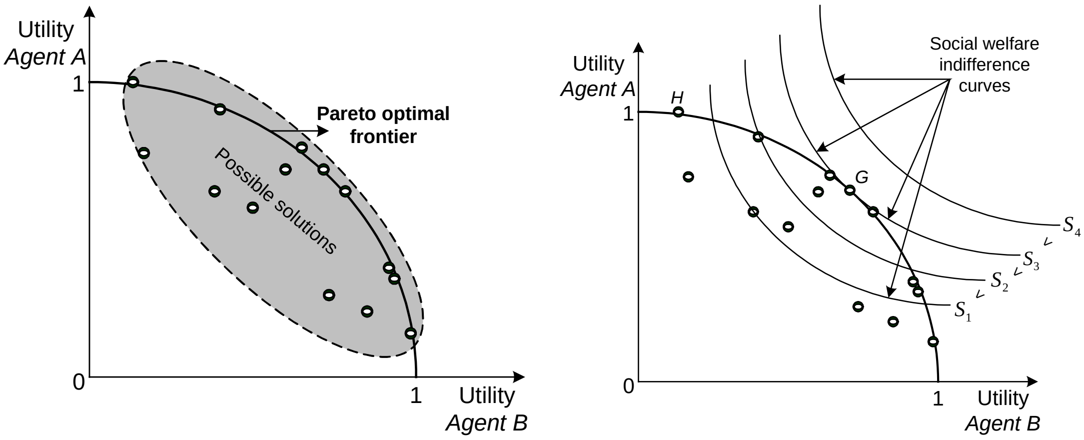

Fig. G-7. Pareto optimal and maximal social welfare. Left: possible solutions and pareto optimal. Right: social welfare indifference curves

5. Rational agents

As we mentioned before, negotiating agents are capable of a number of actions such as evaluating an incoming offer and proposing a counter offer. All these behaviors are based on their personal multi-attribute utility function and reserved utility base line,

$$action_A = \begin{cases} accept & U_A(offer_{inc})/base_A \geq c \\ reject & U_A(offer_{inc})/base_A \leq b \\ offer_{counter} & U_A(offer_{inc})/base_A \in [b,c] \end{cases} \qquad (4)$$

where c and b are pre-designed constants. Through comparing the utility of an incoming offer with the base line, agent A selects one corresponding action on a rational basis. For example, agent A intends to accept the incoming offer, if its utility is 1.5 times (c = 1.5) as high as its utility base line ($base_A$). According to the way in which a counter offer is proposed, two different reasoning models are generated: the conservative model and the reinforcement learning model. In the conservative model, the counter offer is made randomly within the interval of [$base_A$, 1],

$$offer_{counter}^{A} = \arg\{U_A(offer) \geq base_A\} \qquad (5)$$

An agent with the conservative reasoning model is simply a rational agent, and in this paper, is called the conservative agent. Contrary, in the reinforcement learning model, the counter offer is suggested by a simple learning function,

$$offer_{n+1}^{A} = offer_{n}^{A} + a(offer_{n}^{B} - offer_{n}^{A}) \qquad (6)$$

where α is a learning rate ranging between 0 and 1. The counter offer of agent A in the next negotiation round $n + 1$ is a function of both offers given at a former negotiation round. A learning function brings the benefit of learning the preferences of opponents and adapting a strategy by which better payoffs are achieved during the following plays. An agent being capable of such a learning function is taken as a learning agent. In the next section, in order to support a view that learning techniques help agents improve their payoffs in sequential negotiations, the performance of both types of negotiating agents are evaluated in the frame of a balanced contingency management. By using the hybrid protocol, we let two different types of agents (e.g. the conservative agent and the learning agent) run negotiations on behalf of their owners (e.g. fishermen, environmentalists or policy-makers) for a suitable response to an imminent oil spill. As mentioned previously, the towing direction of the spilling vessel and the money compensation are considered. Totally 300 oil spill scenarios randomly generated are presented to the agents. This number is found to be sufficient to distinguish the different performances of agents). In each scenario, five different towing directions result in different damage distributions for coastal sub-areas. Both agents evaluate and rank towing options with regard to the damage level on their interest areas. Out of these 300 scenarios, only 117 cases can be successful traded. This is partly due to the lack of an agreement zone. Another reason derives from the nature of the conservative agent (e.g. randomly selection of the proposals in its possible action space), what may result in a failure in the negotiation under the time constraint, although in a few cases it promote a very fast joint agreement (Soo and Hung, 2002). The average utility gain over all successful negotiations is taken as a measure to evaluate the performance of both agents. The development of the average utility for both agents is presented in Fig. G-8. Unsurprisingly, the learning agent does perform a little better than the conservative agent in terms of the average utility. Since the learning agent, unlike the conservative agent, adapts its strategy gradually by predicting the opponent's preference with a reinforcement learning method. It leads to a better payoff derived for the learning agent when an agreement is reached.

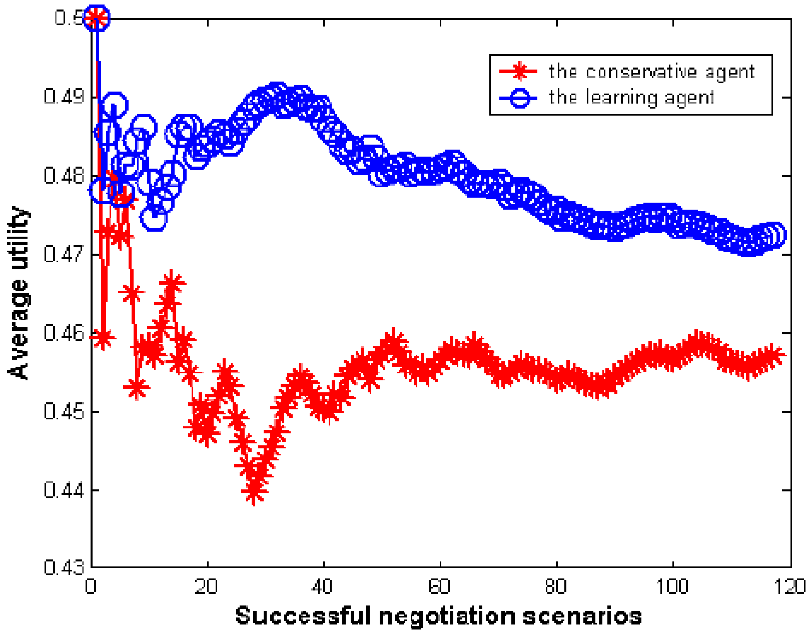

Fig. G-8. Comparisons of average utility outcomes for two different types of agents. The learning agent is marked with circles and the star line refers to the conservative agent

6. Conclusions

The negotiation technique including its protocols, issues and rational agents is demonstrated to robustly depict basic features of real conflict mitigation. It, thus, may assist parties involved in a dispute over environmental decision making problems. In particular, its test of the response to the Prestige oil spill, 2002 shows that the consensus is a win-win solution for parties, once the negotiation is terminated successfully, although sometimes this compromise consensus is not the best decision made by the multi-criteria analysis in Wirtz et al. (2006). Our main conclusions comprise: (i) Among three different conventional protocols the alternating offers results as the best performing negotiation protocol in our case mainly derives from its flexibility as agents may adapt their strategies in sequential negotiation rounds. Moreover, this type of protocol works efficiently in a complex environment where completely contrary demands of agents exist. (ii) In the situation where no strongly different demands exist, the straightforward mechanism of the one-shot performs well. It carries the benefit to be quite "fair" and less time consuming. (iii) The hybrid protocol developed ensures several reasonable properties, since it combines features of both the alternating offer and the on-shot. (iv) Adding compensation as one of the important negotiation issues into a multiple attribute utility function, more feasible trade-off options are generated. (v) When simulation experiments are involved with different rational agents, the learning agent performs well as compared with the conservative agent. This outcome reinforces the view that learning techniques help agents to serve better on behalf of their owners by improving payoffs in sequential negotiations.

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Part H: Comparisons of evaluation methods

1. Similarities and differences

At first glance, the three evaluation approaches mentioned above seem to be quite different, but they appear actually more similar after closer examination. This can be seen more clearly in Fig. H-1, which depicts a clear and traceable decision making process for the three methods. The six steps and their order are common to both approaches of MCA and FCE. While MEM only share five out of the six main steps, as the weights between the criteria are not required for carrying out an appraisal by MEM. At this general level of description one has a broad analogy between evaluation methods. However, considerable differences (e.g. integration of data and further analyses) exist in the stages of overall evaluation and analysis, which are marked with star in Fig. H-1.

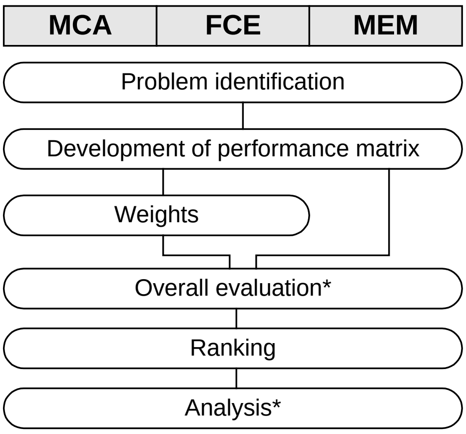


Fig. H-1. Overall application scheme for the three evaluation methods multi-criteria analysis (MCA), fuzzy comprehensive evaluation (FCE) and monetary evaluation model (MEM)

Table H-1 summarizes these differences in more detail. A direct involvement of stakeholders is unique to MCA and FCE. Although all three methods address long term effects, only MEM discounts long-term effects in the oil spill case of combat strategies to present values. This enables us to sum long-term and short terms effects as a convenience. A FCE has no requirement for data and a MEM only partially deals with quantitative data, while quantitative data in specific formats are preferred in MCA. A weighted sum score as indicator used in MCA is not optimal to describe heterogeneous information of oil pollution effects, since it directly, for example, adds apples with bananas. Whilst, indicators (e.g., money) used in environmental economics provides an accepted measure of pollution effects both to the public and decision-makers. With respect of technical feasibility, MCA and MEM are easier to understand and use than FCE. Moreover, a variety of uncertainties may be introduced during set-ups of all three methods. For example, linear aggregation function is main potential source of uncertainties in a MCA. Meanwhile, internal degrees of freedom arise when specifying membership functions in a FCE. When a MEM is applied, one should be careful to check the effect of recovery functions on the ranking result of the alternatives. Finally, both MCA and FCE provide the same analyses to examine the effects of weights on the ranking orders and aid to determine critical criteria, to which rankings of alternatives are sensitive. While, MEM provides economic analyses for quantifying the effectiveness of a proposed management plan.

Table H-1. Unique features to each method

	Methods		
	MCA	FCE	MEM
Involvement of stakeholders	yes	yes	no[13]
Discount long-term effects	no	no	yes
Capability of dealing with data in multiple dimensions	strong	strong	Less strong
Data type	quantitative data	No requirement[14]	quantitative data with a specific format
Intuitive indicator	not intuitive	sort of intuitive	very intuitive
Applicability	very simple	complex	simple
Sources of uncertainty	Linear aggregation	Membership	Recovery function
Types of analysis	1.Effect of changing weights on the ranking 2.Critical criteria determination		1.Benefit cost analysis 2.Cost effectiveness analysis

2. Testing

To directly examine evaluation methods in the same set-up, 36 hypothetical spill scenarios (e.g. the combination of 3 different spill sizes ranging from small to medium to large and 12 hydrographical and meteorological conditions over a yearly period in 2001) are generated and studied in this section. In particular, we focus on the size of the oil spills and combat

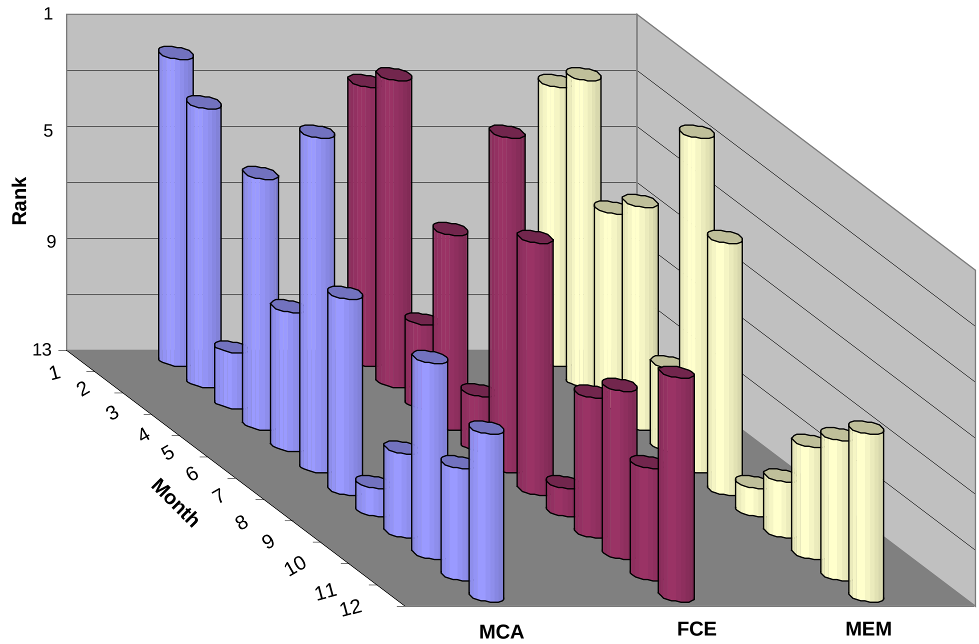
[13] *Given stated preferences methods such as contingent valuation method and stated choice experiments are used in MEM, there also exists an involvement of stakeholders.*

[14] *However it needs to take a variety of fuzzy rules and memberships into account.*

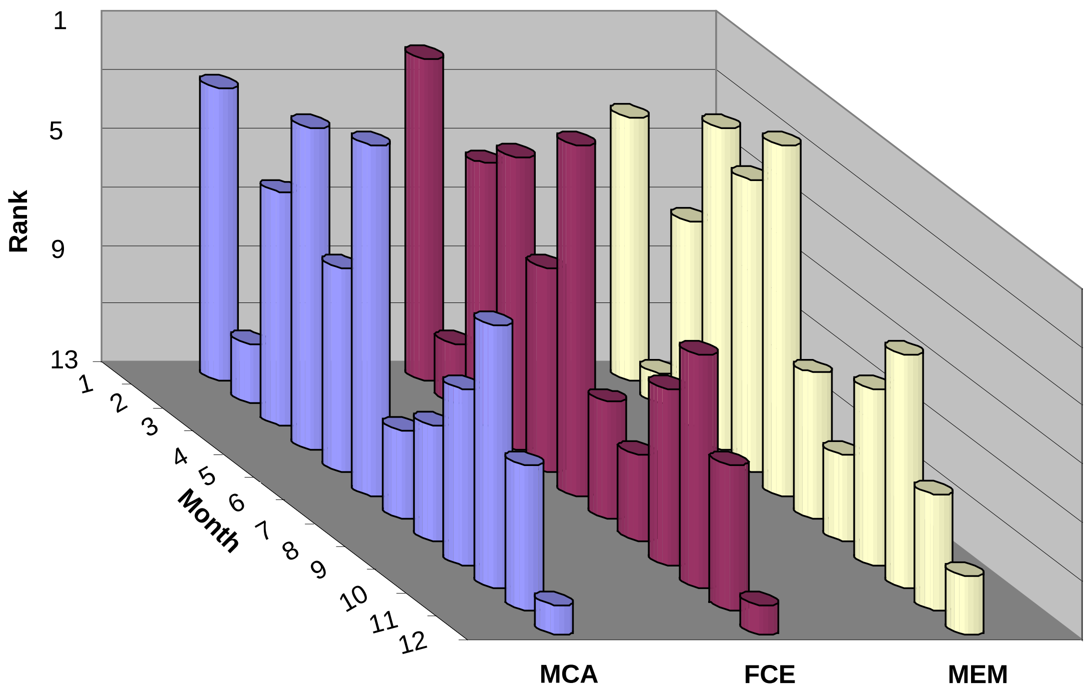
efficiency and investigate factors that affect the evaluation results derived from different methods.

2.1 Compare rankings

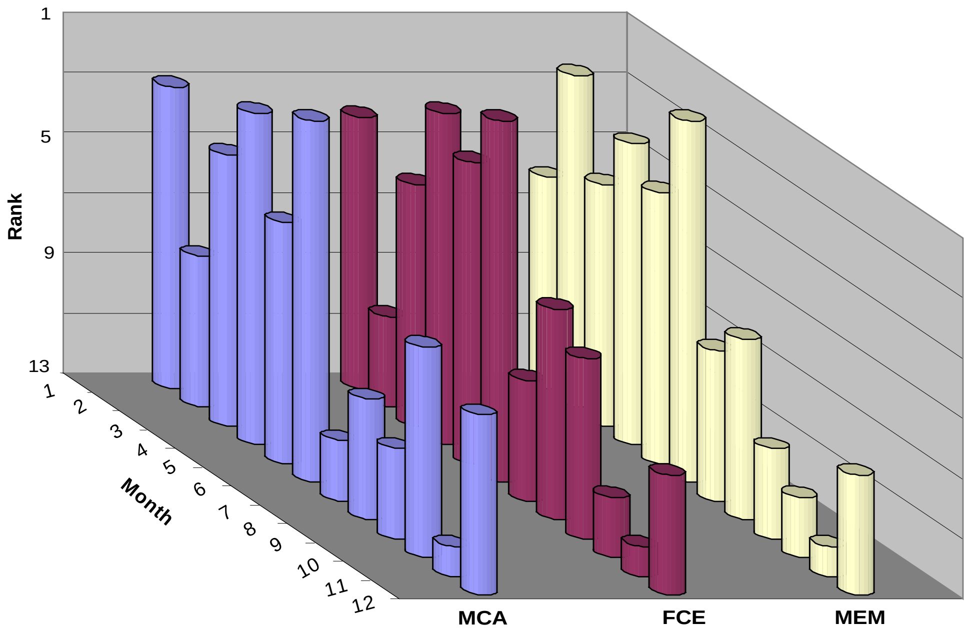
In total, 36 oil spill and combat scenarios are performed by OSCAR and characterize the bio-economic consequences of spills. Each scenario details data relating mass balance of fuel components in various environmental compartments (water surface, shoreline, atmosphere, sediments, etc.), surface distribution over time, response costs and quantities of recovered oil on waters. For each spill size, the 12 spill scenarios depending on weather conditions are ranked in descending order by different evaluation methods, respectively. In general, all methods lead to similar results. For example, in small spills as shown in Fig. H-2(a) June and August are evaluated as the best and worst scenarios, respectively, by all methods. With respect to large spills in Fig. H-2(c), all methods take the case of November as the worst one. In the case of medium size spills, all evaluation methods tend to provide much more similar results compared to the small as well as large spills. More precisely, the spill size as possible exogenous factor could have significant impact on the distribution of the ranking orders. This could be associated partly with the existence of dominant costs. According to MEM, total oil spill costs could include three main cost categories: response costs, environmental damages and socio-economic losses. MEM calculates the total oil spill costs for each of 36 scenarios and the power law like relationship between the total spill costs and the spill size is regressed using these data (see Appendix). The model data reveal a large variability of cost shares for particular cost categories across spill incidents. Generally, the spill size of an incident determines cost shares. Due to the small scale of 7-ton spill, both environmental and economic resources are less damaged. Overall, we found response costs to be the largest cost category, averaging just less than half of the total costs for small incidents. With the increase of the spill size to medium, no relative significance of any one cost category exists as shown in Fig. H-3(b). As compared with the response costs, both environmental damages and socio-economic losses increase more significantly. Three cost categories are then equally distributed. Once the spill size increases further to a large case, on the one hand, response costs will increase gently due to a limitation of combat facilities available. On the other hand, large spills are likely to have high costs from either environmental damages or socio-economic losses or both. Under such circumstances, a dominant category may arise again. Thus, decision makers could be careful to select evaluation approach, if diverged results do appear to erode model's credibility. With respect to large spills, it can be argued that priority should be given to MEM, if it is comprehensive. Otherwise, the outcome of MEM together with other important criteria that fall outside the MEM framework should be included in MCA/FCE.



(a)



(b)



(c)

Fig. H-2. Rankings from three different evaluation methods. (a) small spills: 7 tons; (b) medium spills: 70 tons and (c) large spills: 700 tons

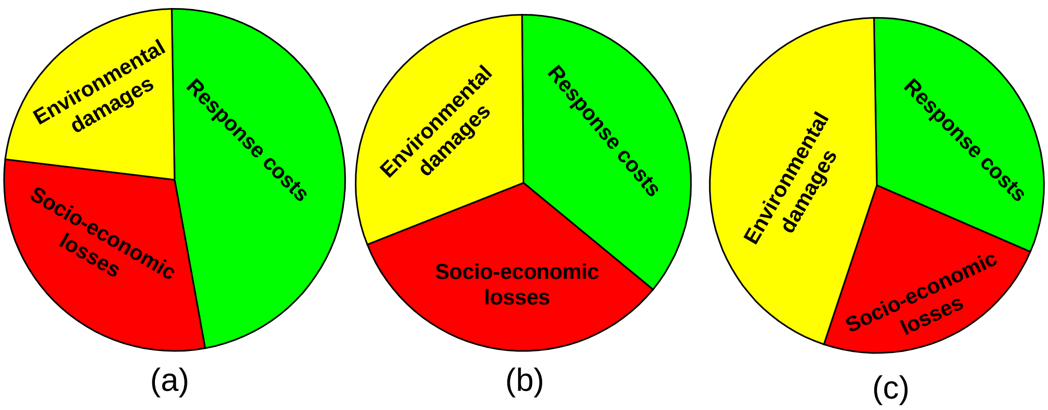


Fig. H-3. Cost shares for different spill sizes. (a) total costs is dominated by response costs in small spills; (b) no dominant costs exist in medium spills and (c) dominant costs (e.g., environmental damages or socio-economic losses) exist in large spills

2.2 Efficiency of combat

The most influential variable determining the efficiency of response activities on seas are combat costs per ton (e.g. response costs/total spill amount) and oil recovered ration (quantities of recovered oil/total spill amount). In this section, 12 spills from the combined data are selected to determine the effect of spill size on the combat efficiency. These 12 spills analysed is for a matrix of three spill sizes and four different months (e.g. April, July, October and January). Four different months are selected as representatives of Spring, Summer, Autumn and Winter, respectively. It is observed from Fig. H-4 that oil recovered ratio increases significantly as spill size increases. For small spills, an average value of recovered ration is only 37%, while 82% on average corresponds to larger spills. This could be explained partly by less spill duration in small spills than that in large spills. In most cases for both small and large spills, time needed to deploy combat facilities on waters is equal. Therefore, responses to large spills are likely to be prompter than those to small spills. Partly due to the fact that the small spills are much easier to dispersed by the wind and current than the large spills. This leads to a harder collection of oil on waters as well. Meanwhile, we regress the combat cost per ton regarding with the spill size (see Fig. H-5). In contrast with the recovered ratio, response costs per ton increase significantly as the spill size decreases. The overall fit of the model as measured by R^2 also meets standards. This demonstrates again that compared with the small spills, responses to large spills are more cost effective.

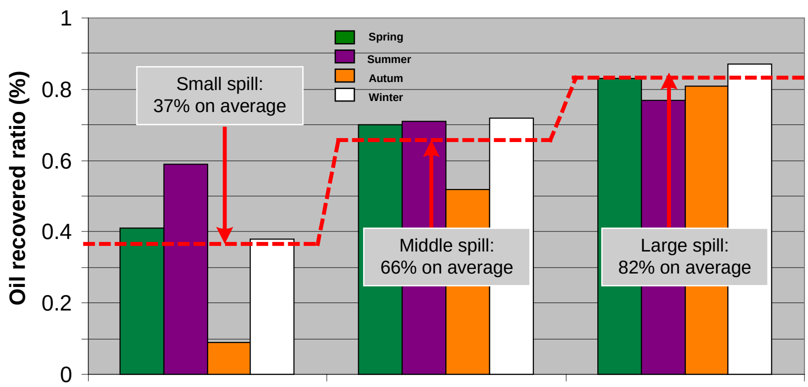


Fig. H-4. The relationship between the oil recovered ratio and the spill size

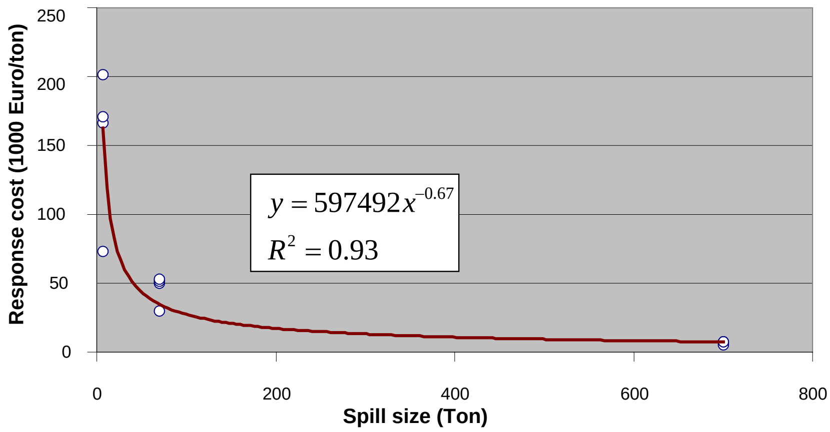


Fig. H-5. Change of response costs per ton with increasing spill size

3. Selection of methods

Each method has its own advantages and disadvantages. For example, advantages of MCA include straightforward application and direct involvement of stakeholders. The result derived from this method will provide a benchmark, if all data are measured in one dimension. However, its disadvantages cover the requirements for the data and limited capability to deal with the data whose relation are non-linear. Given that data are not linearly related with each other, FCE can be regarded as more rational methods than MCA to integrate data. Such an aspect has been listed in Table H-2 as one of the benefits in selecting FCE and MEM, rather than MCA. In summary, the selection of integrated evaluation methods highly depends on the obtained data and knowledge, setting-up, decision process and aims. Table H-2 suggests which method should be preferred corresponding to a variety of situations. In some situations, more than one method are suggested. Moreover, there exist a variety of valuation methods in MEM. Thus, requirements for time, costs and specialists are quite different in carrying out the MEM. Regarding compatibility with other methods, both MCA and FCE are preferred, since the outcome of MEM and other criteria that MEM fails to incorporate could be assigned with weights in MCA/FCE.

Table H-2. Selection of evaluation method

Where		Methods preferred
Decision process	Bottom-up decision	MCA/FCE
	Top-down decision	MCA/FCE/MEM
	Negotiation/ group decision	MCA/FCE (MEM[15])
Setting-up	Low costs	MCA/FCE (MEM[15])
	Short time window	MCA/FCE (MEM[15])
Data and knowledge available	Non-linearity and feed-backs in decision problem	FCE/MEM
	Lexical data	FCE
	Highly uncertain data	MCA/FCE
	Uni-dimensional data	MCA
	Multi-dimensional data	FCE/ MCA /MEM
	No specialist on statistics	MCA/FCE (MEM[15])
Aims	Consideration of long-term effects in money terms	MEM
	Identify critical criteria	FCE/MCA
	Determine a worthwhile investment	MEM
	Compatible with other methods	MCA/FCE

Appendix

MEM calculates the total oil spill costs for each of 36 scenarios. The impact of the spill size as an independent factor on the total spill costs is estimated by a regression analysis. A preliminary and empirical result is reported in the Fig. H-6, in which there is a strong regularity between the total spill costs and the spill sizes and such a regularity follows a power law.

[15] *It depends on valuation methods used.*

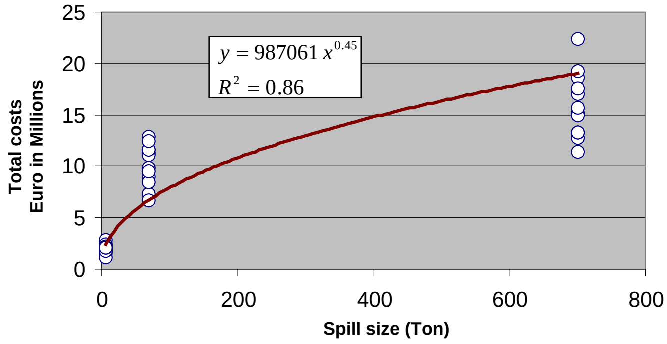


Fig. H-6. Regression of total costs with the spill size

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Erklärung

Hiermit erkläre ich, dass ich mich erstmals um einen Doktorgrad bewerbe und die vorliegende Arbeit selbstaendig verfasst habe. Ich habe keine anderen als die angegebenen Quellen und Hilfsmittel verwendet.

Xin Liu

Den 15. Agust, 2006