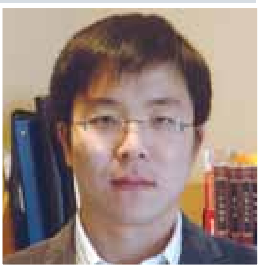
Skimming

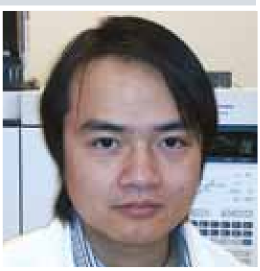
Pu Li

Bing Chen

Baiyu Zhang



Liang Jing



Jisi Zheng

Li, Chen, Zhang, Jing and Zheng use the language of mathematics to describe the efficiency and effectiveness of oil recovery technology.

Who should read this paper?

This paper will be of particular interest to offshore operators, spill response organizations, environmental regulators, coastal and ocean engineers and anyone else with an interest in technical aspects of oil recovery in northern regions.

Why is it important?

When, as former Canadian Prime Minister Jean Cretien once said, "the ship hits the dam," the result can be a gooey, black mess floating on the surface of an otherwise pristine ocean. Those who are charged with the responsibility for responding to such incidences must do so with efficiency and effectiveness. Otherwise, significant negative impacts on the environmental and socio-economic wellbeing of the area will accrue. One of the technologies that is commonly used to recover spilled oil from the surface of the ocean is called a 'skimmer.' One of the most common types of skimmers is a 'drum skimmer.' As the name suggests, these skimmers look like a drum, or barrel, floating on the surface of the ocean. As the drum turns, oil adheres to the surface and is lifted out of the water where it is physically scraped into a receptacle. As one might expect, not all drum skimmers were created equal. The authors of this paper have developed a sophisticated mathematical approach to calculating the efficiency of any given drum skimmer. One of the unique aspects of their work is the ability to consider the impact of any number of physical parameters such as sea state, characteristics of the oil, temperature of the water, etc., on the efficiency of the skimmer. If adapted for use in the field and applied correctly, this approach can support dynamic adaptation of the response strategy and technologies throughout the recovery process, ensuring that the maximum amount of oil is recovered in the minimum amount of time under unpredictable weather conditions in one of the harshest environments on Earth.

About the authors

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A MULTIPLE-STAGE SIMULATION-BASED MIXED INTEGER NONLINEAR PROGRAMMING APPROACH FOR SUPPORTING OFFSHORE OIL SPILL RECOVERY WITH WEATHERING PROCESSES

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ABSTRACT

As one of the most commonly used technologies in offshore oil spill response, skimming is facing challenges in recovering the spilled oil in the north region due to cold weather and harsh marine conditions. It is valuable to simulate and optimize the skimming process to improve efficiency of oil skimming during emergency response especially in harsh offshore environments. However, no studies have reported on integrating optimization and simulation approaches to support the offshore oil spill recovery by skimmers. This study developed a multiple-stage simulation based mixed integer nonlinear programming (MSINP) approach to provide sound decisions for skimming spilled oil in a fast, dynamic and cost-efficient manner, which is especially helpful to harsh environments. In the case study, regression models were developed to simulate the efficiencies of two drum skimmers based on the referenced performance tests. The models were further integrated with the optimization methods to determine the optimal strategy to achieve the maximum oil recovery with constraints of time and resources. The results indicated a 96% recovery efficiency based on the optimal settings. Furthermore, the approach was also tested with the integration of the oil weathering processes (e.g., evaporation, emulsification, and dispersion). The results indicated that with the consideration of evaporation and dispersion, in order to achieve the maximum oil recovery, the optimal setting for the oil recovery would be 5 sets of SK_1 and 15 sets of SK_2, yielding an oil recovery efficiency of 91.5%. The proposed approach was able to efficiently incorporate the regression models and optimization into the same framework and to support efficient skimming for offshore oil spills. The MSINP approach can timely and effectively support offshore oil recovery operations under dynamic conditions and therefore provide expeditious decision-making support during offshore oil spill response in harsh environments.

KEY WORDS

Optimization; Multiple-stage simulation; Nonlinear programming; Offshore oil spill recovery; Weathering processes

NOMENCLATURE

Ψ	=	function of dynamic relation
μ	=	dynamic viscosity of the oil (cP)
μ_0	=	initial viscosity of the spilled oil (cP)
μ_{m-1}	=	parent oil viscosity (cP)
ρ_0	=	initial density of the spilled oil (kg/m^3)
ρ_{m-1}	=	parent oil density (kg/m^3)
ρ^{sat}	=	density of the oil (kg/m^3)
ρ_w	=	density of water (kg/m^3)
A	=	area of the spilled oil (m^2)
A_{ij}	=	constraint coefficients
B_i	=	constraint right hand sides
C_j	=	coefficients of objective function
f	=	objective function
FD	=	dispersion rate
FE	=	evaporation rate
FW	=	fractional water content
g	=	function of coefficient
h	=	index of the previous stage
hs	=	slick thickness (m)
i	=	index of constraint
j	=	index of decision variable
K_a	=	cure fitting constant
K_b	=	mousse viscosity constant
K_c	=	oil-dependent constant
M	=	molecular weight (g/mol)
m	=	index of the current stage
n	=	number of decision variables
ORE	=	oil recovery efficiency (m^3/m^3)
ORR	=	oil recovery rate (m^3/hour)
ORR_n	=	net oil recovery oil (m^3/hour)
p	=	number of constraints
P^{sat}	=	vapour pressure of the spill (Pa)
R	=	gas constant (8.314 m^3·Pa/mol·K)
R^2	=	correlation coefficient
RV_t	=	remaining volume of spilled oil at time t (m^3)
s	=	index of skimmer
SK	=	number of skimmer
SOT	=	slick thickness (mm)
S_t	=	interface tension of oil and water (dyne/m)
st	=	index of stage
T	=	temperature (K)
t	=	time
t_s	=	controllable time interval
U	=	wind speed (m/s)
V	=	cumulatively recovered oil (m^3)
V_0	=	initial volume of spilled oil (m^3)
V_h	=	collected oil in the stage h (m^3)
V_m	=	collected oil in the stage m (m^3)
V_t	=	recovered oil at time t (m^3)
X_j	=	decision variables
y	=	variable for function of coefficient

INTRODUCTION

An oil spill is a release of liquid petroleum hydrocarbons into the environment due to human activities, which is a form of pollution. It often refers to marine oil spills, where oil is released into the ocean or coastal waters. Oil spills include releases of crude oil from tankers, offshore platforms, drilling rigs and wells, spills of refined petroleum products (such as gasoline, diesel) and their by-products, heavier fuels used by large ships such as bunker fuel, and the spill of any oily white substance refuse or waste oil.

Oil spills are serious environmental disasters that often lead to significant negative and long-term impacts on the environment, ecology and socio-economic activities of the area. From 1978 to 1995, there were more than 4,100 major oil spills in the world of 10,000 gallons or more [Etkin and Welch, 1997]. Several serious offshore oil spills also have taken place since 1995, such as the *Sea Empress* in which approximately 5,000 tons of oil reached the United Kingdom coastline [Edwards and White, 1999]. The clean-up cost of this oil spill was estimated to be $120 million USD. When the effects to the economy and environment were taken into account, the final cost was estimated to be $240 million USD [Li et al., 2000]. Another more recent example is the *Deepwater Horizon* oil spill (the BP oil spill) [BP, 2010; BOEMRE, 2011; MMC, 2011] which was an oil spill in the Gulf of Mexico lasting for three months in 2010. It is the largest accidental marine oil spill in the history of the petroleum industry. The spill released about 4.9 million barrels of crude oil [Ramseur, 2010]. The impacts of the spill still continued even after the well was capped, including climate change, fisheries, commercial shipping, military activities, and coastal development, etc. [MMC, 2011]. Some estimates suggested that the total liability could amount to as much as $100 billion USD by the conclusion of the disaster [Griggs, 2011].

Newfoundland and Labrador (NL) produces about 0.27 million barrels of crude oil per day, from three active offshore oil fields which are Hibernia, Terra Nova, and White Rose, representing 10% of Canada's total crude oil production. It is estimated that 86.4 million barrels of oil were produced in the three active oil fields of Newfoundland in 2010. Oil spills in the NL offshore happen more often than environmental assessments predicted. Since 1997, it is estimated that roughly 2,703 barrels of drilling fluids and other hydrocarbons have been spilled into the ocean through about 340 spills reported from NL's offshore [Terry, 2008]. A spill of 1,040 barrels of crude at Terra Nova happened in 2004 followed by a penalty of $290,000 CAD [C-NLOPB, 2007]. In 2004, 96.6 m^3 of synthetic based mud was spilled in the offshore area around White Rose, with penalties amounting to $81,000 CAD [C-NLOPB, 2008]. While the oil spill itself is problematic, the lack of action on these spills is more risky [Terry, 2008].

Because offshore oil spills can cause various impacts and public concerns, it becomes important to provide strategies for rapid and effective spilled oil recovery. Skimming can separate a liquid from particles floating on it or from another liquid and is commonly applied in removing oil floating on water. It is one of the most important technologies in offshore oil spill recovery [Cheremisinoff and Davletshin, 2010]. Skimming technologies were used to assist in the remediation of the *Exxon Valdez* spill in 1989 [Fingas, 2010]. However, it becomes difficult to skim spilled oil in the NL offshore due to conditions of cold weather and harsh environments in northern regions [Turner, 2010]. Environmental conditions in the harsh environments which prevail in the offshore of northern regions are challenging the efficiencies of most spill response technologies. Typical harsh conditions affecting the oil spill recovery operations include the presence and type of sea ice, extreme cold, limited visibility, rough seas, and wind, leading to impact on the fate and behaviour of spilled oil, and thus may reduce the effectiveness of recovery technologies such as booming, herding, and skimmer [Owens et al., 1998; Brandvik et al., 2006]. In general, oil spills are more problematical in harsh environments because of the simple and highly seasonal ecosystems and the logistical challenges of cleaning up spills in regions that are less accessible for sea transport. Each season presents different advantages and drawbacks for spill recovery. The low temperatures can also make hydrocarbons persist, making ice-edge communities particularly vulnerable [AMAP, 2008]. During freeze-up and break-up, drifting ice and limited site access restrict the possible response options and significantly reduce recovery effectiveness [Turner, 2010]. Besides, most offshore oil recoveries require the support of aircraft, vessels, and trained personnel which are highly affected by these harsh environmental conditions [Fingas, 2010]. Therefore, it becomes important to conduct an oil recovery process in harsh environments by skimmers in a timely manner, and this requires optimization of logistical and operational strategies.

A few models have been developed for supporting oil spill recovery by skimmers [Fingas, 2001; Ornitz and Champ, 2003]. For example, Pourvakhshouri et al. [2006] developed a geographic information system (GIS) based optimization model for supporting decision makers to choose the most effective method for recovering spilled oil in the Strait of Malacca. Meanwhile, many optimization models have also been developed based on spatial analysis tools [e.g., Assilzadeh et al., 2001; Brimicombe, 2003]. There are also systems, like the Oil Spill Identification System [Leech et al., 1993], and models like the Oil Spill Risk Analysis Model and the General National Oceanic and Atmospheric Administration Operational Modeling Environment [Price et al., 2003; Beegle-Krause and O'Connor, 2005] that have been developed to support surveillance and risk assessment. However, while these systems support recovery operations, they do not involve numerical optimization techniques, and only a few of them account for the dynamic conditions that exist offshore and highly affect oil spill recovery [Wilhelm and Srinivasa, 1997; Reed et al., 1999; Brebbia, 2001]. Furthermore, no attempt was reported on the integration of optimizations and simulations to support the effectiveness and efficiency of the recovery of oil spilled offshore.

Therefore, the objective of this paper is to develop a multiple-stage simulation based mixed integer nonlinear programming (MSINP) approach to optimizing offshore oil spill recovery especially in harsh environments. The major tasks included: 1) development of a framework for the MSINP approach; 2) evaluation of the performance of drum skimmers for spilled oil recovery and development of simulation models for skimmers; and 3) integration of the simulation models of skimmer efficiency and oil weathering into the MSINP framework and test with a case study of offshore oil spill recovery using drum skimmers.

MULTIPLE-STAGE SIMULATION BASED NONLINEAR PROGRAMMING

Consider a linear program as follows:

$$Min \quad f = C_j X_j \tag{1a}$$

subject to:

$$\sum_{j=1}^{n} A_{ij} X_j \le B_i , \quad i = 1, \cdots, p \tag{1b}$$

$$X_j \ge 0 \tag{1c}$$

where $C_j \in \{R\}^{1\times n}$ is the matrix of coefficients of the objective function; $A_{ij} \in \{R\}^{p\times n}$ and $B_i \in \{R\}^{p\times 1}$ are the matrices of variable constraint coefficients and right hand sides (resources); f is the value of the objective function; X_j is the matrix of decision variables; n is the number of decision variables; and p is the number of constraints.

When C_j are not just constants but also functions linking with some other parameters:

$$C_j = g_j(y) \tag{2}$$

where $g_j(y)$ are functions showing the relations between the coefficients C and parameters y, leading to a simulation-based optimization model as follows:

$$Min \;\; f = g_j(y)X_j \tag{3a}$$

subject to:

$$\sum_{j=1}^{n} A_{ij} X_j \le B_i \, , \quad i = 1, \cdots, p \tag{3b}$$

$$X_j \ge 0 \tag{3c}$$

Equation 3 will be a simple linear model and can be solved by linear programming if $g_j(y)$ is independent from the decision variables (X_j). However, when $g_j(y)$ are dependent on the decision variables, the problem becomes non-linear, especially when $g_j(y)$ are dynamically relating with the decision variables (usually with time series), the problem becomes dynamic and non-linear, and cannot be easily solved [Li et al., 2012]:

$$Min \;\; f_t = \psi\left(f_{t-1}\left(g_j(y_{t-1})X_j\right), g_j(y_t)X_j\right) \tag{4a}$$

subject to:

$$\sum_{j=1}^{n} A_{ij} X_j \le B_i \, , \quad i = 1, \cdots, p \tag{4b}$$

$$X_j \ge 0 \tag{4c}$$

where t and $t-1$ are time indicators in a time series, and $f_t = \psi\,(f_{t-1}\,(\,g_j\,(\,y_{t-1})\,X_j\,),\, g_j\,(\,y_t\,)X_j$ represents relations between the status from the previous and the current stages. For a single stage or globally continuous problem, Equation 4 can be converted as follows:

$$Min \;\; f = \int_0^t \psi\left(f_{t-1}\left(g_j(y_{t-1})X_j\right), g_j(y_t)X_j\right)dt \tag{5a}$$

subject to:

$$\sum_{j=1}^{n} A_{ij} X_j \le B_i \, , \quad i = 1, \cdots, p \tag{5b}$$

$$X_j \ge 0 \tag{5c}$$

It will be more convenient to break the time series into certain stages based on a controllable time interval defined as the minimal time required for shifting one operational condition to another, and is usually determined by the time for equipment deployment, transportation, resource arrangement, etc. This leads to multiple-stage simulation based nonlinear programming as follows:

$$Min \;\; f = \sum_{st=1}^{S}\left[\int_0^{t_s} \psi\left(f_{s-1}\left(g_j(y_{t-1})X_j\right), g_j(y_t)X_j, t\right)dt\right] \tag{6a}$$

subject to:

$$\sum_{j=1}^{n} A_{ij} X_j \le B_i \, , \quad i = 1, \cdots, p \tag{6b}$$

$$X_j \ge 0 \tag{6c}$$

where t_s is time interval in the stage *st.* In some cases, $g_j(y)$ in the same stage can be assumed to be unchanged and Equation 6 can be correspondingly converted to:

$$Min \;\; f = \sum_{s=1}^{N} \psi\left(f_{s-1}\left(g_j(y_{t-1})X_j t_{s-1}\right), g_j(y_t)X_j t_s\right) \tag{7a}$$

subject to:

$$\sum_{j=1}^{n} A_{ij} X_j \leq B_i \,, \quad i = 1, \cdots, p \tag{7b}$$

$$X_j \geq 0 \tag{7c}$$

MODELLING OF OIL SPILL SKIMMING

Consider an offshore spill of Statfjord oil with an amount of 5,000 m^3 and a viscosity of 100 cSt. After boom is deployed, the spill area is confined to 100,000 m^2, and two types of drum skimmers (SK_1 and SK_2) are applied in this area to collect the spilled oil. Between the two types of skimmers, SK_1 has higher oil recovery rate (ORR_1, recovered amount of oil per hour), but its oil recovery efficiency (ORE_1, the percent of oil recovered out of the total oil and water recovered) also decreases faster than that from SK_2 with decreasing slick thickness (SOT); in contrast, SK_2 has lower oil recovery rate (ORR_2), but its oil recovery rate (ORE_2) decreases slower than ORE_1 with decreasing SOT.

In order to determine the efficiencies of the two types of skimmers, ORRs and OREs of these skimmers were collected from previous tests conducted by Environmental Canada and OHMSETT [Schulze, 1998]. According to the collected information, series of net oil recovery rates (ORR_{n1} and ORR_{n2}, defined as the recovery amount of pure oil per hour) were generated based on a calculation of ORRs * OREs under different oil thickness with a viscosity of 1,000 cSt [Schulze, 1998]. Fittings are then applied on the generated ORR_{n1} and ORR_{n2} based on quadratic functions to generate the regression models of ORR_n with the change of spilled oil thickness, representing the recovery efficiencies of the two types of skimmers. Such change of slick thickness is usually caused by the processes of spreading, shifting, weathering (e.g., evaporation, dispersion, dissolution, emulsification, etc.), as well as the oil recovery. The details about the ORR_n of the skimmers as well as the regression models and the correlation coefficients (R^2) of the efficiencies are shown in Figure 1.

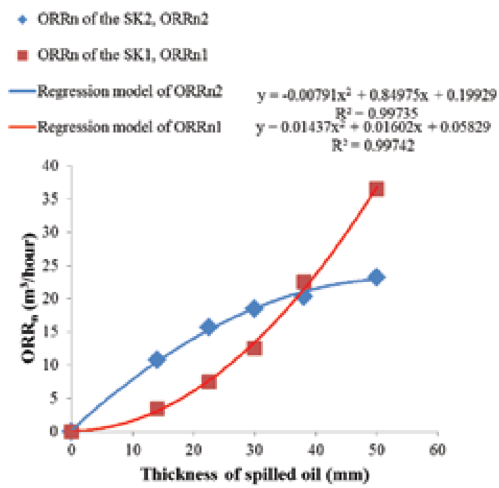

Figure 1: Net oil recovery rates with regression models for the skimmers.

THE COUPLING OF SIMULATION FOR OIL RECOVERY EFFICIENCIES

There are 15 sets of SK_1 and 15 sets of SK_2 onsite and the capacity of vessels used for operation is 20 sets of skimmers. Due to the challenge of transportation no more skimmers and vessels can be supplied within 24 hours. Therefore, the objective of the current stage is to determine the combination of the two types of skimmers in each stage to maximize the collected volume of spilled oil in this 24-hour period.

According to the above information, a general optimization model is generated as follows:

$$Max\ V = \sum_{s=1}^{2} \int_0^{24} SK_s \times ORR_{ns}\ dt \tag{8a}$$

subject to:

$$\sum_{s=1}^{2} SK_s \le 20 \tag{8b}$$

$$0 \le SK_s \le 15 \quad \forall s = 1, 2 \tag{8c}$$

$$SK_s \in \text{integer} \quad \forall\ s = 1, 2 \tag{8d}$$

where s is index of skimmers, t is the point of time during the operational period, SK_S is the number of the applied skimmer, and ORR_{ns} is the corresponding net oil recovery rate for the skimmer.

Because the spill is boomed, it can be assumed that the area of the spilled oil is unchanged in this stage, which is A = 100,000 m^2. Because the initial volume of spilled oil is V_0 = 5,000 m^3, the initial thickness is calculated as follows:

$$SOT_0 = V_0 / A = 5{,}000/100{,}000 = 0.05m = 50mm \tag{9}$$

and at time t, the thickness is as follows:

$$SOT_t = RV_t / A = RV_t / 100{,}000 \tag{10}$$

where SOT_t is spilled oil thickness at time t, and RV_t is the remaining volume of spilled oil at time t.

According to the regression model of ORR_n (Figure 1) and Equation 10, the specific regression model for SK_1 efficiency is generated as follows:

$$\begin{aligned} ORR_{n1t} &= 0.01437(SOT_t \times 1{,}000)^2 \\ &+ 0.01602(SOT_t \times 1{,}000) + 0.05829 \\ &= 0.01437\left(1{,}000\frac{RV_t}{A}\right)^2 \\ &+ 0.01602\left(1{,}000\frac{RV_t}{A}\right) + 0.05829 \end{aligned} \tag{11}$$

where ORR_{n1t} is the oil recovery rate of SK_1 at time t. In addition, the specific regression model for SK_2 efficiency is generated as follows:

$$\begin{aligned} ORR_{n2t} &= -0.00791(SOT_t \times 1{,}000)^2 \\ &+ 0.84975(SOT_t \times 1{,}000) + 0.19929 \\ &= -0.00791\left(1{,}000\frac{RV_t}{A}\right)^2 \\ &+ 0.84975\left(1{,}000\frac{RV_t}{A}\right) + 0.19929 \end{aligned} \tag{12}$$

where ORR_{n2t} is the net oil recovery rate of SK_2 at time t.

Accordingly, Equation 8 can be converted as follows:

$$Max\ V = \int_0^{24} V_t\ dt \tag{13a}$$

subject to:

$$\begin{aligned} V_t &= \sum_{s=1}^{2} SK_s \times ORR_{nst} \qquad \forall t \\ &= SK_1 \times \left(0.01437\left(1{,}000\frac{RV_t}{A}\right)^2 \right. \\ &\left. + 0.01602\left(1{,}000\frac{RV_t}{A}\right) + 0.05829 \right) \\ &+ SK_2 \left(-0.00791\left(1{,}000\frac{RV_t}{A}\right)^2 \right. \\ &\left. + 0.84975\left(1{,}000\frac{RV_t}{A}\right) + 0.19929 \right) \end{aligned} \tag{13b}$$

$$\sum_{s=1}^{2} SK_s \le 20 \tag{13c}$$

$$0 \le SK_s \le 15 \quad \forall s = 1,2 \tag{13d}$$

$$SK_s \in \text{integer} \quad \forall\, s = 1,2 \tag{13e}$$

Where V_t is the collected volume of spilled oil at time t, and the relation between V_t and RV_t is as follows:

$$RV_t = V_0 - \int_0^t V_t \, dt \tag{14}$$

Accordingly, Equation 13 can be converted as follows:

$$Max\ V = \int_0^{24} V_t \, dt \tag{15a}$$

subject to:

$$\begin{aligned} V_t &= \sum_{s=1}^{2} SK_s \times ORR_{nst} \qquad \forall t \\ &= SK_1 \times \left(0.01437 \left(\frac{1000\left(V_0 - \int_0^t V_t \, dt\right)}{A} \right)^2 \right. \\ &\quad \left. + 0.01602 \left(\frac{1000\left(V_0 - \int_0^t V_t \, dt\right)}{A} \right) + 0.05829 \right) \\ &\quad + SK_2 \left(-0.00791 \left(\frac{1000\left(V_0 - \int_0^t V_t \, dt\right)}{A} \right)^2 \right. \\ &\quad \left. + 0.84975 \left(\frac{1000\left(V_0 - \int_0^t V_t \, dt\right)}{A} \right) + 0.19929 \right) \end{aligned} \tag{15b}$$

$$\sum_{s=1}^{2} SK_s \le 20 \tag{15c}$$

$$0 \le SK_s \le 15 \quad \forall s = 1,2 \tag{15d}$$

$$SK_s \in \text{integer} \quad \forall\, s = 1,2 \tag{15e}$$

This model is recursive and usually cannot be directly solved. According to Equation 6, model 15 can be divided into multiple stages dynamic programming. Assuming that the controllable time interval for this case is one hour, then the 24-hour time series can be divided into 24 stages. Based on Equation 7 and an assumption that all parameters are unchanged within a stage, Equation 15 can be converted as follows:

$$Max\ V = \sum_{m=1}^{24} V_m \tag{16a}$$

subject to:

$$\begin{aligned} V_1 &= \sum_{s=1}^{2} SK_s \times ORR_{nsm} \\ &= SK_1 \times \left(0.01437 \left(1{,}000 \frac{V_0}{A} \right)^2 \right. \\ &\quad \left. + 0.01602 \left(1{,}000 \frac{V_0}{A} \right) + 0.05829 \right) \\ &\quad + SK_2 \left(-0.00791 \left(1{,}000 \frac{V_0}{A} \right)^2 \right. \\ &\quad \left. + 0.84975 \left(1{,}000 \frac{V_0}{A} \right) + 0.19929 \right) \end{aligned} \tag{16b}$$

$$V_m = \sum_{s=1}^{2} SK_s \times ORR_{nsm} \qquad \forall m = 2,\cdots,24 \tag{16c}$$

$$= SK_1 \times \left(0.01437 \left(\frac{1000\left(V_0 - \sum_{h=1}^{m-1} V_h\right)}{A} \right)^2 + 0.01602 \left(\frac{1000\left(V_0 - \sum_{h=1}^{m-1} V_h\right)}{A} \right) + 0.05829 \right)$$

$$+ SK_2 \left(-0.00791 \left(\frac{1000\left(V_0 - \sum_{h=1}^{m-1} V_h\right)}{A} \right)^2 + 0.84975 \left(\frac{1000\left(V_0 - \sum_{h=1}^{m-1} V_h\right)}{A} \right) + 0.19929 \right)$$

$$\sum_{s=1}^{2} SK_s \le 20 \tag{16d}$$

$$0 \le SK_s \le 15 \quad \forall s = 1, 2 \tag{16e}$$

$$SK_s \in \text{integer} \quad \forall\, s = 1, 2 \tag{16f}$$

where m is the index of the current stage from the divided 24-hour time series and V_m is the collected spilled oil in stage m, while h is the index of the stages before stage m and V_h is the collected oil in the stage h. This is a multiple-stage simulation based mixed integer nonlinear problem and can be solved by programming software (i.e., MATLAB® with LINDO API®).

The modelling results indicate that the optimal combination of the two types of skimmers is $SK_1 = 5$ and $SK_2 = 15$, yielding a collected spilled oil of 4,794 m^3 in the 24-hour period which means that the recovery efficiency is 96%. The details of the dynamic changes of ORR_n, collected and remaining volumes of spilled oil, and the oil thickness are shown in Figures 2 to 5.

From Figure 2 it can be seen that at the initial stage the net oil recovery rate of SK_1 (ORR_{n1}) is much higher than the net oil recovery rate of SK_2 (ORR_{n2}). However, ORR_{n1} significantly decreases with time and becomes lower than ORR_{n2} after about four hours. On the other hand, ORR_{n2} has relatively insignificant decrease and is predominant during the fifth and twentieth hours. Therefore, SK_1 has high contribution over the recovery in the first few hours but less in the rest, while SK_2 has stable contribution in the whole operational period (Figure 3). This will be one of the most important factors that affect the optimal combination.

Because SK_1 has a high contribution to the oil recovery in the first six hours, the accumulated amount of spilled oil significantly increases in these stages, leading to a significant decrease in the remaining amount as well as the slick thickness. In the following 10 hours (7th-17th hours) ORR_{n1} has already decreased to a low level, leading to less significant increase of accumulated amount as well as a decrease to the remaining amount and thickness compared with the first six hours. However, ORR_{n2} still keeps an acceptable level, thus the accumulated amount stably increases, while the remaining amounts as well as the slick thickness correspondingly decrease. After the 17th hour, both ORR_{n1} and ORR_{n2} are at very low levels,

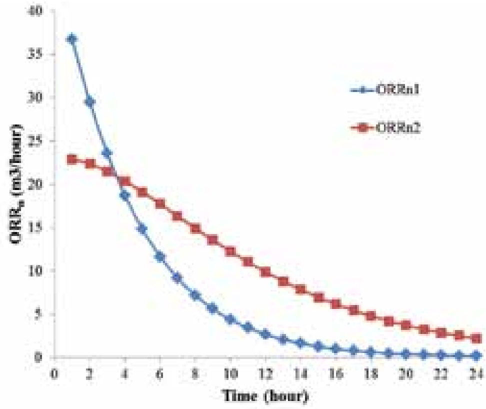

Figure 2: Changes of ORR_n of skimmers during the operational period.

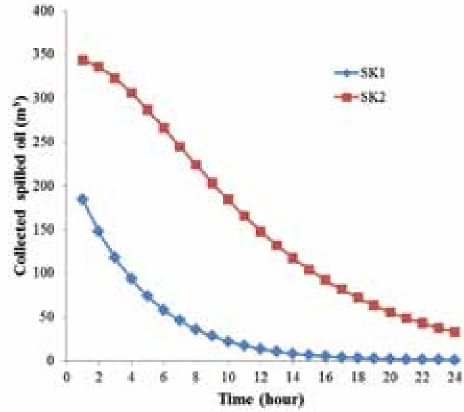

Figure 3: Collected amounts of spilled oil by each type of skimmer.

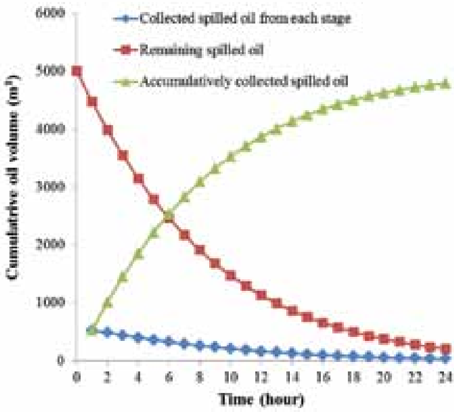

Figure 4: Collected and remaining spilled oil in each stage as well as the accumulative amount of the operational period.

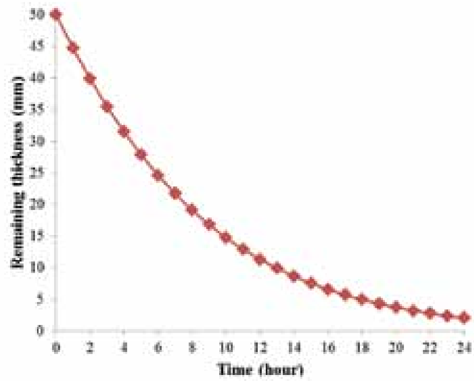

Figure 5: The change of slick thickness in the operational period.

and the collected and remaining amounts as well as the slick thickness only show detectable changes and become stable after the 22nd hour (Figures 4 and 5).

In order to access the recovery settings for the operational periods with lengths that are different from 24 hours (e.g., 5 hours or 10 hours), a series of optimizations are applied to determine the optimal combinations of skimmers with different operational periods. Figure 6 shows the optimal combinations of skimmers when the operational periods vary from 1 to 24 hours. The figure indicates that SK_1 is dominant when the operational periods are within six hours. When the operational period is six hours, the two types of skimmers are competing with each other and the optimal combination is $\{SK_1 = 9, SK_2 = 11\}$ to achieve the best efficiency of oil recovery. In contrast, when the operational periods are over six hours, SK_2 is dominant. Furthermore, due to the decreased efficiency of skimmers, the overall efficiency of oil recovery is decreased with time. The changes in total recovered oil after 20 hours become insignificant when the recovery rate is higher than 90%. Therefore, in practice, it is suggested to use SK_1 during the 1st and 5th hours, a combination of SK_1 and SK_2 with a ratio of 9:11 in the 6th hour, and SK_2 after the 6th hour. Furthermore, it is better to stop using these skimmers and change to other methods after 20 hours of operation.

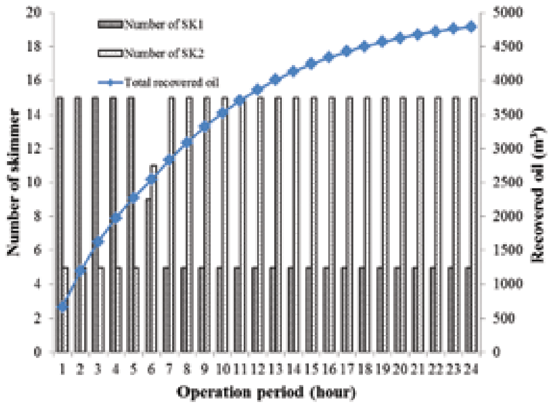

Figure 6: Combinations of skimmers and amounts of recovered oil in operational periods varying from 1 to 24 hours.

THE COUPLING OF SIMULATION FOR OIL WEATHERING PROCESS

In real-world practices, oil recovery is also significantly affected by weathering processes such as spreading and drift, evaporation, natural dispersion, emulsification, biodegradation, etc. [Fingas, 2010]. In this case, because the spilled oil is boomed and the recovery is required to be achieved within a short time period, evaporation, dispersion, and emulsification may play important roles in oil weathering. Therefore, these three processes will be considered as another part of simulation in the MSINP application. The equation for the evaporation process is as follows [Riazi and Edalat, 1996]:

$$FE = 1 - \exp\left(-\left(\left(\frac{1.5\times10^{-5}TU^{0.8}}{M^2}\right)\left(\frac{P^{sat}M}{\rho^{sat}RT}\right)/h_s\right)t\right) \quad (17)$$

where FE is the evaporation rate, T is the temperature (K), U is the wind speed (m/s), P^{sat} is the vapour pressure of the spill (Pa), M is the molecular weight (g/mol), ρ^{sat} is the density of the oil (kg/m^3), R is the gas constant (8.314 m^3·Pa/mol·K), h_s is the slick thickness (m), and t is time (hr). Furthermore, the equation for the dispersion process is as follows [Mackay et al., 1980]:

$$FD = \frac{0.11(U+1)^2}{1+50\mu^{0.5}h_s s_t} \quad (18)$$

where FD is the dispersion rate, μ is the dynamic viscosity of the oil (cP), and S_t is the interface tension of oil and water (dyne/m).

Emulsification is one of the key processes that change the properties and characteristics, which will affect the other weathering processes and consequently the oil recovery operation. Mackay et al. [1980] provided a simulation of emulsification by using the incorporation rate of water into an oil slick:

$$FW = K_b\left(1-\exp\left(\frac{-K_a}{K_b}(U+1)^2 t\right)\right) \quad (19)$$

where FW is the fractional water content, K_a is the cure fitting constant that varies with wind speed (2 * 10^{-6}), K_b is the mousse viscosity constant (0.7 for crude oils and heavy fuel oil) [Zadeh and Hejazi, 2012], and t is time (hr).

The evaporation process, together with the emulsification process, can lead to a change of oil density and viscosity as follows [Guo and Wang, 2009]:

$$\rho^{sat} = FW\rho_w + (1-FW)(\rho_{m-1} + K_b FE) \quad (20)$$

$$\mu = \mu_{m-1}\exp(K_c FE)\exp\left(\frac{2.5FW}{1-K_b FW}\right) \quad (21)$$

where ρ_w is the density of water (kg/m^3), ρ_{m-1} is the parent oil density (kg/m^3), μ_{m-1} is parent oil viscosity (cP), and K_c is the oil-dependent constant between 1 and 10 (1 is for gasoline or light diesel, and 10 for crude oils).

Correspondingly, Equation 16 can be converted as follows:

$$Max\ V = \sum_{m=1}^{24} V_m \tag{22a}$$

subject to:

$$\begin{aligned} V_1 &= \sum_{s=1}^{2} SK_s \times ORR_{nsm} \qquad \forall m = 1 \\ &= SK_1 \times \left(0.01437 \left(1{,}000 \frac{V_0}{A} \right)^2 + 0.01602 \left(1{,}000 \frac{V_0}{A} \right) + 0.05829 \right) \\ &\quad + 0.84975 \left(1{,}000 \frac{V_0}{A} \right) + 0.19929 \end{aligned} \tag{22b}$$

$$FE_1 = \left(1 - \exp\left(- \left(\frac{\left(\frac{1.5 \times 10^{-5} TU^{0.8}}{M^2} \right)}{\left(\frac{V_0}{A} \right)} \left(\frac{P^{sat} M}{\rho_0 RT} \right) \right) \right) \right) \qquad \forall m = 1 \tag{22c}$$

$$VD_1 = V_0 \times \frac{0.11 (U+1)^2}{1 + 50 \mu_0^{0.5} \left(\frac{V_0}{A} \right) s_t} \qquad \forall m = 1 \tag{22d}$$

$$VF_1 = V_0 \times FE_1 \quad \forall m = 1 \tag{22e}$$

$$VD_1 = V_0 \times FD_1 \quad \forall m = 1 \tag{22f}$$

$$\begin{aligned} V_m &= \sum_{s=1}^{2} SK_s \times ORR_{nsm} \qquad \forall m = 2, \cdots, 24 \\ &= SK_1 \times \left(0.01437 \left(\frac{1000 \left(V_0 - \sum_{h=1}^{m-1} (V_h + VF_h + VD_h) \right)}{A} \right)^2 + 0.01602 \left(\frac{1000 \left(V_0 - \sum_{h=1}^{m-1} (V_h + VF_h + VD_h) \right)}{A} \right) + 0.05829 \right) \\ &\quad + SK_2 \left(-0.00791 \left(\frac{1000 \left(V_0 - \sum_{h=1}^{m-1} (V_h + VF_h + VD_h) \right)}{A} \right)^2 + 0.84975 \left(\frac{1000 \left(V_0 - \sum_{h=1}^{m-1} (V_h + VF_h + VD_h) \right)}{A} \right) + 0.19929 \right) \end{aligned} \tag{22g}$$

$$FE_m = \left(1 - \exp\left(- \left(\frac{\left(\frac{1.5 \times 10^{-5} TU^{0.8}}{M^2} \right) \left(\frac{P^{sat} M}{\rho_m{}^{sat} RT} \right)}{\left(\frac{V_0 - \sum_{h=1}^{m-1} (V_h + VF_h + VD_h)}{A} \right)} \right) \right) \right) \tag{22h}$$

$$\forall m = 2, \cdots, 24$$

$$FD_m \frac{0.11(U+1)^2}{1+50\mu_m^{0.5}\left(\frac{V_0-\sum_{h=1}^{m-1}(V_h+VF_h+VD_h)}{A}\right)s_t} \tag{22i}$$
$$\forall m = 2,\cdots,24$$

$$FW_m = K_b\left(1-\exp\left(\frac{-K_a}{K_b}\right)(U+1)^2 m\right) \tag{22j}$$
$$\forall m = 2,\cdots,2$$

$$\rho_m^{sat} = FW_{m-1}\rho_w + (1-FW_{m-1}) \tag{22k}$$
$$(\rho_{m-1}+K_b FE_{m-1}) \quad \forall m = 2,\cdots,24$$

$$\mu \ = \mu_{m-1}\exp(K_c FE_{m-1})\exp\left(\frac{2.5FW_{m-1}}{1-K_b FW_{m-1}}\right)$$
$$\forall m = 2,\cdots,24 \tag{22l}$$

$$VF_m = V_0 \times FE_m \qquad \forall m = 2,\cdots,24 \tag{22m}$$

$$VD_m = V_0 \times FD_m \qquad \forall m = 2,\cdots,24 \tag{22n}$$

$$\sum_{s=1}^{2} SK_s \le 20 \tag{22o}$$

$$0 \le SK_s \le 15 \quad \forall s = 1,2 \tag{22p}$$

$$SK_s \in \text{integer} \quad \forall\, s = 1,2 \tag{22q}$$

where ρ_0 is the initial density of the spilled oil (kg/m^3), and μ_0 is the initial viscosity of the spilled oil (cP).

The inputs for the oil weathering processes are shown in Table 1, and the settings and inputs are the same as the previous one (Equation 16).

The modelling results indicate that the optimal combination of the two types of skimmers is $SK_1 = 5$ and $SK_2 = 15$, which is the same as the one in the case without weathering. This yields an oil recovery of 4,575 m^3 in the 24-hour period, leading to a recovery efficiency of 91.5% when oil weathering processes are involved. This recovery rate is a little lower than the one in the case without weathering due to a fractional loss from evaporation and dispersion. The details about the dynamic changes of ORR_n, the collected, lost and remaining oil, and the changes of oil viscosity and density as well as slick thickness are shown in Figures 7 to 12.

Although the skimmers in this case are the same as those applied without involvement of weathering processes, the net oil recovery rates

Parameter	Value	Parameter	Value
Temperature (T)	298 K	Wind speed (U)	5 m/s
Vapour pressure (P^{sat})	10.4 Pa	Molecular weight (M)	128.2 g/mol
Density of oil (ρ^{sat})	832 kg/m^3	Gas constant (R)	8.314 m^3·Pa/mol·K
Viscosity of the oil (μ)	3.03 cP	Interface tension of oil and water (S_t)	2000 dyne/m

Table 1: Statfjord crude oil characteristics for the weathering processes of evaporation and dispersion [Nazir et al., 2008].

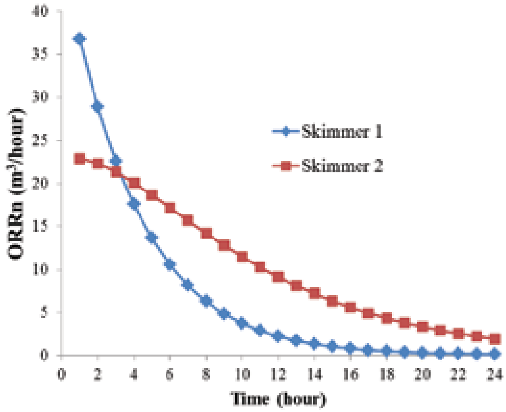

Figure 7: Changes of ORR_n of skimmers with oil weathering during the operational period.

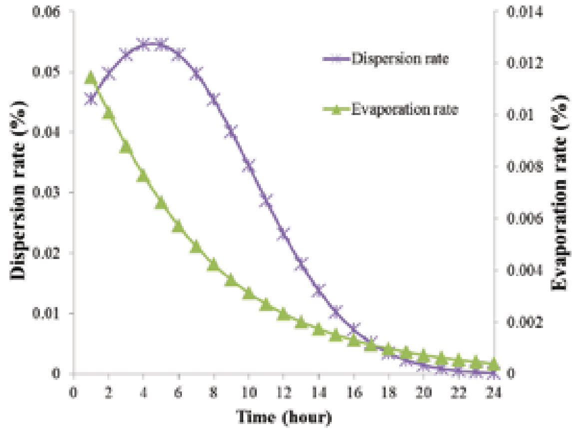

Figure 8: Changes of the evaporation and dispersion rates for each hour in the operational period.

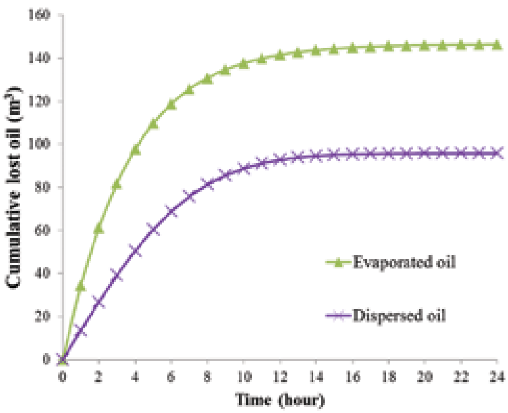

Figure 9: The cumulatively evaporated and dispersed oil during the operating period.

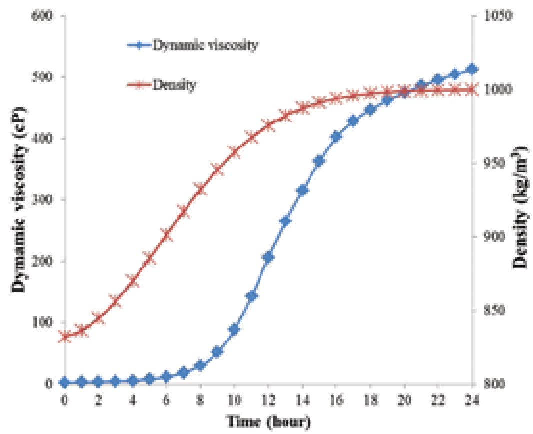

Figure 10: The change of dynamic viscosity and density with oil weathering in the operational period.

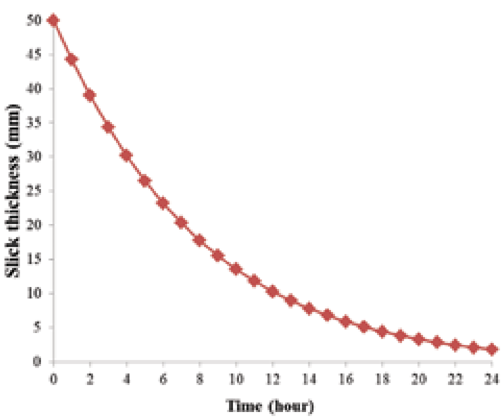

Figure 11: The change of slick thickness with oil weathering in the operational period.

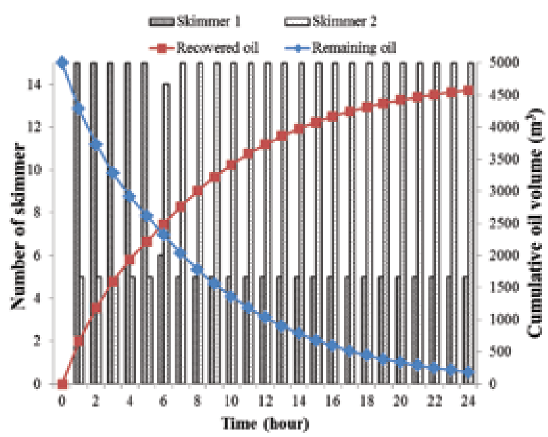

Figure 12: Combinations of skimmers and the fate of spilled oil in operational periods varying from 1 to 24 hours.

drop a little due to the influence from weathering (Figures 2 and 7). Similarly, the changes of slick thickness in this case are considerably more significant than the changes in the previous case in the first 10 hours. However, after the 10th hour, the changes become more or less the same as the ones in the case without weathering (Figures 5 and 11). This is because large amounts of volatile and semi-volatile components in the oil are rapidly lost via evaporation and dispersion, which provide relatively significant contributions to the reduction of the remaining oil (Figures 8 and 9).

Simultaneously, the properties (e.g., viscosity and density) of the spilled oil are also changed by the weathering process (e.g., evaporation and emulsification) (Figure 10), and consequently affect the evaporation and dispersion (Figure 8). Although the rates of evaporation and dispersion still appear at certain percentages and keep decreasing, these rates represent the percentages of the remaining oil from the previous stage/hour and therefore the lost amount after the 12th hour becomes stable at a significantly low level (Figure 9). Therefore, in the later stages of the operational period, the evaporation and dispersion have negligible contribution to the change of the remaining oil, leading to similar changes of slick thickness and recovery efficiencies.

Figure 12 shows the optimal combinations of skimmers and the fate of spilled oil when the operational periods varied from 1 to 24 hours. The result indicates that SK_1 is dominant when the operational periods are within five hours. When the operational period is six hours, two types of skimmers are competing with each other and the optimal combination is $\{SK_1 = 6, SK_2 = 14\}$ to achieve a best efficiency of oil recovery. When the operational periods are over six hours, SK_2 is dominant. This result is similar to the one from the case without weathering, which is because the lost amount of oil from evaporation and dispersion is lower than natural weathering due to the application of oil recovery and is insignificant compared with the recovered amount.

The results demonstrate that the multiple-stage simulation based optimization approach can help to determine the optimum combination of skimmers in different stages of an operational period to achieve best oil recovery. The proposed approach can support offshore oil spill recovery operations by integrating with not only the weathering simulation but also with other phenomena such as weather forecasting and ocean dynamics simulation. This can be very helpful to offshore oil spill recovery in harsh environments where unpredictable weather and oceanic conditions frequently occur. Furthermore, the multiple-stage optimization can help in determining when to adjust the settings of the recovery operation, which is also of importance in improving the efficiency of offshore oil spill recovery.

CONCLUSIONS

This study developed a multiple-stage simulation based mixed integer nonlinear programming (MSINP) approach to provide sound decisions for skimming spilled oil in a fast and dynamic manner, which is especially helpful in harsh environments prevailing in Newfoundland offshore areas. The MSINP approach converts the simulation model into constraints which dynamically link to decision variables, and breaks the time series into stages according to controllable time intervals in a practical manner, leading to multiple stage dynamic programming.

In the case study, regression models were developed to simulate the efficiencies of two drum skimmers based on past performance evaluation tests. The models were further integrated with the optimization methods to determine the optimal strategy to achieve the maximum oil recovery amount within the constraints of time and resources. The results indicated a recovery efficiency of 96% based on the optimal settings, demonstrating that the proposed approach was able to efficiently incorporate the regression models and optimization into the same framework and to support expeditious decision making during offshore oil spill response practices. Furthermore, the approach was also tested with the integration of oil weathering processes (e.g., evaporation and dispersion). The results indicated that with the considerations of evaporation and dispersion, in order to achieve the maximum oil recovery, the optimal operation period for oil recovery would be during the first 16 hours after the spill. In the alterative, a combination of five sets of SK_1 and 15 sets of SK_2 was suggested, yielding an oil recovery efficiency of 91.5%.

The MSINP approach can provide optimal settings for offshore oil spill recovery operations, which can result in significant improvements to the efficiency and effectiveness of oil recovery in northern regions. In addition, the MSINP approach is able to account for dynamic changes in the environment, weathering of spilled oil, and changing resource availability. Thus the approach can support dynamic and expeditious modification of the operational setting during the recovery process under the typically unpredictable weather conditions and harsh environments found in northern regions.

Although a case study of oil recovery using skimmers is provided in this paper, the MSINP approach can globally and dynamically support the whole process of oil recovery, including equipment transportation, deployment, and utilization of containment, skimming, surfactant utilization, in situ burning, and other response tactics.

In our future research, this new approach will be tested and adjusted as needed to more effectively reflect the weathering process and other changes in oil properties. The future research may also focus on the involvement of uncertainties in the MSINP model for supporting decision-making processes in all offshore oil spill responses. The performance of the model will also be evaluated and possibly improved through real-world applications.

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