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Consensus oriented fuzzified decision support for oil spill contingency management

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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. 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 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. 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-

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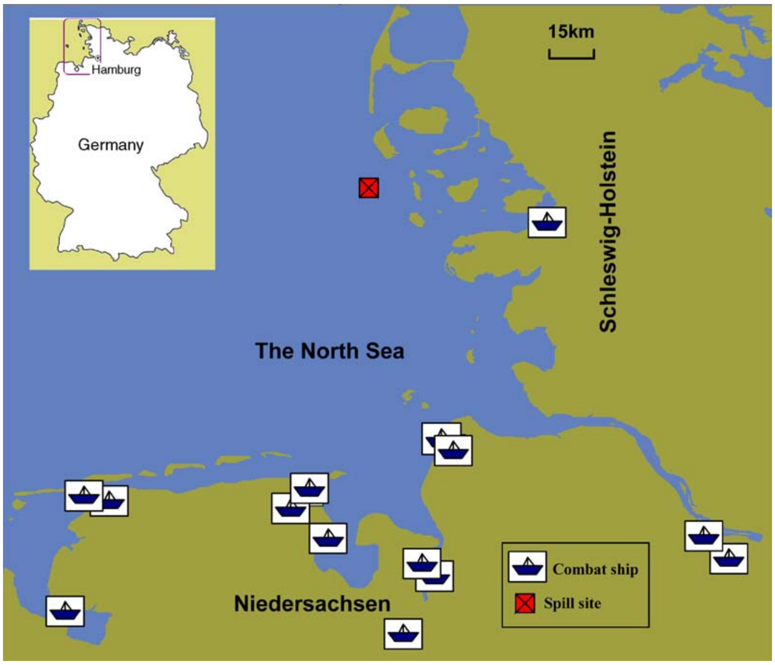

Fig. 1. German North Sea case study area. Both combat vessels and Pallas spill site are highlighted by different marks. Totally, there exist 14 oil combat vessels distributed in selected coastal administrative districts along the German North Sea.

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.

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 oil spill contingency and response (OSCAR) model system developed by SINTEF [23–25], Norway, simulated a variety of combat strategies for a 60-t crude oil spill at the site where the accident of Pallas

Table 1
Response strategies in terms of used combat vessels

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

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.

Table 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

occurred (54°32.5′N; 8°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 four to six 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 2–4, one more combat vessel is assumed while in the alternative 5, only four combat vessels are considered (see Table 1). Fig. 2 shows a two-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. 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 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. 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

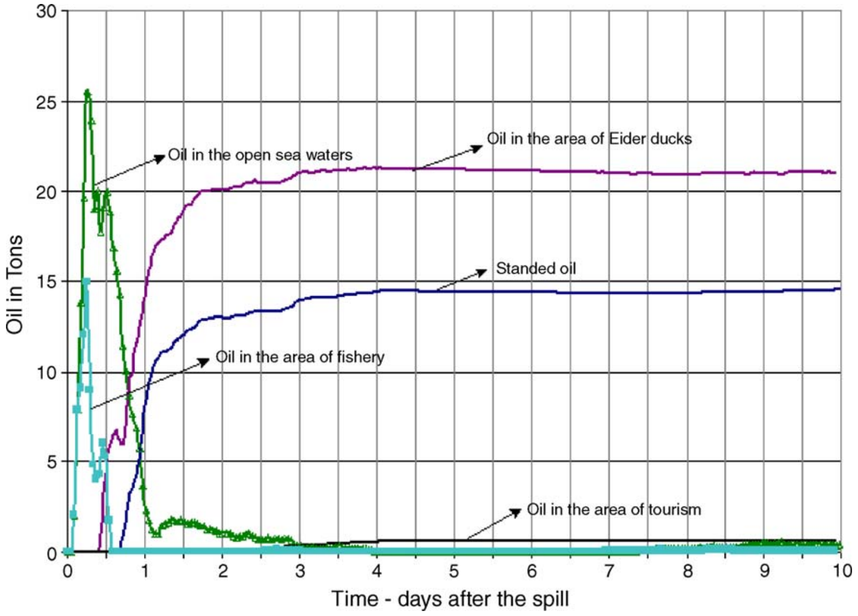

Fig. 2. Simulated oil distribution 10 days after the use of combat strategy (e.g. Alt.1) responding to a hypothetical release (site: 54°32.5′N; 8°17.24′E; spill amount: 60 t). Due to the small footprint in this spill scenario, the quantities of oil accumulated in different economic and ecological areas tend to stabilize after about 2–3 days following the spill.

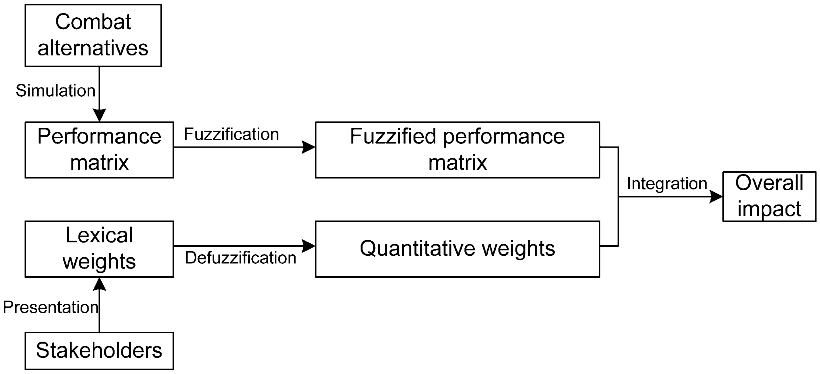

Fig. 3. A brief methodology scheme.

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.

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. 3. In such circumstances, the method of fuzzy comprehensive evaluation 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. 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.

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,

$$u^i = \{\mathrm{VLI}^i, \mathrm{LI}^i, \mathrm{MI}^i, \mathrm{FHI}^i, \mathrm{HI}^i\} \tag{1}$$

where u^i denotes the set of lexical grades for the ith 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

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

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 jth grade of the ith criterion and $e_{ij}^{1,\cdots,4}$ are four scalar parameters for the jth fuzzy grade of the ith criterion. A degree vector (A_i^n) is constructed below:

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

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

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 1 can be applied, it is given by,

$$\varsigma = \{\varsigma_1, \varsigma_2, \ldots, \varsigma_{11}\} = \{0, 0.1, \ldots, 0.9, 1.0\} \tag{4}$$

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.

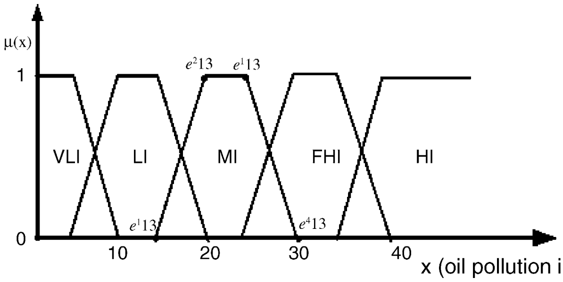

Fig. 4. The fuzzy membership function for criterion stranded oil (SO). VLI, very low impact; LI, low impact; MI, middle impact; FHI, fairly high impact; HI, high impact.

Table 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		

3.4. First-order fuzzy evaluation

A first-order fuzzy degree assignment matrix represents fuzzy degrees of lexical grades associated with those 11 damage levels. An example for criterion SO is shown in Appendix A. 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 3 where policy makers tend to treat these criteria equally important, while groups 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:

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

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:

$$\mathrm{OI}^{s,n} = \frac{\sum_{p=1}^{11} k_p^{s,n} \varsigma_p}{\sum_{\pi=1}^{11} k_\pi^{s,n}} \tag{7}$$

Table 4
Ranking of combat alternatives

Stakeholder	Ranking (1 > 2 > 3 > 4 > 5)
Combat organizations	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

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 B.

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 $\mathrm{OI}^{s,e} < \mathrm{OI}^{s,f}$. 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 4, both combat organizations and policy makers take Alt.5 and 2 as the top two options, while from the view of environmentalists Alt.2 significantly outranks Alt.5.

4.1. Ranking

If we compare the mean rank of five alternatives in Fig. 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 least less controversial, reflecting that all three groups take it as the worst case. Both

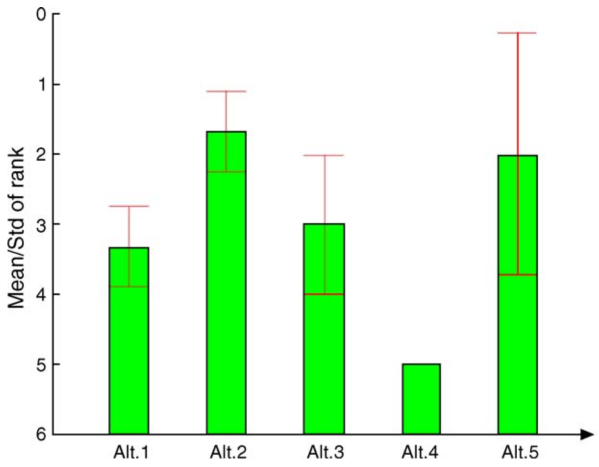

Fig. 5. Rankings of combat alternatives based on FCE. The interval plotted in solid lines indicates the standard deviation value of ranks. The standard deviation of ranks for Alt.4 is zero because all three groups rank it indifferently.

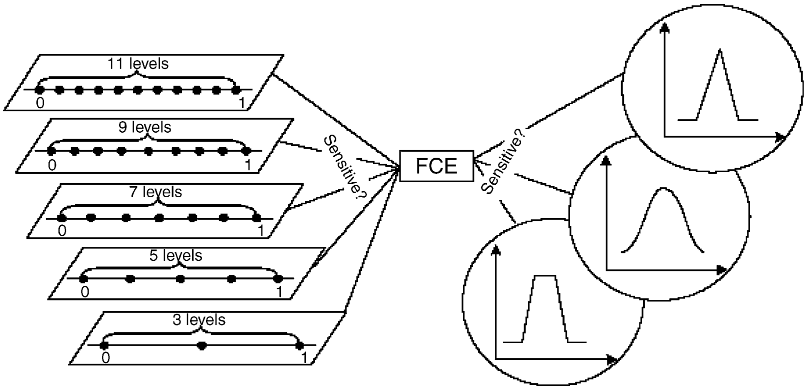

Fig. 6. The internal check of FCE. Different setups regarding the number of damage levels and various membership functions are examined.

Alt.1 and 2 are less controversial and Alt.3 and 5 are the most controversial according to different stakeholders' interests.

Although the Alt.5 outranks both Alt.1 and 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, 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. 6). The ranking result presented in Fig. 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:

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

where $\Delta R(\text{Alt.}j)$ 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. 6). The results are shown in Table 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. 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 seven 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 opti-

Table 5
Sensitivity tests regarding the internal setups of FCE

Tests	Alternatives				
	Alt.1	Alt.2	Alt.3	Alt.4	Alt.5
Membership function					
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
Damage levels					
#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

The ranks of alternatives are indicated by numerical numbers.

mal but the least controversial strategy if compared with other less optimal options (e.g. Alt.1, 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 5.

4.3. Critical criterion

Generally, the rank of an alternative is affected by weight profiles that are, in turn, pre-defined 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. 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. 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.

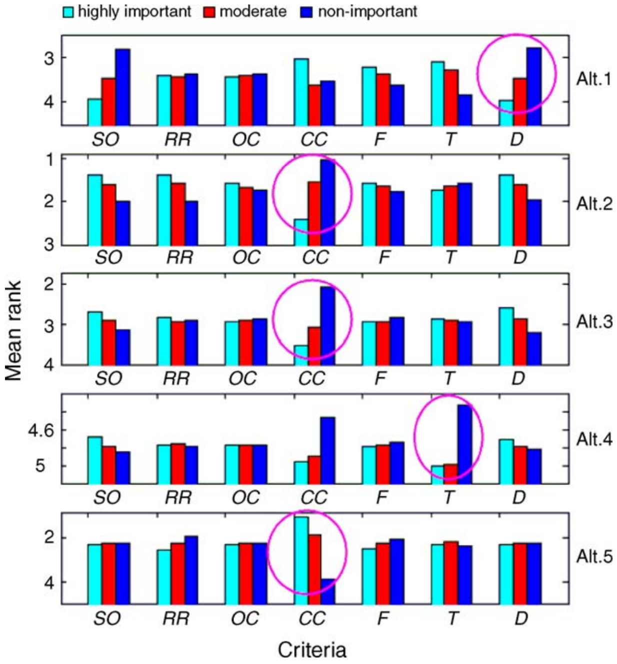

Fig. 7. Sensitivity test for each alternative in terms of each criterion. The importance of each criterion is defined in three different levels. Their changes contribute to the variation of mean rank for each alternative. The most critical criterion for each alternative is highlighted with a circle.

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 modeled 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].

5. Concluding remark

As a computer-aided decision-making tool, the fuzzy comprehensive evaluation 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 [21,22]. Additionally, in order to improve its applicability and robustness, both of the internal and external checks are highly recommended.

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Appendix A

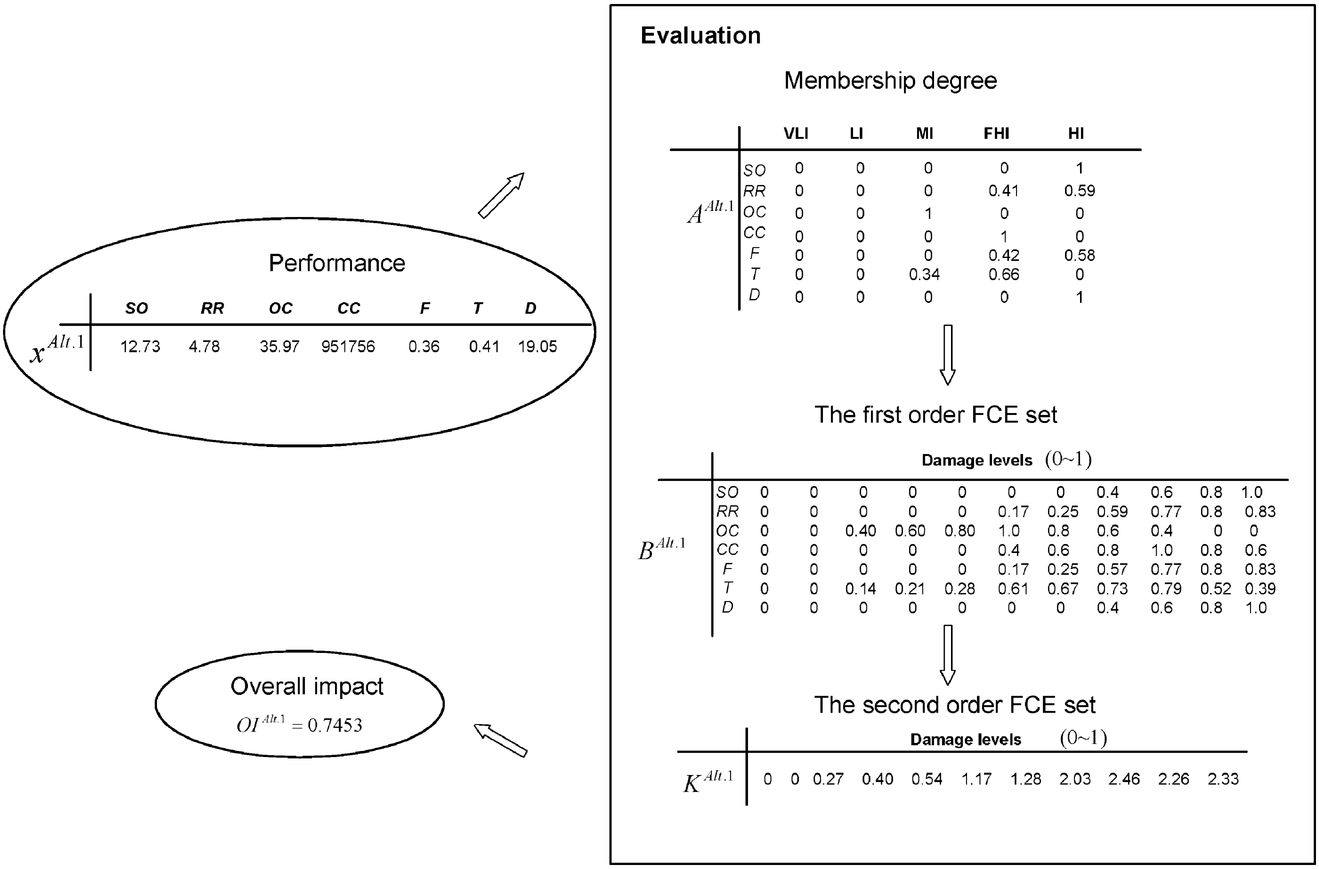
An example of the first-order fuzzy degree assignment matrix for the criterion stranded oil (SO) is as follows:

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 B

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



Performance

$x^{Alt.1}$	*SO*	*RR*	*OC*	*CC*	*F*	*T*	*D*
	12.73	4.78	35.97	951756	0.36	0.41	19.05

Evaluation

Membership degree

$A^{Alt.1}$		VLI	LI	MI	FHI	HI
	SO	0	0	0	0	1
	RR	0	0	0	0.41	0.59
	OC	0	0	1	0	0
	CC	0	0	0	1	0
	F	0	0	0	0.42	0.58
	T	0	0	0.34	0.66	0
	D	0	0	0	0	1

The first order FCE set

$B^{Alt.1}$		Damage levels (0~1)										
	SO	0	0	0	0	0	0	0	0.4	0.6	0.8	1.0
	RR	0	0	0	0	0	0.17	0.25	0.59	0.77	0.8	0.83
	OC	0	0	0.40	0.60	0.80	1.0	0.8	0.6	0.4	0	0
	CC	0	0	0	0	0	0.4	0.6	0.8	1.0	0.8	0.6
	F	0	0	0	0	0	0.17	0.25	0.57	0.77	0.8	0.83
	T	0	0	0.14	0.21	0.28	0.61	0.67	0.73	0.79	0.52	0.39
	D	0	0	0	0	0	0	0	0.4	0.6	0.8	1.0

The second order FCE set

	Damage levels (0~1)										
$K^{Alt.1}$	0	0	0.27	0.40	0.54	1.17	1.28	2.03	2.46	2.26	2.33

Overall impact

$OI^{Alt.1} = 0.7453$

References

[1] C. Hagner, The Economic Productivity at the German Coast, Tech. Rep. GKSS 2003/14, Institute for Coastal Research GKSS Center, Geesthacht, Germany, 2003.

[2] Y. Yu, B. Wang, G. Wang, W. Li, Multi-person multiobjective fuzzy decision-making model for reservoir flood control operation, Water Resour. Manage. 18 (2004) 111–124.

[3] M.A. Sharifi, Integrated Planning and Decision Support System for Sustainable Watershed Development, International Institute for Geo-information and Earth Observation ITC, The Netherlands, 2002.

[4] F. Cavallaro, L. Ciraolo, A multicriteria approach to evaluate wind energy plants on an Italian island, Energy Policy 33 (2005) 235–244.

[5] J.B. Ellis, J. Deutsch, J. Mouchel, L. Scholes, M.D. Revitt, Multicriteria decision approaches to support sustainable drainage options for the treatment of highway and urban runoff, Sci. Total Environ. 334–335 (2004) 251–260.

[6] A. Ferrarini, A. Bodini, M. Becchi, Environmental quality and sustainability in the province of Reggio Emilia (Italy): using multi-criteria analysis to asses and compare municipal performance, J. Environ. Manage. 63 (2001) 117–131.

[7] B.H. Massam, B. Wang, An application of DEFINITE: the quality of life of Chinese seniors in four districts of Toronto, J. Geogr. Inform. Decision Anal. 6 (2002) 57–66.

[8] K.P. Chen, C. Jacobson, R. Blong, Artificial neural networks for risk decision support in natural hazards: a case study of assessing the probability of house survival from bushfires, Environ. Model. Assess. 9 (2004) 189–199.

[9] S.P. Simonovic, Sustainable floodplain management-participatory planning in the Red river basin, Canada, in: Proceedings of IFAC, Venice, 2004.

[10] L.A. Zadeh, Fuzzy sets, Inform. Control 8 (1965) 338–353.

[11] H.J. Zimmerman, Using Fuzzy sets in operational research, Eur. J. Oper. Res. 13 (1983) 201–216.

[12] V. Adriaenssens, B. Baets, P.L.M. Goethals, N. Pauw, Fuzzy rule-based models for decision support in ecosystem management, Sci. Total Environ. 319 (2004) 1–12.

[13] I. Keramitsoglou, C. Cartalis, P. Kassomenos, Decision support system for managing oil spill events, Environ. Manage. 32 (2003) 290.

[14] I. Keramitsoglou, C. Cartalis, C.T. Kiranoudis, Automatic identification of oil spills on satellite images, Environ. Model. Software, in press.

[15] G.A. Mendoza, P. Ravi, Fuzzy methods for assessing criteria and indicators of sustainable forest management, Ecol. Indicators 3 (2004) 227–236.

[16] M.J. Ducey, B.C. Larson, A fuzzy set approach to the problem of sustainability, Forest Ecol. Manage. 115 (1999) 29–40.

[17] S. Marsili-Libelli, Fuzzy prediction of the algal blooms in the Orbetello lagoon, Environ. Model. Software 19 (2004) 799–808.

[18] E.R. Gurocak, N.K. Whittlesey, Multiple criteria decision-making: a case study of the Columbia River salmon recovery plan, Environ. Resour. Econ. 12 (1998) 479–495.

[19] S. Bonvicini, P. Leonelli, G. Spadoni, Risk analysis of hazardous materials transportation: evaluating uncertainty by means of fuzzy logic, J. Hazard. Mater. 62 (1998) 59–74.

[20] J. Stansbury, P.E. Member, I. Bogardi, E.Z. Stakhiv, Risk-cost optimization under uncertainty for dredged material disposal, J. Water Resour. Plan. Manage. 125 (1999) 342–351.

[21] S. Ji, X. Li, R. Du, Tolerance synthesis using second-order fuzzy comprehensive evaluation and genetic algorithm, Int. J. Prod. Res. 38 (2000) 3471–3483.

[22] S. Ji, X. Li, Y. Ma, Optimal tolerance allocation based on fuzzy comprehensive evaluation and genetic algorithm, Int. J. Adv. Manuf. Technol. 16 (2000) 451–468.

[23] O.M. Aamo, K. Downing, M. Reed, Calibration, Verification and Sensitivity Analysis of the IKU Oil Spill Contingency and Response (OSCAR) Model System, Tech. Rep. 42.4048.00/01/96, IKU, Norwegian, 1996.

[24] M. Reed, O.M. Aamo, P.S. Daling, Quantitative analysis of alternative oil spill response strategies using OSCAR, Spill Sci. Technol. 2 (1995) 67–74.

[25] M. Reed, P. Daling, A. Lewis, K.M. Ditlevsen, B. Brørs, J. Clark, D. Aurand, Modelling of dispersant application to oil spills in shallow coastal waters, Environ. Model. Software 19 (2004) 681–690.

[26] L. Clausen, Schwchstelenanalyse aus Anlass der Havarie der Pallas: Bericht, der Ministerpresidentin des Landes Schleswig-Holstein am 4 Mai 1999 Erstattet, Tech. Rep., Bundesverwaltungsamt, Zentralstrelle fuer Zivilschutz, 2003.

[27] T.J. Ross, Fuzzy Logic with Engineering Applications, McGraw-Hill, Inc., 1995.

[28] R. Lahdelma, P. Salminen, J. Hokkanen, Using multicriteria methods in environmental planning and management, Environ. Manage. 26 (2000) 595–605.

[29] V. Ozernoy, Generating alternatives in multiple criteria decision making problems: a survey, in: Y. Haimes, V. Chankong (Eds.), Decision Making with Multiple Objectives, Springer–Verlag, New York, 1984.

[30] X. Liu, K.W. Wirtz, Sequential negotiation in multiagent systems for oil spill response decision-making, Mar. Pollut. Bull. 50 (2005) 469–474.