Decision analysis for marine oil spill response

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The volume of oil transported by tankers has largely increased in the last few decades. Consequently, many accidents have occurred leading to the release of large quantities of oil into the marine environment. Suitable oil spill response techniques must be carried out immediately after an oil spill occurs to recover as much as possible of the spilled oil and to mitigate the ensuing damage to the environment. In this paper, response methods are discussed as well as the decision making process involved in selecting the best method or combination of methods to minimize oil spill costs. A decision tree model is proposed and a hypothetical spill scenario is considered as an application, to demonstrate the validity of the proposed model. The solution is presented and discussed. Sensitivity analysis is then carried out to determine the most influential variables in the decision process. The proposed decision analysis technique is shown to be easily applied and very useful to the decision maker involved in marine oil spill response operations.

في العقود الأخيرة، زاد حجم البترول المنقول باستخدام ناقلات البترول زيادة كبيرة. نتيجة لذلك لقد جرت حوادث كثيرة أدت الى تسرب كميات كبيرة من البترول الى البيئة البحرية. عند حدوث انسكاب للبترول، يجب اتخاذ طرق استجابة مناسبة لاستعادة اكبر كمية ممكنة من البترول المسكوب ولتقليل حدة الضرر البيئي المترتب على ذلك. فى هذا البحث، تمت مناقشة طرق الاستجابة وكذلك عملية اتخاذ القرار المتعلقة باختيار أفضل طريقة أو مجموعة من الطرق للحصول على أقل تكاليف فى حالة انسكاب البترول. وقد تم اقتراح نموذج لشجرة قرار كما تم تطبيقه على سيناريو افتراضي لبترول منسكب لإظهار صحة النموذج المقترح. تم أيضا عرض ومناقشة الحل. لقد تم أيضا القيام بتحليل لحساسية الحل لتحديد المتغيرات الأكثر تأثيرا في عملية اتخاذ القرار. وقد أظهر أسلوب اتخاذ القرار المقترح أنه سهل التطبيق ومفيد للغاية بالنسبة لمتخذ القرار المسئول عن عمليات الاستجابة عند انسكاب البترول في البحر.

Keywords: Oil spill, Response methods, Decision tree, Expected cost, Sensitivity analysis

1. Introduction

Oil spills from tankers and offshore drilling and production operations occur in a very short period of time, thus having serious effects on the environment. The seriousness of an oil spill depends on several factors: size of spill, type of oil spilled, fate of the oil, and environmental conditions such as the weather and time of year.

Minimizing oil spill impacts on the environment, wildlife and affected communities requires rapid and effective response from the responsible party and the appropriate national and local authorities. A contingency plan is usually prepared in anticipation of an oil spill incident. The plan is prepared for a specific site or region and should include recommendations on the best way to respond when a spill occurs [1]. Refs. [1, 2] contain comprehensive up-to-date reviews on marine oil spill response.

Table 1 compiled from various oil spill incidents, lists fourteen major oil spills from ships that have occurred worldwide.

The International Tanker Owners Pollution Federation (ITOPF) has maintained a database of oil spills from tankers, combined carriers and barges, since 1974 [3]. Fig. 1 shows the number of spills over 700 tonnes that have occurred worldwide. The average number is shown to have decreased from 24.1 in the period (1970-79) to 7.3 in the period (1990-99). This is largely due to technical advances in tanker construction, navigation and communication equipment and to the petroleum industry's focus on prevention of oil spills.

In fig. 2, the quantities of oil spilled in thousands of tonnes are shown with some

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Table 1
Major oil spills worldwide

Date	Vessel involved	Location	Amount spilled (1000 tonnes)
1979	Atlantic empress	Off Tobago	287
1991	ABT	Off Angola	260
1983	Castillo de Bellver	South Africa	252
1978	Amoco Cadiz	France	227
1991	Haven	Italy	140
1988	Odyssey	Off Canada	132
1967	Torrey Canyon	England	119
1972	Sea Star	Gulf of Oman	125
1976	Urquiola	Spain	108
1977	Hawaian Patriot	North Pacific	99
1992	Aegean Sea	Spain	72
1989	Exxon Valdez	Alaska	37
1992	Braer	Shetland	85
1996	Sea Empress	Milford Haven	70+

years (1979,1983 and 1991) having considerably large amounts due to a single large incident. Fig. 3 shows the incidence of spills larger than 700 tonnes by cause, from 1974 to 2000.

In the aftermath of an oil spill, what oil spill response method or combination of methods should be adopted? A decision process must be applied to select appropriate response method options. The decision maker (usually the responsible party) is faced with a complex problem, having to balance the potentially high and uncertain cost of oil spill damage with the similarly high cost of cleanup operations [4]. A decision analysis technique is needed to help the decision maker. This paper proposes such a technique.

2. Marine oil spill response

Oil spill response means actions that are taken to confirm the occurrence of an oil spill, stop its flow from the source, contain it, collect it, protect areas from damage by it, minimize its effects on the environment and cleanup affected areas.

2.1. Factors affecting the fate of spilled oil

When oil is spilled into the sea, it spreads over the water surface forming an oil slick. The rate at which the oil spreads and the thickness of the oil slick depend on the sea water temperature and the type of oil. A light oil spreads faster than a heavy oil [5]. The oil composition changes with time. A portion evaporates, another portion dissolves in the water column, and some components become emulsified and disperse as small droplets. Under the action of waves, oil emulsifies and forms what is known as *chocolate mousse*. Heavy residues form tar balls. Oil slicks travel downwind, and when a slick hits the shore it is stranded with possibly dire consequences to the environment.

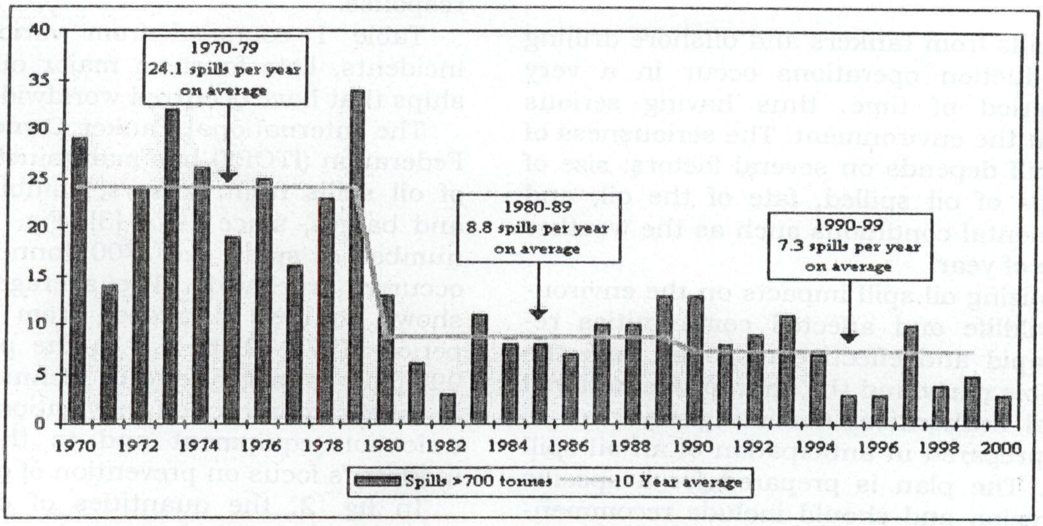

Fig.1. Number of spills over 700 tonnes [3].

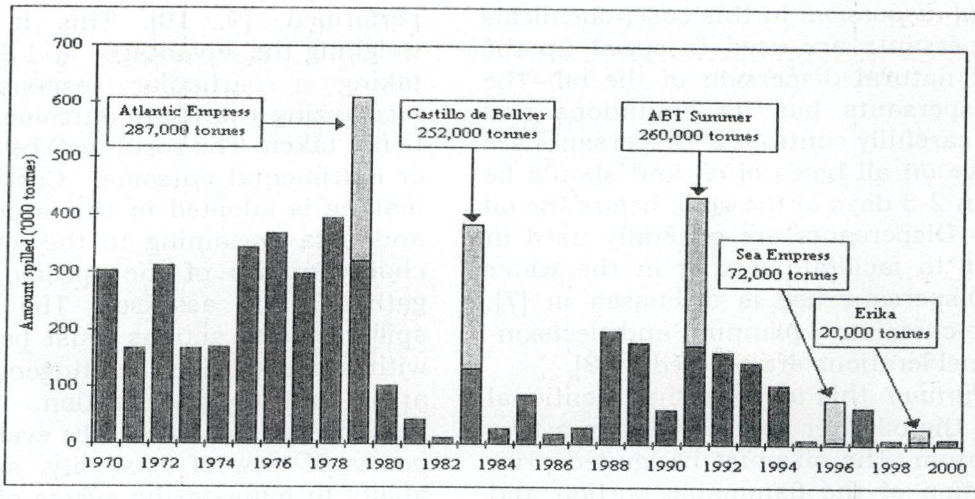

Fig. 2. Quantities of spilled oil [3].

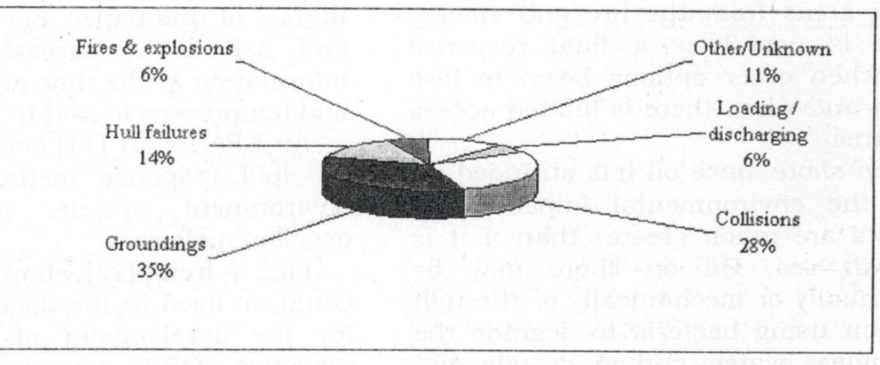

Fig. 3. Incidence of spills >700 tonnes by cause, 1974-2000 [3].

2.2. Oil spill response methods

It is obviously advantageous to remove oil spills while still at sea. Oil spill response is a challenging task and is only initiated if the spilled oil threatens a shoreline or important marine life. Various response methods have been developed and may be used if it is determined that the spilled oil will pose a threat to coastal areas [6]. The most commonly used response options are:

a) *Do nothing*: in this option, nature is allowed to take its course and the ultimate fate of the oil will depend on the strength and direction of the wave action and water column movement. In this option, no spilled oil is recovered and extensive damage will result if the oil hits the shore. It is important to monitor the movement of the spilled oil so that if it is observed to move towards the shore, prompt response is initiated.

b) *Offloading*: if the oil is leaking at a slow rate and can be recovered from the source, offloading the oil is a good option provided the necessary equipment and oil storage and transport facilities are available, the weather permits and the offloading operation can be performed safely.

c) *Mechanical containment and recovery*: in this case, the pollutant is contained using booms and removed from the environment by mechanical means such as skimmers. This option involves a high capital investment, low effectiveness in bad weather and a need for disposal facilities for the removed oil. In this method, a portion of the oil is recovered and may be recycled.

d) *Chemical dispersion*: in this case, chemicals called dispersants are used to speed up the process of natural dispersion of the oil. The use of dispersants has its limitations and should be carefully controlled. Dispersants are not effective on all types of oil and should be used within 2-3 days of the spill, before the oil emulsifies. Dispersants are generally used in deep water to facilitate mixing in the water column. Dispersant use is discussed in [7], while their chemistry, planning and decision-making considerations are covered in [8].

e) *In-situ burning*: this involves the intentional burning of the oil after containing it in a fire-resistant boom. The oil must be ignited prior to evaporation of the flammable portion and prior to weathering of the oil. Precautions must be taken to protect workers and surrounding areas from the fire and smoke. This option is useful as a final response technique, when other options begin to lose effectiveness and when there is limited access to the spill area.

f) *Cleanup on shore*: once oil has stranded on the shore, the environmental impacts and cleanup costs are much greater than if it is dealt with at sea. Oil on shore may be removed manually or mechanically or through bioremediation using bacteria to degrade the oil into harmless water, carbon dioxide and fatty acids. Bioremediation is a safe and effective technique for environmentally sensitive areas. When will the cleanup begin and end at a certain location will depend upon an agreed set of environmental standards based on the location's sensitivity to both the oil and cleaning methods. Sometimes, it is recommended to leave the shore to recover naturally.

2.3. The decision making process

Managing a spill response operation involves a decision making process whereby identified along with a set of specified goals. These goals may include reducing the cost of the spill, minimizing the damage to the environment or other objectives as appropriate. If the goal is to minimize different alternatives (response methods) are the damage to the environment, a Net Environmental Benefit Analysis (NEBA) must be performed, [9, 10]. This is a process of weighing the advantages and disadvantages of taking a particular response action and recognizing the likely outcomes if that action is not taken. The result will be a net beneficial or detrimental outcome. Cost-based decision making is adopted in this study. Information and data pertaining to the location and the characteristics of the specific spill must be gathered and assessed. The objectives and spill response actions must be in compliance with a pre-specified contingency plan for the area under consideration. The proposed response actions should be evaluated from the points of view of feasibility, safety, cost and ability to mitigate the effects of the spilled oil on the environment. The response actions can include one or more of the methods described in §2.2 of this paper. Each oil spill is different and has to be assessed on the available information at the time and hence the decision making process is said to be spill-specific.

An EPA report [11] covering the selection of oil spill response methods gives important environment specific guidelines to help decision makers.

Fig. 4 from [12] shows a target tree that could be used in the decision making process for the development of immediate oil spill response (OSR) measures. The target tree layout may change in each single oil spill case. The shown tree assumes mechanical cleanup to be the primary response option. This is usually true for many countries, e.g. Egypt and USA [13]. In many European countries, e.g. UK and Belgium, chemical dispersion is the primary response option [13,14]. In the target tree of fig. 4, chemical dispersion is the secondary response option while cleaning-up on coast is the only remaining option to be used if the oil reaches the coast.

2.4. Uncertainties associated with oil spill response

The decision making process can be complicated because of uncertainty about what the future holds. During a marine oil spill operation, decisions are made without exactly knowing what the ultimate outcome will be. Many different uncertain events might

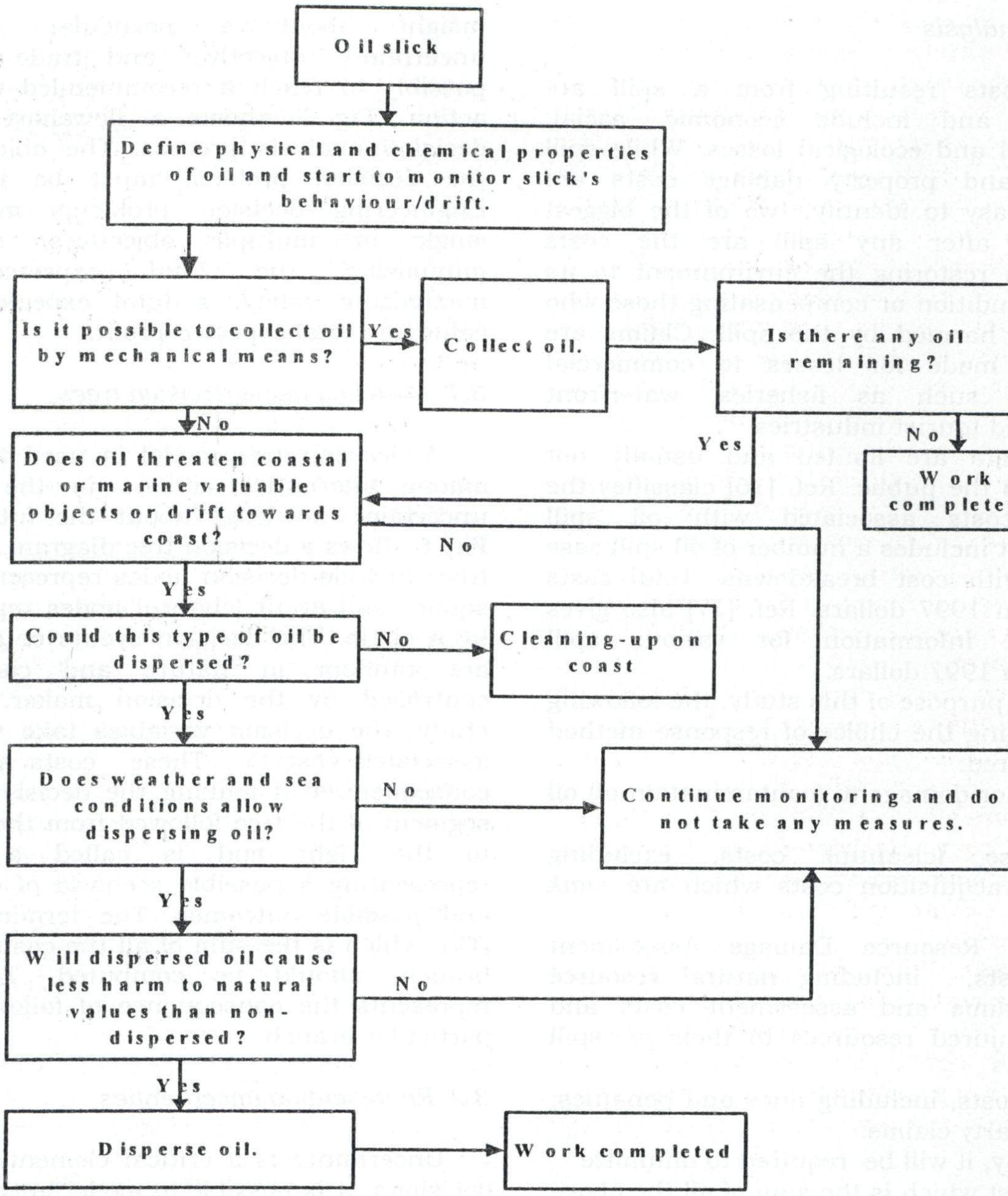

Fig. 4. Oil spill response target tree [12].

influence the decision process. Possible outcomes resolve from an uncertain event. Ref. [15] discusses uncertainties in oil spill modeling. The most important uncertainties result from the weather. To quantify these uncertainties, short- and long-term weather and wave forecasts must be available. It is important to be able to predict the movement of the oil and whether or not it is likely to hit the shoreline. The success of a particular response option is highly uncertain. Predicting the possible outcomes and the effectiveness of a certain response option and comparing it to the other available options is crucial to the decision process. The expected effectiveness of each option must be evaluated within certain time limits [8]. Measures of success must be defined and quantified so that the alternatives may be compared.

2.5. Cost analysis

The costs resulting from a spill are numerous and include economic, social, recreational and ecological losses. While spill response and property damage costs are relatively easy to identify, two of the biggest unknowns after any spill are the costs involved in restoring the environment to its pre-spill condition or compensating those who have been harmed by the spill. Claims are frequently made for losses to commercial enterprises such as fisheries, waterfront facilities and tourist industries .

Cost data are limited and usually not available to the public. Ref. [16] classifies the different costs associated with oil spill incidents. It includes a number of oil spill case histories with cost breakdowns. Total costs are given in 1997 dollars. Ref. [17] also gives some cost information for various spill incidents in 1997 dollars.

For the purpose of this study, the following costs affecting the choice of response method are considered:

a) Loss of or damage to (contamination of) oil costs.

b) Response (cleanup) costs, excluding equipment acquisition costs which are *sunk costs*.

c) Natural Resource Damage Assessment (NRDA) costs, including natural resource damage claims and assessment costs and restoring injured resources to their pre-spill condition.

d) Other costs, including fines and penalties, and third party claims.

In this study, it will be required to minimize the total cost which is the sum of all the above costs.

3. Decision analysis

Decision analysis provides structure and guidance for thinking systematically about hard decisions [18]. It helps the decision maker take actions with confidence and provides analytical tools to solve systematic decision problems.

Decision analysis is a source of information helping the decision maker to gain insight about a particular situation, uncertainty, objectives and trade-offs, and possibly to reach a recommended course of action. Fig 5 shows a flowchart for the decision analysis process. The objectives of the decision problem must be identified. Engineering decision problems may have single or multiple objectives, such as minimizing the total expected cost, maximizing safety, a total expected utility value and total expected profit.

3.1. Modeling using decision trees

A decision tree model is used to choose among alternative actions in the face of uncertain knowledge about the future [19]. Fig. 6 shows a decision tree diagram. Decision trees include decision nodes represented by a square and event (chance) nodes represented by a circle. The decision events or outcomes are random in nature and cannot be controlled by the decision maker. In this study, the decision variables take values of associated cost C_i . These costs are direct consequences of making the decisions. Each segment of the tree followed from the left end to the right end is called a branch representing a possible scenario of decisions and possible outcomes. The terminal value (TV), which is the sum of all the costs along a branch, should be computed. This (TV) represents the consequence of following this particular branch.

3.2. Representing uncertainties

Uncertainty is a critical element of many decisions. It is possible to model uncertainties through the appropriate use of probability. A chance event is an uncertain event having more than one possible outcome. For the possible outcomes of an event (chance) node, the probabilities P_i must be between 0 and 1 and they must add up to 1.

Probabilities associated with outcomes of an uncertain event are very difficult to estimate. A good estimate should be based on available data and previous experience. Many subjective judgments are usually made in decision analysis.

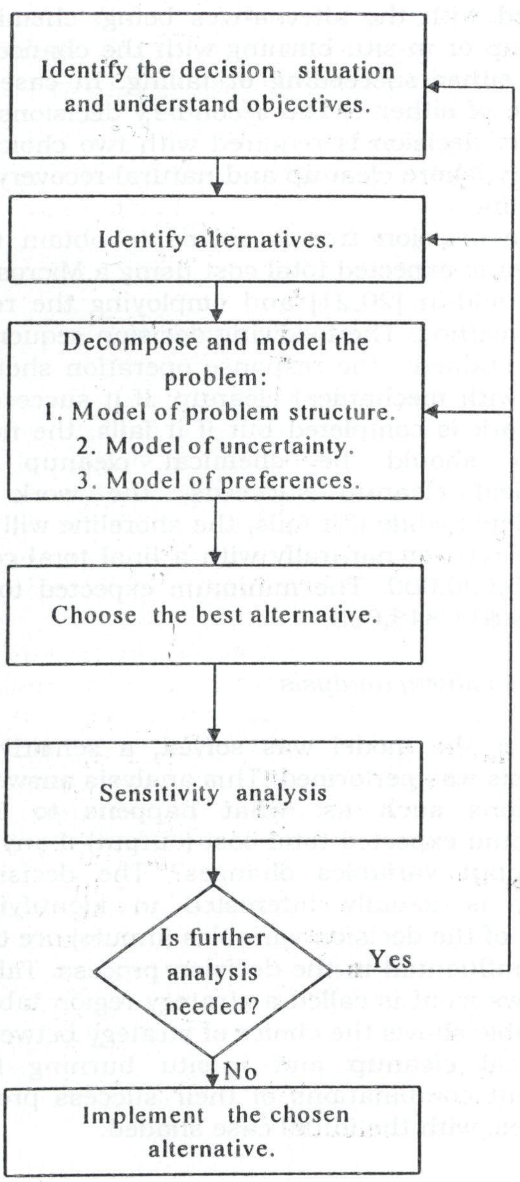

Fig. 5. Decision analysis process flowchart [18].

3.3. Solving decision trees

To choose among possible alternatives, the alternative with the lowest expected monetary value (EMV), in a cost minimization problem must be picked. To find the EMVs, a procedure called rolling back is performed. Referring to fig. 6, we start at the terminal nodes on the far right-hand side of each branch and move to the left, (1) calculate EMVs for each outcome of an event (chance) node and each decision (alternative) of a decision node, and (2) choose the branch with

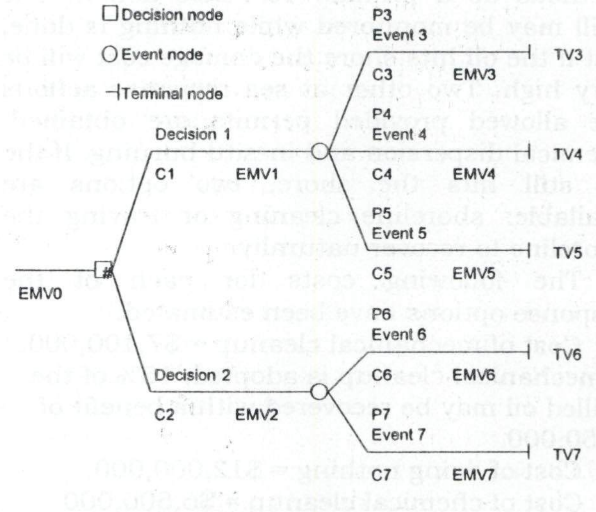

Fig. 6. Decision tree diagram.

the lowest EMV when a decision node is encountered. Therefore:

$$TV3 = C1 + C3 = EMV3$$
$$TV4 = C1 + C4 = EMV4$$
$$TV5 = C1 + C5 = EMV5$$
$$TV6 = C2 + C6 = EMV6$$
$$TV7 = C2 + C7 = EMV7$$
$$EMV1 = EMV3 \times P3 + EMV4 \times P4 + EMV5 \times P5$$
$$EMV2 = EMV6 \times P6 + EMV7 \times P7$$
$$EMV0 = MIN\ (EMV1, EMV2)$$

The number # in the decision node square is equal to 1 if EMV0 = EMV1, and equal to 2 if EMV0 = EMV2.

4. Application example

To demonstrate the applicability of the decision analysis technique to the decision making process in marine oil spill response, a hypothetical oil spill incident scenario is assumed.

4.1. Oil spill incident scenario

An oil tanker has run aground and is sinking near the shoreline. There are seabirds nearby, fishing grounds and tourist facilities. A large amount of oil has been spilled out of the tanker. The contingency plan for the spill area dictates the use of mechanical cleanup methods as a primary response action. The spill may be monitored while nothing is done, but if the oil hits shore the damage cost will be very high. Two other at sea response actions are allowed provided permits are obtained: chemical dispersion and in-situ burning. If the oil still hits the shore, two options are available: shoreline cleaning or leaving the shoreline to recover naturally.

The following costs for each of the response options have been estimated:

a) Cost of mechanical cleanup = $7,100,000. If mechanical cleanup is adopted, 15% of the spilled oil may be recovered with a benefit of $750,000.
b) Cost of doing nothing = $12,000,000.
c) Cost of chemical cleanup = $6,500,000.
d) Cost of in-situ burning = $7,400,000.
e) Cost of shore cleanup = $8,000,000.
f) Cost of natural recovery of shoreline = $2,000,000.

The probability of success of mechanical cleanup is estimated to be 0.3, that of chemical cleanup to be 0.7, and that of in-situ burning to be 0.6.

4.2. Minimum-cost solution

The decision tree model of fig.7 is proposed for the given incident scenario. The primary decision is to choose between two alternatives, namely, mechanical cleanup and doing nothing. The outcomes of the mechanical cleanup decision are either success or failure. In the case of failure, a secondary decision is needed with the alternatives being: chemical cleanup or in-situ burning with the chance of each either succeeding or failing. In case of failure of either of the secondary decisions, a tertiary decision is required with two choices, namely, shore cleanup and natural recovery of shoreline.

The decision tree is solved to obtain the minimum expected total cost using a Microsoft Excel add-in [20,21] and employing the roll-back method. The following decision sequence was obtained: the response operation should start with mechanical cleanup. If it succeeds, the work is completed but if it fails, the next action should be chemical cleanup. If chemical cleanup succeeds, the work is completed while if it fails, the shoreline will be left to recover naturally with a final total cost of $15,600,000. The minimum expected total cost is $11,845,000.

4.3. Sensitivity analysis

After the model was solved, a sensitivity analysis was performed. This analysis answers questions such as: what happens to the minimum expected total cost (output) if any of the input variables changes? The decision maker is usually interested in identifying which of the decision variables (inputs) are the most influential in the decision process. Table 2 shows what is called a strategy region table. The table shows the choice of strategy between chemical cleanup and in-situ burning for different combinations of their success probabilities, with the initial case shaded.

Table 2
Strategy region table

P(ChemOK) \ P(BurnOK)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1.0	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem
0.9	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem
0.8	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem
0.7	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem
0.6	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem
0.5	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Burn
0.4	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Burn	Burn
0.3	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Burn	Burn	Burn
0.2	Chem	Chem	Chem	Chem	Chem	Chem	Chem	Burn	Burn	Burn	Burn
0.1	Chem	Chem	Chem	Chem	Chem	Chem	Burn	Burn	Burn	Burn	Burn
0.0	Chem	Chem	Chem	Chem	Chem	Burn	Burn	Burn	Burn	Burn	Burn

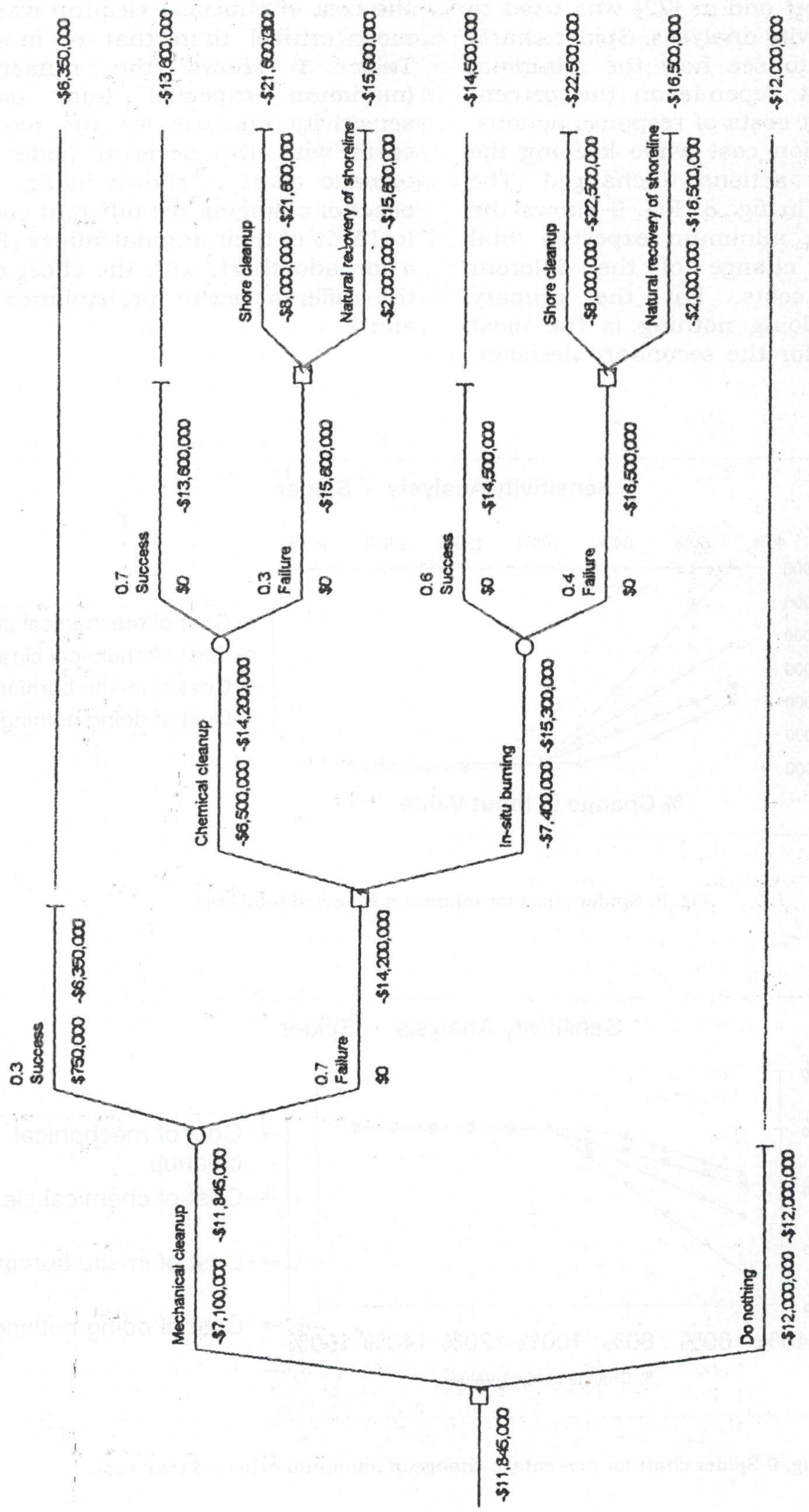

Fig. 7. Marine oil spill response decision tree.

A Microsoft Excel add-in [22] was used to perform the sensitivity analyses. Spider charts were constructed to see how the minimum expected total cost depends on the percent change for different costs of response actions, changing each action cost while keeping the cost of the other actions unchanged. The results are shown in fig. 8. Fig. 9 shows the percent change in minimum expected total cost for percent change of the different response action costs. For the primary decision, cost of doing nothing is the most influencing, while for the secondary decision, the cost of chemical cleanup was found to be more critical than that of in-situ burning. Table 3 shows the numerical results (minimum expected total cost) of the sensitivity analysis for the most influential costs with the decision node sequence. A tornado chart is shown in fig. 10, with the effect of changing the different costs from 50% to 150% of their original values. Fig. 11 shows a tornado chart, with the effect of fluctuating the different event probabilities between 0 and 1.

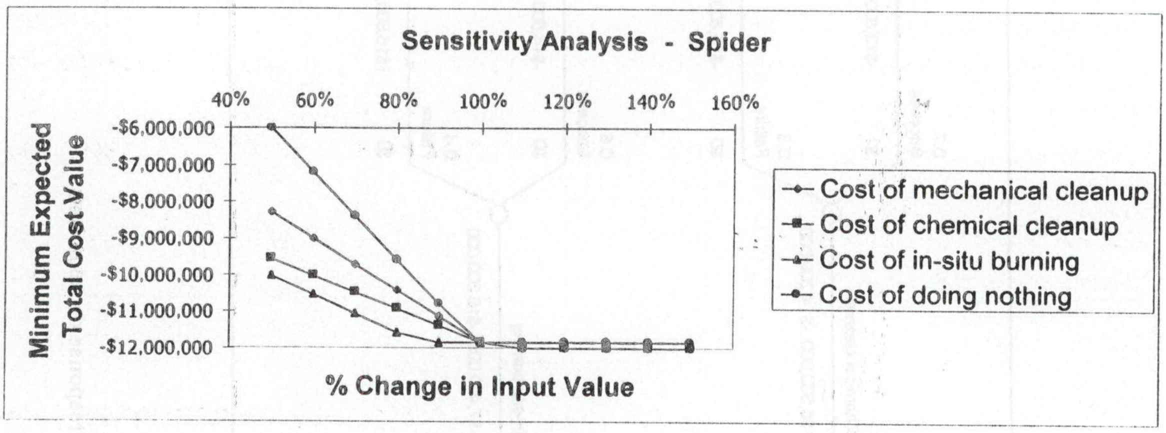

Fig. 8. Spider chart for minimum expected total cost.

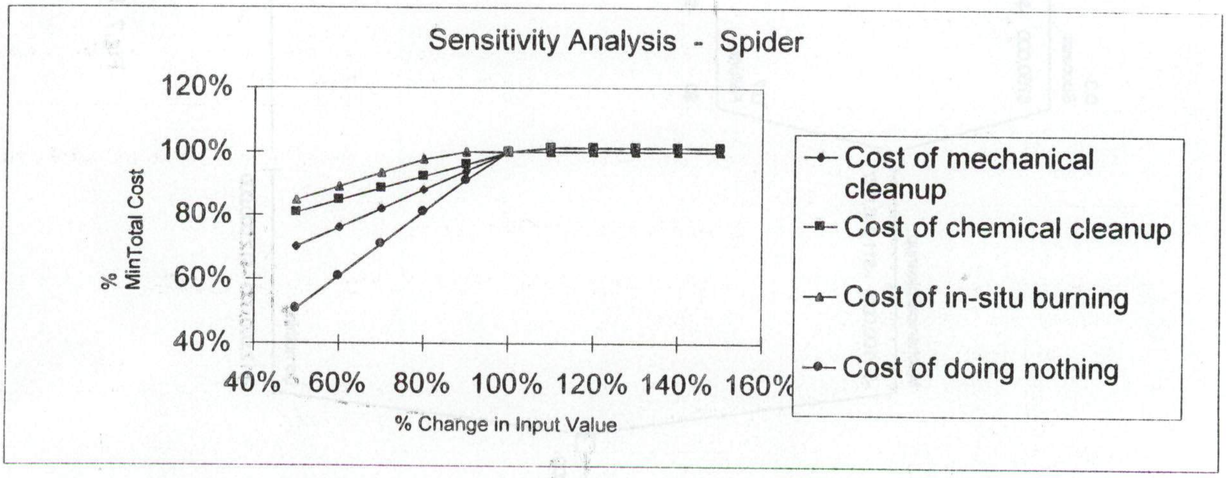

Fig. 9 Spider chart for percentage change in minimum expected total cost.

Table 3
Results of sensitivity analysis, minimum expected total cost and decision node sequence

	50%	60%	70%	80%	90%
Change in cost of mechanical cleanup	-$8,295,000	-$9,005,000	-$9,715,000	-$10,425,000	-$11,135,000
Decision node sequence	1,1,2	1,1,2	1,1,2	1,1,2	1,1,2
Change in cost of chemical cleanup	-$9,570,000	-$10,025,000	-$10,480,000	-$10,935,000	-$11,390,000
Decision node sequence	1,1,2	1,1,2	1,1,2	1,1,2	1,1,2
Change in cost of in-situ burning	-$10,025,000	-$10,543,000	-$11,061,000	-$11,579,000	-$11,845,000
Decision node sequence	1,2,2	1,2,2	1,2,2	1,2,2	1,1,2
Change in cost of doing nothing	-$6,000,000	-$7,200,000	-$8,400,000	-$9,600,000	-$10,800,000
Decision node sequence	2	2	2	2	2
	110%	120%	130%	140%	150%
Change in cost of mechanical cleanup	-$12,000,000	-$12,000,000	-$12,000,000	-$12,000,000	-$12,000,000
Decision node sequence	2	2	2	2	2
Change in cost of chemical cleanup	-$12,000,000	-$12,000,000	-$12,000,000	-$12,000,000	-$12,000,000
Decision node sequence	2	2	2	2	2
Change in cost of in-situ burning	-$11,845,000	-$11,845,000	-$11,845,000	-$11,845,000	-$11,845,000
Decision node sequence	1,1,2	1,1,2	1,1,2	1,1,2	1,1,2
Change in cost of doing nothing	-$11,845,000	-$11,845,000	-$11,845,000	-$11,845,000	-$11,845,000
Decision node sequence	1,1,2	1,1,2	1,1,2	1,1,2	1,1,2

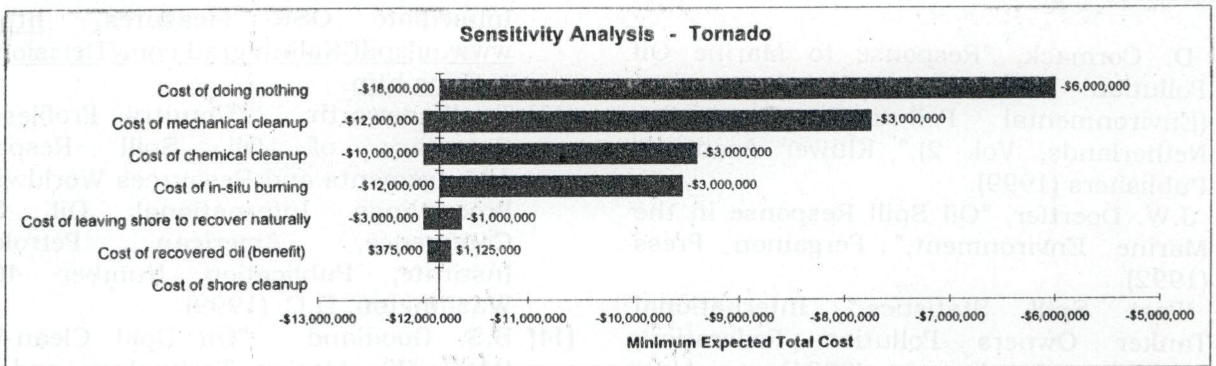

Fig. 10. Tornado chart showing the effect of different cleanup costs on the minimum expected total cost.

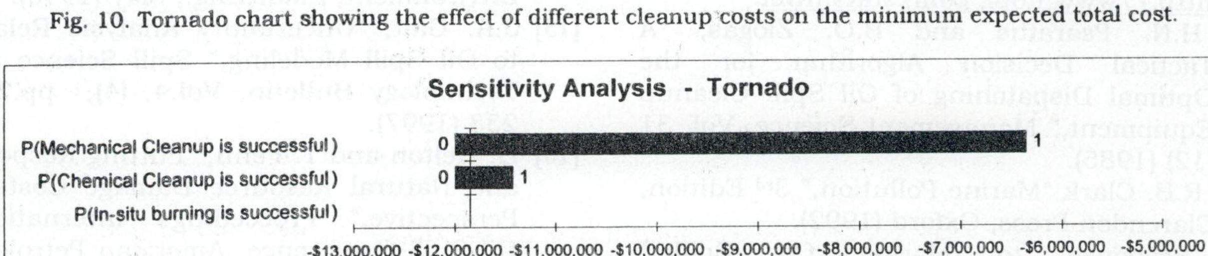

Fig. 11. Tornado chart showing the effects of the main response method's probabilities of success on the minimum expected total cost.

5. Conclusions and recommendations for future work

A decision analysis technique during marine oil spill response is a useful aid to the decision maker concerned with choosing between different response methods. Previous oil spill experiences provide information on cost and success or effectiveness of various response techniques. Such information may be used in the decision process when an oil spill incident occurs. Different decision tree models may be used to represent different spill incidents, depending on the appropriate contingency plan. The following future work is recommended:

1) An environmental damage assessment based on NEBA should be performed and environmental damage quantified.
2) A multi-objective model instead of a single objective model should be used where both costs and environmental damage are taken into consideration.
3) Work is needed to quantify the uncertainties to be used in the analysis.

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