A decision-making model for oil spill response at the tactical level

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Abstract

The present paper addresses the tactical level of the oil spill response decision-making process, that determines the actions required to respond to a specific spill. In the broader area of the incident, a number of response facilities may exist. These facilities are equipped with known quantities and types of oil response equipment. The decision-maker needs to determine from which facilities to dispatch units to the spill site and, moreover, the types and quantities of the units to be dispatched. The objective is to respond to the specific spill in an optimal way; one approach is to respond optimally on a cost basis. The above tactical problem is modeled as an optimisation problem by applying the linear programming theory. An illustrative application of the model is finally presented.

Keywords

Oil spill response; tactical decision-making; linear programming.

1. Introduction

The oil spill decision-making process is divided into three hierarchical levels: the strategic, the tactical and the operational one (Anthony, 1965 and Psaraftis & Ziogas, 1985). The present paper addresses the tactical level, that determines the actions required to respond given a specific spill. At the strategic level, potential future spills are of concern, while at the operational level more detailed actions to be taken on the scene of a specific spill are determined.

The decision-making problem at the tactical level can be described as follows. A spill of known characteristics occurs. In the broader area of the incident, a number of response facilities exist (usually they are located at ports). These facilities are equipped with known quantities and types of oil response equipment of certain characteristics (oil recovery capacity, etc.). The decision-maker needs to determine from which facilities to dispatch units to the spill site and, moreover, the types and quantities of the units to be dispatched.

The objective is to respond to the specific spill in an optimal way. "Optimal" is subject to interpretation. In the model presented in this paper, the approach adopted is to respond optimally on a cost basis. In this case, the decision-maker's objective is to minimise the total cost, by balancing the response (system) costs and the spill damage costs with the introduction of a relative weight coefficient. Other approaches would set as primary objective to minimise the response time or maximise the coverage of spill (e.g. Belardo et al, 1984).

The above tactical problem is modelled as an optimisation problem by applying the linear programming theory. The values of the decision variables that meet the constraints and minimise the objective function are the solution to the problem.

It should be noted that the presented model has been developed in the context of the on-going EC-funded research project EU-MOP, which addresses the design of an intelligent robot system capable of responding to oil spills. The EU-MOP concept comprises autonomous unmanned oil-cleaning robot vessels of Monocat and Catamaran types and of sizes ranging in length from approximately 1 to 3 m (Figure 1), each one equipped with a number of sensors (for navigation, oil detection etc.). EU-MOP units will operate as a swarm to clean a spill (Figure 2).

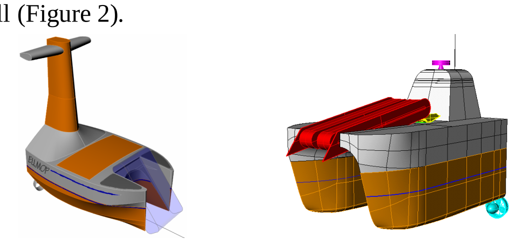

Fig. 1: Monocat and Catamaran type EU-MOP units

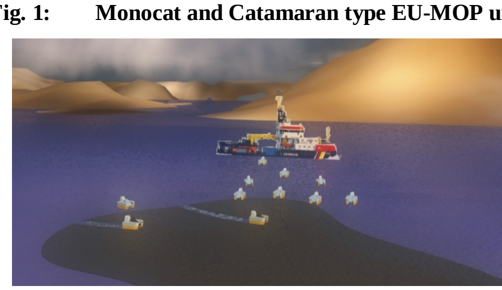

Fig. 2: EU-MOP swarm in operation

The control station of a swarm will be located on a mother ship (Fig. 2), which will transport the response units to the spill site, with the assistance of other supply (transport) vessels, if required by the total number of units to be dispatched. The EU-MOP tactical decision maker will have the task of determining from which facilities to dispatch response equipment to a spill site and, moreover, the types and quantities of the units to be dispatched. The EU-MOP tactical response command and information flows are shown in Figure 3.

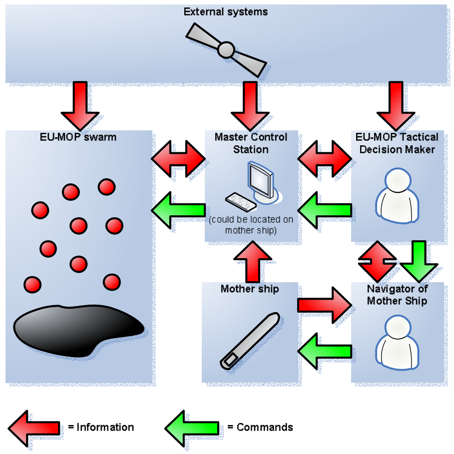

Fig. 3: EU-MOP command and information flows

The rest of the paper is organised as follows. After a brief literature review in Section 2, the problem is defined in Section 3 and the solution algorithm is presented in Section 4. The mathematical formulation of the problem is provided in Section 5. In Section 6, the model input and relevant calculations are outlined, while in Section 7, an illustrative example of the model is presented. Section 8 concludes the paper.

2. Literature Review

The present paper refers to the tactical problem of the oil spill decision-making process, that is part of an integrated work in the EU-MOP project that also covers the strategic problem. In this section, reference is made to the literature that provided the necessary background to this work and an understanding of the accumulated knowledge and experience in the field. Many of these papers address the strategic problem, solution of which is an input to the tactical problem. As the strategic problem was developed in parallel to and as an aggregation of tactical problems, such papers are also discussed next. However, the comments are restricted to points mainly relevant with the modelling of the tactical level problem.

A seminal paper about the strategic planning of oil spill response is the one by Psaraftis et al. (1986). The paper deals with the strategic aspect of the oil spill response problem. It presents the development of a model for allocating appropriate levels and types of clean-up capability to respond to future oil spills among points of high oil spill potential.

The present work has adopted quite many elements from this model. For example, the objective of the problem is to minimise the expected algebraic sum of the response system costs and the costs due to damages from spills, the latter balanced with a user-specified "weight" coefficient. Also, many problem parameters have been adopted as suggested in this paper (various cost & technical parameters, etc.).

On the other hand, the presented model addresses a more complicated response infrastructure that requires the dispatch of a mother vessel and possibly more than one supply vessels for the transportation of response units from the facilities to a spill site (in accordance with the EU-MOP concept).

The paper by Psaraftis & Ziogas (1985) provided an example of a tactical level decision-making algorithm. This paper describes a deterministic methodology for the optimal allocation of resources for cleaning up a specific spill after its occurrence is made known. This is also the rationale of the tactical algorithm in the presented model.

Moreover in the present work, the approach in Psaraftis & Ziogas' paper regarding the hierarchical levels of the oil-spill decision-making process (i.e. strategic, tactical and operational), the distinction of the respective decision variables and their interaction have been followed (see also Anthony, 1965). For example, equipment acquisition costs and other costs that have been committed at the strategic decision level are sunk costs and are not considered in the tactical problem.

On the other hand, the present model differs structurally from Psaraftis & Ziogas' one. The major difference is that their model is part of a broader model ("the MIT oil spill model"), where spill incidence, damage assessment, the strategic model and other components are equally distinct parts and therefore external to the tactical problem. In the end, Psaraftis & Ziogas construct a tactical model solved at discreet time steps using a dynamic programming solution algorithm, with numerous inputs furnished externally. Instead, the presented tactical problem is a stand-alone model (e.g. with a built-in damage assessment algorithm) with an original and simplified structure using a linear programming solution algorithm.

On the other hand, this model also forms part of a broader simulation tool that addresses the strategic decision-making of the oil spill response procedure. In that simulation, the tactical model is recalled and run numerous times in the search for a solution to the strategic problem.

A paper by Belardo et al. (1984) presents an alternative approach to oil-spill response decision-making. The objective in this model is not to minimise a function of cost, but to maximise the overall probability of covering an oil spill incident. The notion of "coverage" is appropriately defined in terms of the availability of the needed resources within a critical time; that is before the spill hits the shore. The model can accommodate a budget constraint, but does not consider the trade-offs between the spill response and damage costs on a cost/benefit basis. An alternative model according to this rationale is also under development and will hopefully be used at a later stage for verification and comparison purposes.

From Belardo et al.'s model, the damage potential assessment rationale has been adopted. Accordingly, a spill incident is placed into one of three distinct groups of (ranked) damage potential, following the assessment of its impact on various target categories.

A paper by Iakovou et al. (1996) has been taken into account and certain similarities with the presented model can be identified. First, of all, the solution of the strategic problem is not addressed independently of the tactical problem. Strategic level decisions are evaluated by taking into account their impact on post oil spill decisions. Also, a linear integer programming algorithm is used, with the integrality relaxed, as in the presented model. Another similarity is the critical time to respond to a spill incident that is introduced as a constraint.

However, the above model requires significant data preparation work. Transportation costs are assumed to comprise both clean-up and damage costs expressed in the model through a ratio of unit cost to unit time parameter. The present model is more detailed and explicit in calculating these costs and introducing them in the objective function of the optimisation.

Other relevant papers include Charnes et al. (1979), Charnes et al. (1976), and Srinivasa and Wilhelm (1997). Also, a paper by Iakovou et al. (1994) reviews the models that had been developed up to that time regarding oil-spill response planning. Their commentary covers historical data analysis, strategic decision-making, tactical decision-making, and operational decision-making. Alidi (1993) undertakes a similar review. The previously-discussed papers are considered as the most relevant to the present work and the most representative and influential regarding the work done in the field by researchers in the last decades. To the best of our knowledge, no other significant and relevant work has appeared in the literature.

3. Problem Definition

3.1 Oil-Spill Response Decision-Making

The present paper addresses the tactical level of the oil spill decision-making process, that determines the actions required to respond to a specific spill.

The decision-making problem at the tactical level can be described as follows. A spill of known characteristics occurs. In the broader area of the incident, a number of response facilities exist (usually they are located at ports). These facilities are equipped with known quantities and types of oil response equipment of certain characteristics (oil recovery capacity, etc.). The decision-maker needs to determine from which facilities to dispatch units to the spill site and, moreover, the types and quantities of the units to be dispatched.

The objective is to respond to the specific spill in an optimal way. “Optimal” is subject to interpretation. In this model, the approach adopted is to respond optimally based on a cost criterion. In this case, the decision-maker’s objective is to minimise the total cost, by balancing the response (system) costs and the spill damage costs with the introduction of a relative weight coefficient.

In general, more expenses devoted in response (an increase in response costs) will result in the faster collection of more oil, i.e. in a reduction of the spill damage costs. The overall spill damage costs are the no-response costs (that would be incurred if no response took place) minus the damage costs that would result from the amount of oil that is collected. A weight coefficient is used to determine the relative value of response vis-à-vis damage costs, as it will be later explained.

The above tactical problem is modelled as an optimisation problem by applying the linear programming theory. The values of the decision variables that meet the constraints and minimise the objective function are the solution to the problem.

3.2 Formulating an Appropriate Model

The case is considered where I available response (stockpiling) facilities - each with up to E types of response equipment - exist nearby the area of the spill site.

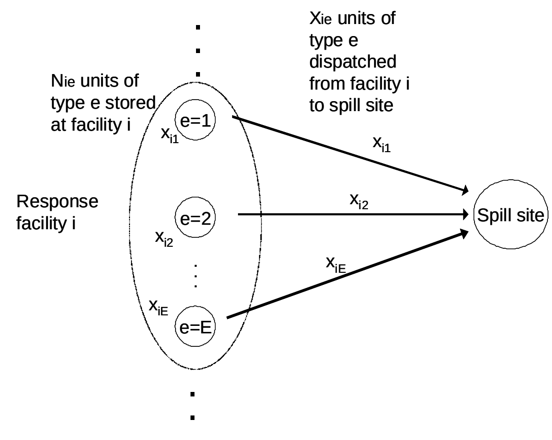

Fig. 4: Problem definition

At each response facility i (i ϵ I), N_{ie} units of type e are stored (see Figure 4). An oil spill incident of known characteristics occurs. Depending on the characteristics of the oil spill incident, specific needs arise for the dispatch of x_{ie} units of type e from facility i to the spill site.

The tactical level decision-making answers the question of how many units x_{ie} of each type e should be dispatched from each facility i to the spill site, so as to minimise the total costs (balancing the system costs and the potential damage costs).

4. The Solution Algorithm

4.1 Decision Variables

The decision variables determine the type of equipment and the corresponding number of units that will be dispatched from each facility to the spill site, where a spill of certain characteristics occurs (simultaneous dispatch of equipment from more than one facilities is of course possible). Also, the decision variables determine whether a mother vessel will be dispatched to the spill site and whether additional supply vessels will be dispatched and from which response facilities (in accordance with the EU-MOP concept).

The solution to the problem is the set of the decision variables that minimises the value of the objective function.

4.2 Objective Function

The objective function to be minimised is the total cost. The total cost consists of the response costs, the response benefit and the no-response costs[1].

Total cost = (response costs) + (response benefit) + (no-response costs) (1)

The response costs are the transportation and clean-up costs of dispatching a number of units to the spill site, plus the operational costs of the mother/supply vessels.

The response benefit (negative costs) result from the (partial or total) recovery of the spilled oil, which corresponds to a reduction in the total damage (potential) costs of the spill.

The no-response costs are the expected total damage (potential) costs that would result from the spill incident, if no response took place.

It is the response costs and the response benefit that will be optimised, as the no-response costs are determined from the data of the problem; hence the values of the decision variables do not influence the no-response costs.

It is obvious that the response costs should be less than the response benefit (i.e. their algebraic sum should take a negative value, which signifies a benefit in the cost/benefit weighted balance) for the dispatch of response equipment to be justifiable. Moreover, the absolute value of the algebraic sum of the response costs and the response benefit should not exceed the no-response costs, otherwise excessive expenses will be devoted to the clean-up of the spill.

The tactical problem (as defined) is a linear one, and so a linear programming algorithm finds the optimal solution. In fact, the problem is a linear integer programming (IP) one, as the decision variables take integer values (moreover, those decision variables that refer to the mother/supply vessels are binary). In practice, integrality is relaxed (only for the non-binary decision variables) and the corresponding linear mixed-integer programming (MIP) problem is solved (LP relaxation) using the branch-and-bound simplex method (more on the relevant theory in Hillier & Lieberman, 1995). For each possible set of decision variables, a new value for the objective function is recalculated. When the optimisation is complete, an optimal solution (or set of decision variables) is found, which yields the best (cost) value for the objective function.

During the search for the optimal solution, the decision variables are changed across allowable ranges according to the preset constraints.

4.3 Constraints

The decision variables can take values that satisfy the applied constraints:

Constraints 0: The decision variables that determine the number of response units that will be dispatched from each facility to the spill site are non-negative integers (integrality to be relaxed). The decision variables that determine whether a mother vessel will be dispatched to the spill site and whether a supply vessel will be dispatched from a facility are binary (0/1) variables.

Constraint 1: The number of units of each equipment type that are dispatched from a facility to the spill site cannot exceed the total number of units of that type stored at the facility.

Constraint 2: The total response clean-up capacity (in tonnes / h) (adjusted with the operational efficiency rate of each equipment type) that is dispatched to the spill site and operates for the available clean-up time must be limited. A limit can be set by the spill size (tonnes) multiplied by a desired coverage coefficient CC (a CC greater than 1 signifies the dispatch of extra capacity to compensate for operational clean-up inefficiencies and introduces a safety margin).

Constraint 3: The dispatch of equipment of certain type to the spill incident should be made only when that type is operational with respect to the oil type, the weather conditions and the sea type at the spill site.

Constraint 4: The dispatch of equipment of certain type to the spill theatre should be made only when the time limitations are respected. The time limitations require that a response unit reaches the spill before the spill hits the shore (this limitation can be relaxed) and that the available time for its clean-up operation (that is the time from the moment the unit arrives at the spill until the spill hits the shore) is greater than a minimum time period set by the decision-maker.

Constraints 5: A supply vessel is to be used for the dispatch of certain response equipment from a facility to the spill site.

Constraints 6: A mother vessel is to be used for the dispatch of certain response equipment from a facility to the spill site. Constraints 5 and 6 basically refer to the EU-MOP response concept.

5. Mathematical Formulation

5.1 Model Parameters and Decision Variables

Explanations follow on the parameters used in the mathematical formulation of the model.

General parameters:

$i \in I$: Response facility;

$e \in E$: Type of response equipment;

$o \in O$: Oil type of the spill incident;

1 The fixed costs of opening some or all of the candidate response facilities and the variable acquisition and storage costs of the response equipment are sunk costs in the tactical decision-making problem. They are addressed in the strategic decision-making problem instead.

w є W: Weather conditions category of the spill incident;

s є {0,1}: Direction of the spill (away from the shore or towards the shore);

u_e (tonnes / h): Oil recovery capacity of 1 unit of type e equipment;

RE_e : Recovery efficiency rate of type e equipment;

T_{ie} (h): Available time for on-site cleaning operations at the spill site for type e units dispatched from i ;

TT_i (h): Total time of operations (travel to + on-site cleaning + return) at the spill site for units dispatched from i ;

MTT (h) = median (TT_i) : Assumption for the total time of operation of the mother vessel dispatched to the spill site;

TMIN (h): Minimum available time that justifies dispatching equipment for on-site cleaning operations;

v (tonnes) : Size of recorded spill;

CC: Desired coverage coefficient of the spill incident (CC=1 corresponds to the exact size of the spill);

N_{ie} : Maximum number (storage capacity) of type e units at facility i;

DC_e : Variable to determine whether type e is operational with respect to the oil type, the weather conditions and the sea type at the spill site;

DT_{ie} : Variable to determine whether type e units can be dispatched from facility i to the spill site within the time limitations.

<u>Cost parameters</u>:

SDC: The system / damage costs coefficient;

CT_{ie} (euros): Cost of transporting 1 unit of type e equipment from i to the spill site;

b_e (euros/h): Clean-up (operational) cost of 1 unit of type e equipment;

CO_o (euros/tonne): Cost of oil of type o;

DP : Damage potential coefficient assigned to the damage group where the spill incident is placed (explained later);

CSV (euros / h): operational cost of supply vessel (SV);

ECMV (euros / h): extra operational cost of mother vessel (MV) (compared to SV);

<u>Decision variables</u>:

x_{ie} : Number of type e units dispatched from facility i to the spill site;

SVi є {0,1}: Binary variable to determine whether a supply vessel is dispatched from facility i to the spill site;

MV є {0,1}: Binary variable to determine whether a mother vessel is dispatched to the spill site.

5.2 Objective Function

As it has been explained, the objective function is an expression of cost and specifically the total cost that has to be minimised (Eq. 2).

$$\textbf{\textit{T}}\text{otal Cost} = \sum_i \sum_e x_{ie} \cdot (CT_{ie} + b_e \cdot T_{ie} - SDC \cdot u_e \cdot T_{ie} \cdot RE_e \cdot CO_o \cdot DP) + \sum_i SV_i \cdot TT_i \cdot CSV + MV \cdot MTT \cdot ECMV + SDC \cdot v \cdot CO_o \cdot DP \qquad (2)$$

The first term corresponds to the response (system) costs (associated with the dispatched equipment units) minus the response benefit resulting from the (partial or total) recovery of the spilled oil.

The second and third terms correspond to the response (system) costs associated with the supply vessels and the mother vessel respectively.

The last term corresponds to the no-response costs.

5.3 Constraints

<u>Constraints 0</u>: Integrality in constraint (a) below is actually relaxed and the LP relaxation of the IP problem is solved (actually an MIP problem), as already explained. In practice, the solution is integral or near-integral (see Iakovou et al., 1996) and in the latter case, it is rounded to obtain a near-optimal solution.

$$\begin{aligned} &a)\ x_{ie} \geq 0 \ \text{ integers } \forall\, i, e \\ &b)\ SV_i,\ MV \in \{0,1\}\ \forall\, i \end{aligned} \qquad (3)$$

<u>Constraint 1</u>: The number of units of equipment type e dispatched from facility i to the spill site cannot exceed the total number of units of type e stored at i.

$$x_{ie} \leq N_{ie} \quad \forall\, i, e \qquad (4)$$

<u>Constraint 2</u>: Limit set to the total response capacity (adjusted with the efficiency rate and for the clean-up time) that is dispatched to the spill site. The desired coverage coefficient is taken into account.

$$\sum_i \sum_e x_{ie} \cdot RE_e \cdot u_e \cdot T_{ie} \leq CC \cdot v \qquad (5)$$

<u>Constraint 3</u>: The dispatch of equipment of type e to the spill incident is possible only when type e is operational with respect to the oil type, the weather conditions and the sea type at the spill site. A dummy variable is used for this purpose.

$$\sum_i x_{ie} \leq DC_e \ \forall\, e \qquad (6)$$

<u>Constraint 4</u>: The dispatch of equipment of type e to the spill incident is possible only when the time limitations are respected. A dummy variable is used for this pur-

pose.

$$x_{ie} \leq DT_{ie} \;\; \forall i, e \tag{7}$$

Constraints 5: The following constraints require that a supply vessel is to be used whenever the dispatch of certain response equipment (e.g. e = 1...m) from a facility to the spill site is to take place.

$$\begin{aligned} &a)\;\; SV_i \cdot 1000 \geq \sum_{e=1}^{m} x_{ie} \;\; \forall i \\ &b)\;\; SV_i \leq \sum_{e=1}^{m} x_{ie} \;\; \forall i \end{aligned} \tag{8}$$

The figure "1000" that appears in (a) above can be any number greater than the sum of all available units of types e = 1...m stored at the response facilities.

Constraints 6: The following constraints require that a mother vessel is to be used whenever the dispatch of certain response equipment (e.g. e = {1,2,3}) (and therefore of at least one supply vessel) from a facility to the spill site is to take place (if the supply vessel to be dispatched is only one, that will also be the mother vessel).

$$\begin{aligned} &a)\;\; MV \cdot 10 \geq \sum_{i} SV_i \\ &b)\;\; MV \leq \sum_{i} SV_i \end{aligned} \tag{C6}$$

The figure "10" that appears in (a) above can be any number greater than the sum of all response facilities (or possibly dispatched supply vessels).

6. Model Input and Relevant Calculations

The input data required for the model to run can be distinguished in spill data, the cost coefficient, response equipment data and facilities data.

6.1 Spill Data

The required spill incident data include:

- spill size (in tonnes);
- spill oil type;
- oil type characteristics (persistent / non-persistent and cost in euros / tonne);
- spill coverage coefficient;
- sea type (e.g. open ocean area, enclosed sea, shallow water area);
- weather conditions category (calm / moderate / rough);
- spill direction ("moving towards shore" or "away from shore");
- distance from shore (in nautical miles);
- speed approaching shore (knots);
- additional time for response (hours) – relaxation of preset time limit (i.e. the time it would take the spill to hit the shore).

The spill incident is placed in a damage potential group (A - High, B - Medium, C - Low), according to an internal calculation routine. This routine is extensively used in the strategic model, where numerous spill sites (and potential spill incidents) are examined. In the tactical problem, we need to place a known spill incident in a damage potential group. The required input for the calculation routine and for the spill site, where the incident occurs (in the tactical problem), should therefore normally be available to the decision maker from a database, constructed before the tactical decision-making point is reached. The required input is:

- a damage potential coefficient assigned to each group A, B, C;
- a score range (scale of 1-10) set for placing a spill incident in each group;
- a score 1-10 (from least sensitive to most sensitive) depending on the spill site geographical location;
- a relative weight for each of the target categories: "fish", "birds", "mariculture" and "beach-tourism";
- a score 1-10 (from least to most severe) regarding the relative impact of "size", "oil type", "distance from shore", "direction of spill", and "location" on potential damage to "fish", "birds", "mariculture" and "beach-tourism";
- a score (scale of 1-10) for the possible values of the parameters "size", "oil type", "distance from shore", and "direction" of a spill incident.

6.2 The System / Damage Costs Coefficient

The system / damage costs coefficient takes a value from the decision-maker. This coefficient expresses the relative value of 1 monetary unit spent for the response system compared to 1 monetary unit of spill damage. It represents how much the decision maker is willing to pay in system costs in order to reduce damage costs by 1 monetary unit (e.g. 1 euro).

Setting to this coefficient a value greater than 1 means that greater value is placed on the spill damage cost, rather than to the system cost (compared to what the monetary values of these costs suggest). Or in other words, a high value of the coefficient increases the relative importance of damage costs vis-à-vis system costs. A default value would be 1 (i.e. the relative monetary values represent the actual relative weight placed on the system / damage costs).

6.3 Response Equipment Data

The required data for each response equipment type include:

- nominal oil recovery capacity (tonnes/h);
- recovery efficiency rate;
- operational / clean-up cost (euros/h);
- weather conditions operational limits (calm / moderate / rough);
- type of oil operational limits (e.g. persistent / non-persistent);
- type of sea operational limits (e.g. open ocean area, enclosed sea, shallow water area);

- clean-up operations minimum time length (h);
- supply vessel cost / rental rate (euros/h);
- extra cost for mother vessel / rental rate (euros/h).

6.4 Response Facilities Data

The required data for each response facility include:

- distance (nautical miles) from the spill site;
- number of units stored from each equipment type;
- average response speed (knots) for each equipment type;
- transportation cost (euros/mile) per unit of each equipment type.

7. Illustrative Example

7.1 Problem Overview

In this Section, we apply the model to an illustrative tactical decision-making problem taking place in the Aegean Sea with fictitious yet realistic input data.

A spill incident occurs offshore Cape Sounio (Figure 5). In the area nearby the spill incident, 6 response facilities exist, listed in Table 1 (with their distances from the spill site).

Table 1: Response Facilities

Facility	Port	Distance from spill site
1:	Piraeus	26 NM
2:	Syros	48 NM
3:	Rhodes	226 NM
4:	Heraklion	139 NM
5:	Githion	122 NM
6:	Kalamata	174 NM

Fig. 5: Illustrative problem overview

7.2 Data

Indicatively, we provide certain model data below.

Spill data:

- Spill size: 800 tonnes;
- Type of oil: crude oil;
- Type of sea: enclosed sea (sea type II);
- Weather conditions: moderate;
- Spill coverage coefficient: 1.2;
- Spill direction: towards shore;
- Distance of incident from shore: 10 NM;
- Speed approaching shore: 0,1 kts;
- Damage potential group: A (output of damage assessment routine according to preset criteria).

System / damage cost coefficient: 1

Response equipment data: 4 different response equipment types are available, as listed in Table 2.

Table 2: Response Equipment Types

Type 1:	EU-MOP Small Size
Type 2:	EU-MOP Medium Size
Type 3:	EU-MOP Large Size
Type 4:	Other response equipment

The basic characteristics of the above response equipment are given in Table 3.

Table 3: Response Equipment Data

Equipment type=	**1**	**2**	**3**	**4**
Oil recovery capacity (tonnes/h)	0,11	0,53	0,76	1,00
Recovery efficiency rate	0,66	0,66	0,66	0,66
Operational / clean-up cost (euros/h)	50	180	200	1.000
Weather conditions operational limits (1:operational; 0: not operational)				
calm	1	1	1	1
moderate	0	1	1	1
rough	0	0	1	0
Type of sea operational limits (1:operational; 0: not operational)				
sea-type I	0	0	1	1
sea-type II	1	1	1	1
sea-type III	1	0	0	1

Also:

- supply vessel operational cost: 2,000 euros/24h
- mother vessel operational cost: 12,000 euros/24h

Data related to the response facilities were assumed to be similar across all facilities, as shown in Table 4.

Table 4: Facilities' related data

Equipment type	**1**	**2**	**3**	**4**
Units / facility	30	10	4	2
Average response speed (kts)	15	15	15	10
Transportation cost (euros/mile)	5	20	25	50

7.3 Results

The model provided the results discussed next. First of all, enough response units were dispatched for all of the spilled oil to be recovered. The number of units of each equipment type dispatched from each facility to the spill site are shown in Figure 6.

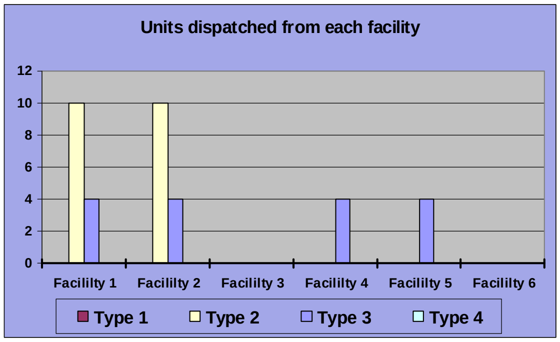

Fig. 6: Units dispatched (case 1)

We notice that no units of Type 1 are dispatched, as they are not operational under the weather conditions at the spill site (see data). Type 4 is not preferred due to cost / benefit considerations, given the assumed data. Response takes place with a mix of Type 2 and 3 equipment and, moreover, Type 3 appears to be preferable to Type 2 (from a cost/benefit point of view), as from facilities 4 and 5 only Type 3 units are dispatched, rather than those of Type 2.

Distance is also important. Units are dispatched from the closest facilities to the spill incident (facilities 1 and 2 dispatch more equipment than facilities 4 and 5), while the distant facilities 3 and 6 are not mobilised, even though they are stored with Type 3 units, which present a cost advantage when distance is the same.

Also according to the model results, 1 mother vessel and 3 supply vessels need to be used for the transport of the equipment to the spill site from the 4 facilities that are mobilised. The operational costs for these vessels amount to €80,479 for the whole operation and the costs associated with the dispatch and operation of the response equipment per se are €304,796. All of the spilled oil is removed and the potential damage cost is eliminated.

The damage-related cost estimations obviously depend on the model input. For example, an increase of the value of the system / damage cost coefficient from 1 to 2 (which places double value on 1 cost unit of potential damage from the spill, compared to 1 cost unit spent on response), did not change the number of units dispatched to the spill site (this was expected, all the spilled oil had been collected in the first case anyway). However, the figures of the damage-related cost estimations doubled accordingly.

Sensitivity analyses of the model results regarding any of the input parameters can also be easily performed. For example, a reduction in the operational cost of Type 2 units from 180 euros/h to 120 euros/h changed the previous results, as shown in Figure 7.

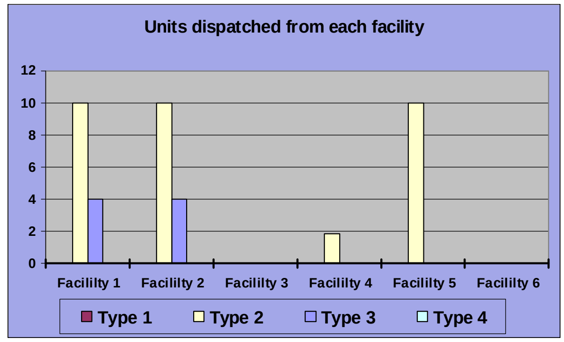

Fig. 7: Units dispatched (case 2)

The above results signify that Type 2 units are now more competitive vis-à-vis Type 3 units compared to case 1 (Fig. 6) from a cost/benefit point of view. Therefore, from facilities 4 and 5, Type 2 units are now exclusively dispatched (and consequently more in number). As facility 5 is closer to the spill site, than facility 4, all Type 2 units from facility 5 are dispatched and fewer from facility 4.

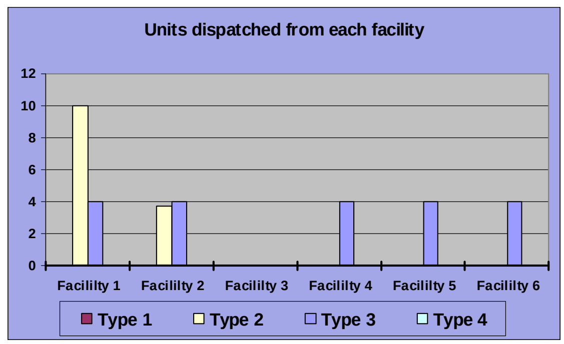

Fig. 8: Units dispatched (case 3)

As another example, in Figure 8 the results are shown, when the oil recovery capacity of Type 3 units is increased to 0,80 tonnes/h (from 0,76 tonnes/h in case 1). The performance per unit of Type 3 response equipment is now better vis-à-vis Type 2 equipment, the use of which is reduced compared to case 1 (Fig. 6). Instead, more Type 3 units are dispatched from the next less distant Facility 6.

8. Conclusions

In this paper, we presented a model that supports the oil spill response decision-making process at the tactical level. At this level, the actions required to respond to a specific spill (that has already occurred) are determined. In the broader area of the incident, a number of response facilities exist. These facilities are equipped with known quantities and types of oil response equipment. The tactical decision-maker needs to determine from which facilities to dispatch response units to the spill site and, moreover, the types and quantities of the units to be dispatched. The objective is to respond to the specific spill in an optimal way on a cost/benefit basis.

Previous models of oil spill response decision-making were reviewed and some of their features were adopted. However, the presented model is novel in many respects. It explicitly takes into account a number of cost and technical parameters and introduces a number of realistic operational constraints. Yet, it is simple enough to operate as a stand-alone model. The above tactical problem is modeled as an optimisation problem by applying the linear programming theory. Also, a user-"calibrated" built-in routine is utilised to assess the damage potential of any spill incident. Moreover, a complicated response infrastructure is supported that requires the dispatch of a mother vessel and possibly more than one supply vessels for the transportation of response units from the facilities to a spill site, in accordance with the EU-MOP concept.

An illustrative application of the model was finally presented to demonstrate its modelling potential in solving complex tactical decision-making problems. The model also easily allows the undertaking of sensitivity analyses with respect to its input data and assumptions.

As explained, the approach adopted is to respond optimally on a cost basis. Although the response time is not optimised, time constraints are applied (e.g. response before the spill hits the shore). As a suggestion for further research, another approach could set as primary objective the minimisation of the response time or the maximisation of the coverage of the spill (e.g. as in Belardo et al, 1984).

It should be noted that the above model is part of a work that also addresses the strategic level decision-making, to be presented in another paper.

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