SIMULATION OF COUNTERMEASURES FOR OIL-SPILL EMERGENCY MANAGEMENT

Agostino Bruzzone, Alessandra Orsoni, Simone Viazzo

Department of Production Engineering, University of Genoa

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Abstract

The paper illustrates the key features of a Decision Support System (DSS) designed and implemented for oil-spill emergency scenario management. The tool consists of a simulation environment where counteraction resources may be modeling and customized to analyze the performance of alternative oil-spill reaction strategies in relation to the morphology of the particular geographic location.

Introduction

A Decision Support System (DSS) was developed for the quantitative assessment of alternative reaction measures to oil-spill emergencies: the tool provides a context where the logistics of the countermeasures (in terms of number, type, and location of the available resources) can be designed, planned, and tested for effectiveness before actual implementation. The counteraction resources are defined and customized to operate in a simulation environment, where the dynamic evolution of spilled oil can be anticipated and graphically displayed as a function of the local meteorological conditions and environmental factors. Sensitivity analysis and scenario testing were conducted customizing the DSS for the study of oil-spill emergencies in the vicinity of the North-Western Italian Coast (Northern-Tirrenum Sea). The paper illustrates the key features of the DSS focusing on resources modeling and customization for spill emergency scenario management.

Research Background

The research presented in this paper builds upon the experience cumulated by the authors in the modeling of emergency situations related to industrial accidents (Mosca., Giribone and Bruzzone, 1994; Giribone and Bruzzone, 1994), and in the simulation of logistic operations related to harbors and maritime environments (Merkuriev, Bruzzone and Novitsky, 1998). Previous work has focused on resources management for fire-fighting (Mosca, Bruzzon, and Giribone, 1995) and oil-spill pollution containment (Giribone, Bruzzone and Caddeo, 1995) based on artificial intelligence and virtual reality techniques (Mosca, Giribone and Bruzzone (1996), as stand alone optimization tools. Simulation tools have also been implemented to analyze the environmental impacts of oil-spill in port areas (Bruzzone, Giribone, Mosca and Rapallo (1999). Quite recently the authors have been involved in the development of a detailed graphically based simulation model of oil-spill behavior in seawater (Orsoni and Viazzo, 2002; Orsoni and Viazzo, 2002), as phase I of a major research project in collaboration with CETENA-Fincantieri (i.e. the research center affiliated with a leading Italian ship-building company) for oil-spill emergency management. Phase II of this same project is the object of this paper, which focuses on the modeling and customization of oil-spill counteraction resources and on their implementation in the graphically-based simulation tool. The research steps and results concerning the modeling of oil-spill behavior will be briefly summarized in the remaining of this section, as they are thoroughly discussed in previously published work (Orsoni and Viazzo, 2002; Orsoni and Viazzo, 2002).

The first important step in modeling the behavior of spilled oil in seawater is the definition of the physical and chemical phenomena driving the process. Based on relevant literature (Riazi, and Enezi 1999; Al-Mukhareq, 1998) and with the support of the University of Kuwait, the authors isolated the key driving phenomena: transport, spreading, evaporation, dissolution, and sedimentation, and wrote suitable equations to describe their influence on oil-spill behavior as determined by the relevant meteorological conditions and environmental factors (Orsoni and Viazzo, 2002). A statistical data pre-processing module was developed to account for the stochastic variability of the meteorological conditions (e.g. temperature, wind, currents, and waves). The module was fed with 19 years worth of historical data provided by the Hydrographic Institute of the Italian Navy to build the probability distributions associated to the direction and intensity of wind, currents, and waves for the north-western Italian coastal area. The simulation tool was then designed using a hybrid time management approach (Orsoni and Viazzo, 2002), which combines the features of stochastic, discrete-event simulation and continuous simulation. The former one is intended to account for the variability of weather conditions and spill characteristics (e.g. the introduction of additional spills), while the latter one takes care of the integration of the differential equations driving the behavior of the spill according to the Euler approach over a finely meshed grid: the entire coastal region between Varazze and Genoa-Multedo (characterized by the presence of an important oil terminal), spanning hundreds of kilometers, was divided into square cells measuring 100 m × 100 m. At each integration step punctual values are extracted from the probability distributions associated to each of the meteorological influencing factors and their values are distributed across the grid. In order to ensure consistent distribution of the vectorial variables, such as wind, currents, and waves, a spanning function was built into the model, which applies mass and momentum conservation principles across the region's cells, accounting for the orographic morphology of the coastal profile. The model was fully tested based on historical and experimental data provided by the University of Kuwait.

Modeling of Counteraction Resources

The representation of possible reaction scenarios in the context of the simulation model already discussed, requires the accurate definition of the different counteraction resources available and of the respective intervention capabilities and functions. The types of countermeasures considered for the purposes of the model include: oil removal, distribution of solvent agents, and placement of floating containment strips. At the simulation level a single object category was defined for the representation of the different counteraction resources, namely ships. A generalized ship object may be generated and customized to represent a particular instance of ship with user-specified characteristics. A particular instance of ship may be abilitated to perform any combination of the three types of counteractive functions: oil removal, distribution of solvent agents, placement of containment strips, respectively. The timing of ship intervention with respect to the three anticipated intervention modes may be characterized and accounted for during the simulation as a function of a specified set of variables and initialization parameters including: initial position, base of reference, operative speed for different levels of sea conditions, and set-up/departure times. The model accounts for the stochastic variability of such times by associating to each one of them appropriate probability distributions, characterized by the respective mean and standard deviation values.

The sequence of operations that each ship needs to perform, since the very beginning of the simulation run, is prescribed by the user in the format of a sequence of encoded orders, which not only specify the types of operations to be performed and their timing, but may also involve waiting for specified intervals of simulated times and dynamically specified activities, entirely depending on the current spill parameters and location. For instance, dynamic orders may be formulated as " reach the western-most point of the spill". In summary an order may specify that the ship, after completing the preparation and departure phases/tasks, should reach a specified location identified either by its actual geographic location (e.g. coordinates), by the local characteristics of the spill (e.g. highest concentration point), and/or by its position relative to the current location and spread of the spill. The user may specify that the ship must reach the location characterized by the highest pollutant concentration, or even the Northern-most location characterized by the highest concentration. In this latter case, as simulation time elapses, the ship will adjust its position to the designated target, which may progressively move due to the variability of the local meteorological conditions (e.g. wind, currents, and waves) and depending on the effectiveness of the locally active countermeasures (e.g. efficiency of pollutant containment/removal in given directions/zones). The number of ships that may be simultaneously defined and activated is unlimited, while the maximum number of operations prescribed for each ship was set to 100.

The motion of the ships is simulated considering the local sea conditions and their influence on the maximum speed and on the limiting linear and angular accelerations. The effect of local currents is also accounted for, however the model does not account for the inertial forces contrasting the deceleration of the ship once the target location has been reached. It is assumed that the ship relies on its engines to maintain the desired position.

Characterization of Resources Intervention Capabilities

The abilitation of the individual intervention capabilities for the different resources is based upon the specification of the parameters that drive and describe the potential of each ship with respect to each active intervention mode.

Resources characteristics and potential relative to solvent agents distribution

The representation of the intervention mode corresponding to solvent agents distribution requires the characterization of the resource in terms of type of solvent, quantified in terms of solvent efficiency (i.e. number of kilograms of pollutant dissolved by one kilogram of solvent), of storage capacity, pumping rate, solvent distribution and refill methods. With respect to solvent distribution and refill, three strategies are defined and may be specified by the user for the purposes of each simulation run:

- Distribution of solvent until supply lasts, as determined by storage capacity/current level, and return to base for refill
- Distribution of solvent until supply lasts, as determined by storage capacity/current level, and in situ supply/refill through auxiliary ships
- Distribution of solvent until supply lasts, as determined by storage capacity/current level, without refill (activity ends as soon as solvent runs out)

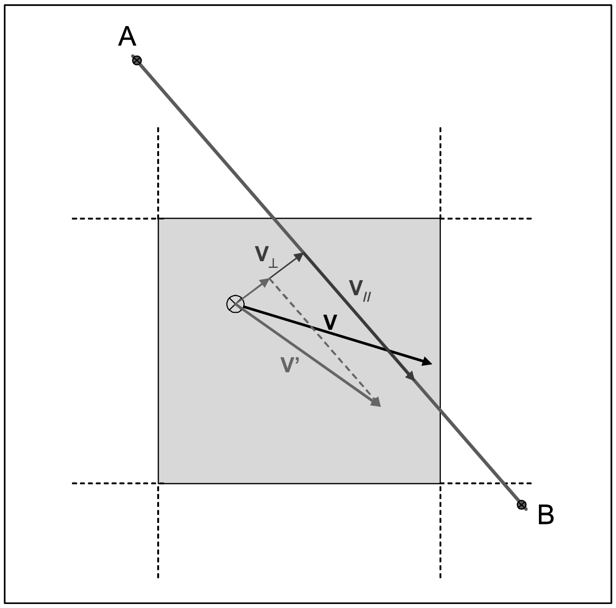
The refill operations associated to the first two strategies are characterized by stochastic durations with specified mean and standard deviation (approximately twice the duration of set-up/departure operations)

Resources characteristics and potential relative to the placement of floating containment strips

The characteristics of the intervention mode corresponding to the placement of floating containment strips are encoded as orders only for the resources abilitated to perform such operations. For each abilitated ship a total length of available containment strips may be specified. The strip placement order may specify the point of origin (A) and the destination point (B). If the resource has an overall length of containment strips available greater or equal to the distance AB (calculated as the geometric distance between the two locations), the strips are placed as specified starting from point A until B is reached. If, on the other hand, the total length available on board is shorter than AB, the strips are still placed starting from A and proceeding along the AB direction until the entire available length has been used up. For the purposes of the simulation run, the strip starts to be effective only once the placement of the entire specified length has been completed, therefore the model does not account for partial effects associated to the portion of strip already in place while the resources are completing placement activities. The model accepts a maximum of 100 strips of any specified length.

The main function of these floating devices is the containment of the pollutant, reducing its spreading in the direction perpendicular to the strip according to a factor that depends on the type of device, expressed in terms of device efficiency, and on the current sea conditions (i.e. strong currents and waves increase the pollutant flow rate by-passing the floating strip). The model accounts for the primary containment effects of these floating devices by modifying the sum of the transport vectors acting on the enclosed pollutant. Transport vectors include pollutant spreading relative to water surface (until equilibrium thickness is reached for the specified characteristics of the air-water-oil interface), wind, currents, and waves; the sum of the corresponding velocity vectors is decomposed into two components, perpendicular and parallel to the strip (AB), respectively. As shown in figure 1, this latter component is not affected by the presence of the strip and, thus, remains unchanged, while the former one is reduced according to a factor that accounts for the current sea conditions (i.e. intensity of currents and waves) expressed in the Beaufort scale.

Figure 1: Impact of containment device (AB) on pollutant transport velocity



Defining the efficiency of the floating device as the percentage of the incoming pollutant flow that it is able to contain, the scaling factor for the velocity component perpendicular to the strip can be calculated as (1 – device_efficiency). For each value of the Beaufort scale a percentage value may be specified in the model, which represents the correction factor applied to the device efficiency to account for actual sea conditions. For instance it is possible to specify that for Beaufort levels smaller or equal to 3 the correction factor is 1, corresponding to 100% overall containment efficiency, for Beaufort level 4 the correction factor may be 0.8, thus ensuring 80% of the containment efficiency measured in calm waters. The values of the efficiency correction factor need to be specified for the entire range of the Beaufort scale that may be observed in the geographic area of interest.

Figure 1 shows a 100 m ×100 m integration cell crossed by containment strip AB. The effect of this device is also shown in the figure: transport velocity V is decomposed into $V_{//}$ and $V\perp$, parallel and perpendicular to the strip, respectively. Of these $V_{//}$ remains unchanged, while $V\perp$ is reduced proportionally to the factors specified above. The resulting vector V' is assumed as new transport velocity for the entire cell. In the simulation model the containment strip is graphically represented as a line, however its effects are accounted for only in terms of number of cells crossed/reached by the strip. The impact of this approximation is negligible given that the size of the integration cells (100 m ×100 m) defined to study the dynamics of the spill is very small compared to the geographic area examined. Given the extreme points A and B, the model calculates the coordinates of "n" intermediate points, where "n" is a number depending on the number of cell-sides included in the distance AB. Vectorial decomposition of the local transport velocity and adjustment of perpendicular component applies to the entire cell crossed/touched by the strip: the model does not discretize containment effects with resolution higher than the size of a cell (i.e. cell fraction).

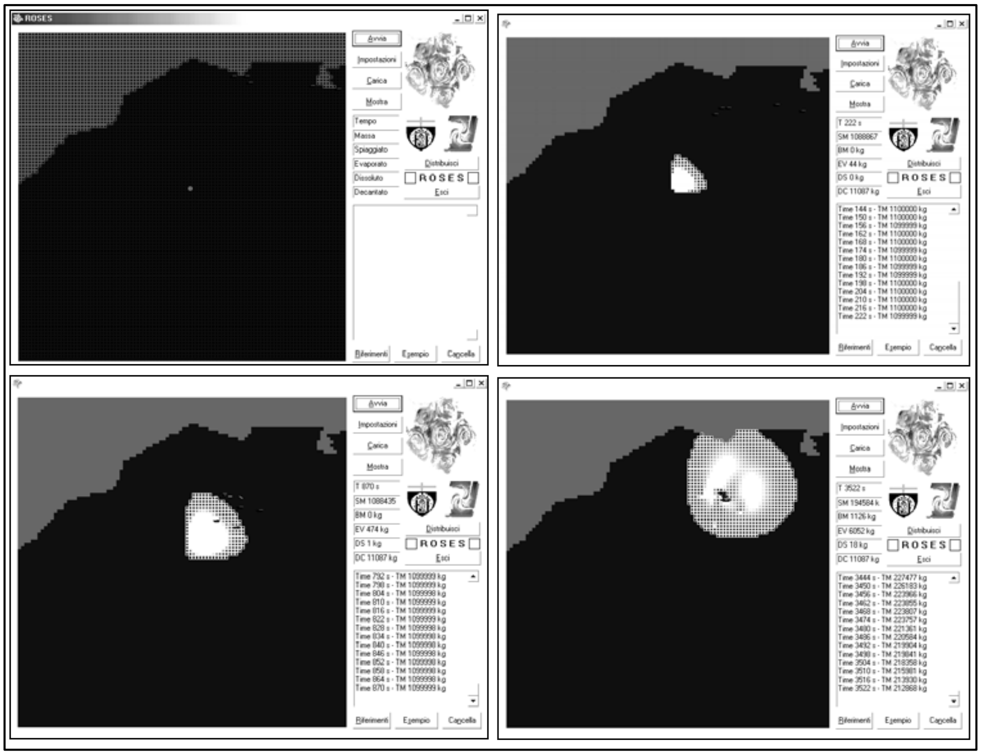
Resources characteristics and potential relative to pollutant removal

Resource intervention in terms of pollutant removal requires that the ship reaches a pre-defined location, for instance the one characterized by the highest concentration of pollutant. The elimination of the hydrocarbon by suction is modeled as a mass flow rate leaving the plane of the sea surface on which the pollutant is spread. The representation of such a flow may be quantified as a vector having intensity equal to the suction capacity of the pumping group on board of the ship and direction perpendicular to the pollutant's plane. As the distribution of pollutant concentration varies from one integration step to the next one both due to the active transport phenomena and due to the actions of other containment measures, the model continuously updates the target suction point, and, thus, the position of the ship accordingly.

Graphic User Interface

The graphic user interface of the model dynamically displays the evolution of the pollutant relative to the coastal profile, accounting for its orographic morphology. In particular the model displays the presence of pollutant limited to the regions characterized by a minimum value of pollutant concentration, according to a user-specified threshold value. Different concentration levels are differentiated by color coding, therefore different color shades are associated to different concentration levels. The GUI also displays the cumulative quantities of pollutant still sailing, already beached, evaporated, dissolved in seawater, and sank, and updates the corresponding values at each integration step. The integration step is assumed to be of approximately a few seconds (typically 6 seconds). The project phase described in this paper involved the addition of the dynamic representation of the containment resources (i.e. not just the representation of their effects in the elimination/containment of the pollutant, but also their graphic display in terms of dynamic location, speed, and impact on pollutant concentration and transport). Figure 2 represents four snapshots of a same scenario: the first one, in the top left corner, represents the beginning of the simulation run, and thus the upload of the map describing the coastal profile and the initialization of the transport vectors through the previously defined "spanning" procedure, and the introduction of the pollutant, shown as a tiny dot in the figure, in the specified location and amount. In the second snapshot (top right corner) the pollutant has spread and its center of mass has moved towards the shore, while the counteraction resources shown at sea, already moving towards the spill. In the third snapshot (bottom left corner) the resources are approaching their designated location and the pollutant has further spread moving closer to the shore. In the fourth one (bottom right corner), the resources are operating in their designated locations and the pollutant has reached its maximum spread and reached the shore.

Figure 2: Sample graphical representation of pollutant dynamic evolution in the presence of containment resources



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T 222 s
SM 1088867
BM 0 kg
EV 44 kg
DS 0 kg
DC 11087 kg

Time 144 s - TM 1100000 kg
Time 150 s - TM 1100000 kg
Time 156 s - TM 1099999 kg
Time 162 s - TM 1100000 kg
Time 168 s - TM 1100000 kg
Time 174 s - TM 1099999 kg
Time 180 s - TM 1100000 kg
Time 186 s - TM 1099999 kg
Time 192 s - TM 1099999 kg
Time 198 s - TM 1100000 kg
Time 204 s - TM 1100000 kg
Time 210 s - TM 1100000 kg
Time 216 s - TM 1100000 kg
Time 222 s - TM 1099999 kg
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T 870 s
SM 1088435
BM 0 kg
EV 474 kg
DS 1 kg
DC 11087 kg

Time 792 s - TM 1099999 kg
Time 798 s - TM 1099999 kg
Time 804 s - TM 1099998 kg
Time 810 s - TM 1099999 kg
Time 816 s - TM 1099999 kg
Time 822 s - TM 1099999 kg
Time 828 s - TM 1099998 kg
Time 834 s - TM 1099998 kg
Time 840 s - TM 1099998 kg
Time 846 s - TM 1099998 kg
Time 852 s - TM 1099998 kg
Time 858 s - TM 1099998 kg
Time 864 s - TM 1099998 kg
Time 870 s - TM 1099999 kg
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T 3522 s
SM 194584 k
BM 1126 kg
EV 6052 kg
DS 18 kg
DC 11087 kg

Time 3444 s - TM 227477 kg
Time 3450 s - TM 226183 kg
Time 3456 s - TM 223966 kg
Time 3462 s - TM 223855 kg
Time 3468 s - TM 223807 kg
Time 3474 s - TM 223757 kg
Time 3480 s - TM 221361 kg
Time 3486 s - TM 220584 kg
Time 3492 s - TM 219904 kg
Time 3498 s - TM 219841 kg
Time 3504 s - TM 218358 kg
Time 3510 s - TM 215981 kg
Time 3516 s - TM 213930 kg
Time 3522 s - TM 212868 kg
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Conclusion

The paper presented the design and implementation features of a DSS for oil-spill emergency management focusing on counteraction resources definition and scenario customization. A major strength of the model is its ability to graphically display the dynamic evolution of the spill against the coastal profile of the affected waters as driven by the local meteorological conditions and by the user-defined reaction strategy. The relevance of the model is easily understood in light of the tragic events recently occurred in the vicinity of the Galitian coast. The DSS may actually find application both as an off-line tool for personnel training and as an on-line tool for quick strategy assessment and comparison in actual emergency situations.

Authors Biographies

Alessandra Orsoni is currently an Assistant Professor in the Department of Production Engineering (DIP) of the University of Genoa (Genoa, Italy). She was a Research Associate in the Department of Materials Science and Metallurgy at the University of Cambridge, UK. She received both her MS in Mechanical Engineering (1996) and her Sc.D in Engineering Systems Design and Innovation (2000) from the Massachusetts Institute of Technology, Cambridge, MA, USA. Her research interests include modeling, simulation, and AI techniques applied to industrial problem solving with focus on the logistics of the supply chain.
http://st.itim.unige.it/liophant/memb/aorsoni.html

Agostino G. Bruzzone began his engineering studies at the Italian Naval Academy and earned his Mechanical Engineering degree from the University of Genoa. Today he is teaching as professor in Department of Production Engineering of the Genoa University, "Project Management", "Industrial Plants". He works with University of Genoa in the field of simulator-based applications for industrial plants, developing new methodologies and AI system integration techniques. He is the Director of the McLeod Institute for Simulation Science, Genoa Centre. He is founder member and president of the Liophant Simulation Club.

http://st.itim.unige.it/itim/people/agostino.html

Simone Viazzo is a Research Associate in the Production Engineering Research Group at the University of Genoa (Genoa, Italy). He received his Bachelor's Degree in Management Engineering from the University of Genoa (Savona, Italy), and he is currently involved in several projects focusing on industrial logistics and supply chain management.

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