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Least Cost Optimization of Offshore Oil Spill Clean-Up Technologies

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ABSTRACT: In this study, cost optimization model has been developed to minimize the costs associated with oil spill cleanup subject to some constraints. The model would also be used in estimating the anticipated cleanup cost of any given spill with respect to the amount of spilled oil in tonnes. The model developed using updated cost data collected from case studies of some selected spills and from the current prices of cleanup chemicals and technologies was developed using the Linear Optimization Software (LiPS). The optimization model result gave $4400/ton as the per-unit cost of oil spilled per tonne. To validate the model, the result of the model ($4400/ton) was compared to the available data of the average per-unit costs of the numerous previous spill incidents including average costs of crude Oil Spills (US Spills $14,520.66/ton, Non US Spills $3,963.12/ton and All spills $7,250.04/ton); average costs due to distant of spill from 0km to 500km of the shore (US Spills 18,934.83/ton, Non US Spills $7,385.73/ton and All Spills $8,534.67/ton);average cost of spill due to location for offshore spills (US Spills $6,873.72/ton, Non US Spills $8,570.10/ton, All spills $8,292.94/ton); average costs due to size of spilled oil between 0 to 500tons (US Spill $20,260.37/ton and Non US Spills $34,172.93/ton);average regional per unit costs (North America $19,814.63/ton, Latin America 3,055.76/ton, Africa $3,163.93/ton, Europe $10,807.83/ton, South Pacific $5,698.88/ton, Middle East $1,057.50/ton, and Asia $27,495.83/ton) and the average per unit cost of oil spill in Nigeria now ($16,061.36/ton) . Implementation of the model result gave a 72.61 percentage reduction to the current average per unit cost of mitigating oil spill in Nigeria
KEYWORDS: Offshore Oil-spill, Clean-up Technologies, Cost optimization

I. INTRODUCTION

Oil spill incidents have occurred in various parts and at different times along our coast. Some major spills in the coastal zone are the GOCON's Escravos spill in 1978 of about 300,000 barrels, SPDC's forcados Terminal tank failure in 1978 of about 580,000 barrels and TexaoFuniva – 5 blow out cut in 1980 of about 400,000 barrels. Other oil spill incidents are those of the Abudu pipe line in 1982 of about 18,818 barrels, the Jesse Fire Incident 40,000 barrels, The most publicized of all oil spills in Nigeria occurred on January 17 1980 when a total of 37.0 million liters of crude oil got spilled into the environment. This spill occurred as a result of a blow out at Funiwa 5 offshore station which spilled into the Atlantic Ocean from an oil industry facility and that damaged 340 hectares of mangrove (Nwilo and Badejo[3], 2005).

According to the Department of Petroleum Resources, between 1976 and 1996 a total of 4647 incidents resulted in the spill of approximately 2,369,470 barrels of oil into the environment. Of this quantity, an estimated 1,820, 410.5 barrels (77%) were lost to the environment. A total of 549,060 barrels of oil representing 23.17% of the total oil spilt into the environment was recovered. The highest recorded spill so far occurred in 1979 and 1980with a net volume of 694, 117.13 barrels and 600,511.02 barrels respectively (Shell Petroleum Development Company, 1996)[4].

Available records for the period of 1976 to 1996 indicates that approximately 6%, 25% and 69% respectively of total oil spilled in the Niger Delta Area, were in land, swamp and offshore environments respectively. Also between 1997 and 2001, Nigeria recorded a total number of 2,097 oil spill incidents (Shell Petroleum Development Company, 1996)[4].

Thousands of barrels of oil have been spilt into the environment through our oil pipelines and tanks in the country. This spillage is as a result of our lack of regular maintenance of the pipelines and storage tanks. Some of these facilities have been in use for decades without replacement. Sabotage is another major cause of oil spillage in the country. Some of the citizens of this country in collaboration with people from other countries engage in oil bunkering. They damage and destroy oil pipelines in their effort to steal oil from them. SPDC claimed in 1996 that sabotage accounted for more than 60 percent of all oil spilled at its facilities in Nigeria, stating that the percentage has increased over the years both because the number of sabotage incidents has increased (Shell Petroleum Development Company, 1996)[4].

Pirates are stealing Nigeria's crude oil at a phenomenal rate, funneling nearly 300,000 barrels per day from our oil and selling it illegally on the international trade market. Nigeria lost about ₦7.7 billion in 2002 as a result of vandalization of pipelines carrying petroleum products. The amount, according to the PPMC, a subsidiary of NNPC, represents the estimated value of the products lost in the process. Illegal fuel siphoning as a result of the thriving black market for fuel products has increased the number of oil pipeline explosions in recent years. In July 2000, a pipeline explosion outside the city of Warri caused the death of 250 people. An explosion in Lagos in December 2000 killed at least 60 people. The NNPC reported 800 cases of pipeline vandalization from January through October 2000. As at January 2001, Nigeria had lost about 4 billion dollars in oil revenues in 2000 due to the activities of vandals on our oil installations. The government estimates that as much as 300,000 bbl/d of Nigerian Crude is illegally bunkered (Freighted) out of the country. In Nigeria, fifty percent (50%) of oil spills is due to corrosion, twenty eight percent (28%) to sabotage and twenty one percent (21%) to oil production operations. One percent (1%) of oil spills is due to engineering drills, inability to effectively control oil wells, failure of machines and inadequate care in loading and unloading of oil vessels (Nwilo and Badejo, 2008)[5].

An oil spill is the accidental release of a liquid petroleum hydrocarbon into the environment, especially marine areas, due to human activity, and is a form of pollution. The term is usually applied to marine oil spills, where oil is released into the ocean or coastal waters, but spills may also occur on land. Oil spill may be due to releases of crude oil from tankers, offshore platforms, drilling rigs and wells, as well as spills of refined petroleum products (such as gasoline, diesel) and their by-products, heavier fuels used by large ships such as bunker fuel, or the spill of any oily refuse or waste oil. Spilt oil penetrates into the structure of the plumage of birds and the fur of mammals, reducing their insulating ability, and making them more vulnerable to temperature fluctuations (National Oceanic and Atmospheric Administration, 2010)[6].

Oil spills at sea are generally much more damaging than those on land, since they can spread for hundreds of nautical miles in a thin coating of oil. This can kill sea birds, mammals, shellfish and other organisms it coats. Oil spills on land are more readily containable if a makeshift earth dam can be rapidly bulldozed around the spill sites before most of the oil escapes, and land animals can avoid the oil more easily (Etkin, 1999)[7].

Table 2.2: per unit oil spill cleanup cost byoil type (1999 US$)

Oil Type	US Spills ($)	Non-US Spills ($)	All Spills ($)
No. 2 diesel fuel	3,607.38/tonne 3.24/liter	1,699.32/tonne 1.53/liter	2,307.90/tonne 2.07/liter
Light crude	3,131.08/tonne 2.86/liter	4,554.06/tonne 4.09/liter	4,265.94/tonne 3.83/liter
No. 4 fuel	--	23,893.38/tonne 21.47/liter	23,893.38/tonne 21.47/liter
No. 5 fuel	8,693.58/tonne 7.81/liter	24,272.64/tonne 21.81/liter	23,190.72/tonne 20.84/liter
Crude	14,520.66/tonne 13.05/liter	3,963.12/tonne 3.56/liter	7,250.04/tonne 6.52/liter
Heavycrude	21,091.56/tonne 18.95/liter	6,447.42/tonne 5.79/liter	8,540.70/tonne 7.68/liter
No. 6 fuel	18,066.30/tonne 16.24/liter	16,275.84/tonne 14.63/liter	16,952.04/tonne $15.33/liter

Source: Etkin, 2000[23]

Table 2.3: per-unit cleanup costs by degree of shoreline oiling (1999 US $)

Shoreline Length Oiled	US Spills ($)	Non-US Spills ($)	All Spills ($)
0-1 km	2,644.11/tonne 2.37/liter	5,530.66/tonne 4.97/liter	5,086.00/tonne 4.57/liter
2-5 km	5,991.33/tonne 5.38/liter	6,150.37/tonne 5.53/liter	5,793.00/tonne 5.21/liter

8-15 km	10,540.42/tonne 9.47/liter	6,304.60/tonne 5.67/liter	5,876.00/tonne 5.28/liter
20-90 km	15,164.62/tonne 13.63/liter	6,863.19/tonne 6.17/liter	6,612.00/tonne 5.94/liter
100 km	27,303.53/tonne 24.54/liter	9,061.36/tonne 8.14/liter	11,398.00/tonne 10.24/liter
500 km	51,962.94/tonne 46.70/liter	10,404.21/tonne 9.35/liter	16,443.00/tonne 14.78/liter

Table 2.4: per-unit marine oil spill cleanup costs by location type (1999 US $)

Location	US Spills	Non-US Spills	All Spills
In-Port	$34,089.30/tonne $30.63/liter	$12,983.04/tonne $11.67/liter	$19,674.25/tonne $17.68/liter
Nearshore	$25,066.44/tonne $22.53/liter	$17,931.06/tonne $16.11/liter	$22,442.69/tonne $20.17/liter
Offshore	$6,873.72/tonne $6.18/liter	$8,570.10/tonne $7.70/liter	$8,292.94/tonne $7.36/liter

Source: Etkin, 2000[23]

Table 2.5: per-unit marine oil spill cleanup cost by spill size for non-us spills(1999 US $)

Spill Size	US $/tonne	US $/liter
0.34-3.4 tonnes 379-3,785 liters	77,896.33/tonne	70.00/liter
3.4-17 tonnes 3,785-18,925 liters	31,035.34/tonne	27.89/liter
17-34 tonnes 18,925-37,850 liters	10,687.65/tonne	9.60/liter
34-340 tonnes 37,850-378,500 liters	9,757.86/tonne	8.77/liter
340-1,700 tonnes 378,500-1,892,500 liters	6,390.95/tonne	5.74/liter
1,700-3,400 tonnes 1,892,500-3,785,000 liters	3,686.74/tonne	3.31/liter
3,400-34,000 tonnes 3,785,000-37,850,000 liters	2,367.69/tonne	2.13/liter
>34,000 tonnes >37,850,000 liters	357.56/tonne	0.32/liter

Source: Etkin(2000)[23]

Table 2.6: per-unit marine oil spill cleanup cost byspill sizefor us spills(1999 US $)

Spill Size	US $/tonne	US $/liter
<34 tonnes <37,850 liters	141,466.34/tonne	127.13/liter
34-68 tonnes 37,850-75,700 liters	26,804.75/tonne	24.09/liter
68-170 tonnes 75,700-189,250 liters	13,854.58/tonne	12.45/liter
170-680 tonnes 189,250-757,000 liters	12,101.04/tonne	10.87/liter

680-3,400 tonnes 757,000-3,875,000 liters	10,038.64/tonne	9.02/liter
3,400-34,000 tonnes 3,785,000-37,850,000 liters	772.20/tonne	0.69/liter

Source: Etkin (2000)[23]

Table 2.7: oil spill cleanup cost comparison bytechnique (1999 US $)

Cleanup Technique	Mean Cost/Tonne	Mean Cost/Liter
Dispersants only	$2,184.40/tone	$1.96/liter
Dispersants Primarymethod	$2,556.98/tone	$2.30/liter
Dispersant Secondary/tertiarymethod	$14,233.17/tone	$12.79/liter
Other methods only (No dispersants)	$12,802.94/tone	$11.51/liter

Source: Etkin (1998)

Table 2.8:per-unit marine non-us oil spill cleanup costs by primary cleanup methodology(1999 US $)

Primary Method	US $/tone	US $/liter
Manual	$23,403.45/tone	$21.03/liter
Mechanical	$9,611.97/tone	$8.64/liter
Dispersants	$5,633.78/tone	$5.06/liter
In Situ Burning	$3,127.87/tone	$2.81/liter
Natural	$1,286.00/tone	$1.15/liter

Source: Etkin(2000)[23]

Table 2.9: average per-unit marine oil spill cleanup costs by nation/region (1999 US $)

Nation/Region	US $/liter	US $/tonne
North America		
Canada	$5.85	$6,508.14
United States	$23.02	$25,614.63
Average	$17.81	$19,814.63
Latin America		
Argentina	$2.08	$2,316.61
Brazil	$5.03	$5,600.72
Chile	$0.82	$910.42
Mexico	$0.76	$850.32
St. Kitts/Nevis	$2.77	$3,085.81
Uruguay	$3.03	$3,368.25
Venezuela	$10.62	$1,817.83
Average	$2.75	$3,055.76
Africa		
Egypt	$3.98	$4,428.90
Morocco	$8.69	$9,675.07
Mozambique	<$0.01	$6.09
Nigeria	$1.59	$1,766.75
South Africa	$2.62	$2,917.54

Average	$2.84	$3,163.93
Europe		
Denmark	$10.05	$11,180.41
Estonia	$6.13	$6,820.62
Finland	$1.90	$2,115.29
France	$2.07	$2,301.58
Germany	$9.62	$10,702.67
Greece	$7.67	$8,530.29
Ireland	$4.32	$4,807.49
Italy	$5.88	$6,541.19
Latvia	$8.28	$9,212.35
Lithuania	$0.07	$78.12
Netherlands	$5.98	$6,655.37
Norway	$20.77	$23,118.08
Spain	$0.39	$438.68
Sweden	$14.06	$15,642.36
UK	$2.77	$3,082.80
Yugoslavia	$1.36	$1,541.40
Average	$9.71	$10,807.83
South Pacific		
Australia	$5.38	$5,991.33
New Zealand	$2.51	$2,791.35
Average	$5.12	$5,698.88
MiddleEast		
Israel	$2.08	$2,313.60
United Arab Emirates	$0.57	$636.99
Average	$0.95	$1,057.50
Asia		
Hong Kong	$4.00	$4,452.94
Japan	$31.11	$34,619.92
Malaysia	$68.93	$76,589.29
Philippines	$0.61	$676.51
Singapore	$0.35	$390.61
South Korea	$11.52	$12,814.96
Average	$24.71	$27,495.83

Source: Etkin (2000)[23]

Table 2.14: evaluation criteria for marine oil spill remediation methods

Criteria	Definition	Score (%)
Efficiency	95.99% removal	20
Time	Removes contaminant within days	15
Cost	Relatively inexpensive	15
Impact on Marine life	No health risks involved with method	10
Level of difficulty	Easy to maintain and operate	10
Weather	Favorable for application of method	10
Reliability	The method works the majority of the times	5
Oil Recovery	Chances of oil recovery	5
Effect on physical/chemical characteristics of oil	Do not change physical/chemical characteristic of oil	5
The need for further treatment	No further treatment required	5

Total	**100%**

Source: USEPA(1999a)[26]

Table 2.15: assessment of marine oil spill remediation methods

	Physical methods			Chemical Methods			
Criteria	(1) Booms	(2) Skimmers	(3) Adsorbent	(4) Dispersants	(5) Solidifiers	(6) In- situ Bu	(7) Bioremediation
Efficiency (A)	10	10	10	13	7	17	18
Time (B)	10	10	8	8	8	13	7
Cost (C)	7	7	8	8	7	10	12
Impact on Marine life (D)	9	9	9	9	5	3	9
Level of difficulty (E)	2	2	2	2	4	5	8
Weather (F)	5	5	4	4	8	5	10
Reliability (G)	2	2	2	2	2	3	4
Oil Recovery (H)	4	4	1	1	1	0	0
Effect on physical/chemical characteristics of oil (I)	5	5	0	0	0	0	0
The need for further treatment (J)	1	1	1	1	0	3	5
Total Score 1	**55**	**55**	**45**	**54**	**47**	**59**	**73**

Source: USEPA (1999a)

2.17 Exchange rates

Table 2.18: Table showing the historical value of one U.S. Dollar in Nigerian naira - PM = Parallel Market.

Date	**Naira per US$**	**Date**	**Naira per US$**
1972	0.658	1993	17.30 (21.90 PM)
1973	0.658	1994	22.33 (56.80 PM)
1974	0.63	1995	21.89 (71.70 PM)
1975	0.616	1996	21.89 (84.58 PM)
1976	0.62	1997	21.89 (84.58 PM)
1977	0.647	1998	21.89 (84.70 PM)
1978	0.606	1999	21.89 (88-90 PM)
1979	0.596	2000	85.98 (105.00 PM)
1980	0.550 (0.900 PM)	2001	99-106 (104-122 PM)
1981	0.61	2002	109-113 (122-140 PM)
1982	0.673	2003	114-127 (135-137 PM)
1983	0.724	2004	127-130 (137-144 PM)
1984	0.765	2005	132-136
1985	0.894 (1.70 PM)	2006	128.50-131.80
1986	2.02 (3.90 PM)	2007	120-125
1987	4.02 (5.90 PM)	2008	115.50-120
1988	4.54 (6.70 PM)	2009	145-171
1989	7.39 (10.70 PM)	2010	148.21-154.8
1990	7.39 (10.70 PM)	2011	151.05-165.1
1991	8.04 (9.30 PM)	2012	155.09-161.5
1992	9.9	2013	153.21-162.9

Source:http://www.exchangerates.org/history/NGN/USD/T

From the historical table of world exchange rates the current exchange rate of dollar to naira is as shown below:

min. = 197.96 (June 21, 2015)
avg. = 199.00
max. = 200.28 (May 11, 2015)
From the above, it can be deduced that in 1999, the average conversion rate of $1 to naira is N21.89 and in 2015 it is N199.00

Sources of Data
Data for this work was collected from Journals; oil and gas companies websites like DAWG Incorporation, SPDC, etc ; oil spill clean-up Products and chemicals' websites like Clear Tech Global, etc; Oil and Gas Agencies like USEPA, etc and other sites related to oil and gas.

Assumptions in the Model
The assumptions used in the model formulation are as follows:
i It is assumed that any spill occurring beyond 500km from the shore is allowed to degrade by natural means. Also spills between 350 to 500km are treated by in-situ-burning.
ii It is assumed that the maximum combination of technologies in any giving time is three(3) technologies
iii It is assumed that cleanup must have commenced on or before seven days from the time of spill.
iv It is assumed that the oil type is Crude Oil.
v It is assumed that that the model focuses only on the cost implication of the technology used for the cleanup ; it does not consider other factors like environmental pollution, loss of wild life, loss of cargo cost, vessel salvage/ repair cost, cost due to personal injuries(loss of life, permanent disability, and temporary injuries), and Authority service costs.
vi The currency used in the model is the US Dollars of 1999 value
vii It is assumed that the model is for oil spill offshore not exceeding 5000tons
viii It is assumed that:
(a) Bioremediation (χ_1) is applied at a distance less than 10 nautical miles from seashore or in estuaries, it is therefore given by

$$\chi_1 \leq 10 \qquad 4.2$$

(b) Booms or Barriers (χ_2) are used either with in-situ burning (χ_3) or with skimmers (χ_4) and adsorbents (χ_5).
When it is used with in-situ burning, the in situ burning is at a distance of about 200 nautical miles from the shores and is given by;

$$\chi_2 + \chi_3 \leq 200 \qquad 4.3$$

(c) When Booms are used with skimmers and adsorbent, the distance from the shores is about 200 nautical miles from the shores. This is given by:

$$\chi_2 + \chi_4 + \chi_5 \leq 200 \qquad 4.4$$

(d) Dispersants are used with skimmers. It is used at a distance a little more than 10 nautical miles from the shores. The equation of Dispersant as constraint when used with skimmers is given by:

$$\chi_6 + \chi_4 \geq 10 \qquad 4.5$$

(e) Solidifiers are used at a distance of about 10 nautical miles from the shore: The equation of dispersant as a constraint is given by

$$\chi_7 \leq 10 \qquad 4.6$$

Formation of Model for Least Cost Mitigation of Oil Spillage
The model applies for oil spills not exceeding 500km from the sea shores, spills beyond 500km from the shores are assumed to degrade by nautical means, without applying any technology/technique. Seven techniques of mitigation are considered. Let the extent of application of any of the mitigation techniques be represented by X_1, X_2, X_3, X_4, X_5, X_6, and X_7, miles also let unit cost per nautical mile be C_1, C_2, C_3, C_4, C_5, C_6, C_7, respectively for booms, skimmers, adsorbent, dispersants, solidifiers, in-situ burning and bioremediation.
The problem is defined by the combination of the above and will result in least cost.

Hence the total cost $Z = \Sigma(CX) \quad = C_1X_{1+}C_2X_2+C_3X_{3+}C_4X_4 + C_5X_5+ C_6X_6 + C_7X_7 \qquad (4.1)$

Constraints to the Model
Local Constraints: Bioremediation (χ_1) is applied at a distance less than 10 nautical miles from seashore or in estuaries, it is therefore given by

$\chi_1 \leq 10$ (4.2)

Booms or Barriers (χ_2) are used either with in-situ burning (χ_3) or with skimmers (χ_4) and adsorbents (χ_5). When it is used with in-situ burning, the in situ burning is at a distance of about 200 nautical miles from the shores and is given by;

$\chi_2 + \chi_3 \leq 200$ (4.3)

When Booms are used with skimmers and adsorbent, the distance from the shores is about 200 nautical miles from the shores. This is given by:

$\chi_2 + \chi_4 + \chi_5 \leq 200$ (4.4)

Dispersants are used with skimmers. It is used at a distance a little more than 10 nautical miles from the shores. The equation of Dispersant as constraint when used with skimmers is given by:

$\chi_6 + \chi_4 \geq 10$ (4.5)

Solidifiers are used at a distance of about 10 nautical miles from the shore: The equation of dispersant as a constraint is given by

$\chi_7 \leq 10$ (4.6)

The Optimization Equation

Minimise Z = $C_1\chi_1 + C_2\chi_2 + C_3\chi_3 + C_4\chi_4 + C_5\chi_5 + C_6\chi_6 + C_7\chi_7$ (4.7)

Subject to

$\chi_1 < 10$ (4.8)

$\chi_2 + \chi_3 \leq 200$

$\chi_2 + \chi_4 + \chi_5 \leq 200$

$\chi_6 + \chi_4 \geq 10$

$\chi_7 < 10$

$X_{i=1-7} = 0$ or 1

Constant Costs of the Model

Table 4.1 Constant costs of the model

Technology	Symbol	Cost ($)
Bioremediation	C_1	76
Booms	C_2	853
In-situ-Burning	C_3	282
Skimmers	C_4	440
Adsorbent	C_5	401
Dispersant	C_6	2,184
Solidifiers	C_7	4,693

These constants where derived as shown in the appendix

The Complete Optimization Equation With Constant Costs

Minimise Z = 76\chi_1$ + 853\chi_2$ + 282\chi_3$ + 440\chi_4$ + 401\chi_5$ + $2,184$\chi_6$ + 4693\chi_7$ **4.1**

Subject to

$\chi_1 \leq 10$ 4.2

$\chi_2 + \chi_3 \leq 200$ 4.3

$\chi_2 + \chi_4 + \chi_5 \leq 200$ 4.4

$\chi_6 + \chi_4 \geq 10$ 4.5

$\chi_7 \leq 10$ 4.6

$X_{i=1-7} = 0$ or 1

Result of the Model Using Linear Programming Software (LIPS)

Table 4.2: Simplex iteration

*** Phase II --- Start ***

Basis	X1	X2	X3	X4	X5	X6	X7	s8	s9	s10	s11	s12	RHS

s8	1	0	0	0	0	0	0	1	0	0	0	0	10
s9	0	1	1	0	0	0	0	0	1	0	0	0	200
s10	0	1	0	1	1	0	0	0	0	1	0	0	200
X6	0	0	0	1	0	1	0	0	0	0	-1	0	10
s12	0	0	0	0	0	0	1	0	0	0	0	1	10
Obj.	76	853	282	-1744	401	0	4693	0	0	0	2184	0	21840

Variable to be made basic -> X4
Ratios: RHS/Column X4 ->{ - - 200 10 - }
Variable out of the basic set -> X6

The Table above is the simplex iteration for the model. From the iteration, the input data(variables) are the seven clean-up technologies used in the model (X1,X2,X3,X4,X5,X6, and X7. The variable to be made basic from the model is X4(Skimmers) because it gave the highest objective output ifor both positive and negative values. The variable X6 is the variable out of basic set because it gave 0 objective output for both positive and negative value.

Table 4.3: * Phase II --- Iteration 1 *****

Basis	X1	X2	X3	X4	X5	X6	X7	s8	s9	s10	s11	s12	RHS
s8	1	0	0	0	0	0	0	1	0	0	0	0	10
s9	0	1	1	0	0	0	0	0	1	0	0	0	200
s10	0	1	0	0	1	-1	0	0	0	1	1	0	190
X4	0	0	0	1	0	1	0	0	0	0	-1	0	10
s12	0	0	0	0	0	0	1	0	0	0	0	1	10
Obj.	76	853	282	0	401	1744	4693	0	0	0	440	0	4400

>> Optimal solution FOUND
>> Minimum = $4400

From the table above, it can be seen that the optimal solution to the model is $4400 and it is produced by the basic variable X4(Skimmers).

Table 4.4: Results - variables

Variable	Value	Obj. Cost	Reduced Cost
X1	0	76	-76
X2	0	853	-853
X3	0	282	-282
X4	10	440	0
X5	0	401	-401
X6	0	2184	-1744
X7	0	4693	-4693

The above table shows the value and the reduced costs corresponding to each of the variables (clean-up technologies) as produced by the linear programing software. It is only X4(Skimmers) that have a positive value of 10 and a reduced cost of 0. All other variables have negative values.

Table 4.5: Results - constraints

Constraint	Value	RHS	Dual Price
Row1	0	10	0
Row2	0	200	0
Row3	10	200	0
Row4	10	10	440
Row5	0	10	0

The above table shows the values and dual prices of each of the constraints. It is Row 4 constraint ($X6+X4_4 \geq 10$) which gave both a positive value of 10 and a positive dual price of $440. All other rows gave dual prices of 0.

Sensitivity Analysis

Table 4.6: Cost range

Variable	Current COST	Min COST	Max COST	Reduced Cost

X1	76	0	+infinity	-76
X2	853	0	+infinity	-853
X3	282	0	+infinity	-282
X4	440	0	2184	0
X5	401	0	+infinity	-401
X6	2184	440	+infinity	-1744
X7	4693	0	+infinity	-4693

The table above shows the sensitivity analysis for the cost range of the variables in the model. It is only X4 (Skimmers) that gave a positive maximum cost of $2184. All other variables have positive-infinite values as their maximum costs.

Table 4.7: RHS range

Constraint	Current RHS	Min RHS	Max RHS	Dual Price
Row1	10	0	+infinity	0
Row2	200	0	+infinity	0
Row3	200	10	+infinity	0
Row4	10	0	200	440
Row5	10	0	+infinity	0

Table 4.7 above is the sensitivity analysis for the constants of the model. From the analysis, only Row4($X6+X4_4 \geq 10$) produced a maximum range of 200. All other Rows produced positive- infinite values as their maximum range.

II. DISCUSSION

Table 4.4 represents the starting of the Simplex iteration for the Model. From the table, it can be seen that it is only the objective value of X4 that is negative (-1744), all other objective functions where either 0 or positive. Therefore the variable to be made basic is X4, but X6 has an objective value of 0 which made it the variable out of the basic set. Also from Table 4.5 (Table showing the final iteration; iteration 1), it can be seen that the Optimum Solution for the Model was found to be $4400.

From Table 4.6, the values and objective costs as well as the reduced costs of each variables where presented, X4 is the only variable with a positive value of 10 and an objective function of 440. All other variables have no value. Also X4 has a reduced cost of 0 while all other variables have negative reduced costs. Table 4.7 shows that Row4 (representing constraint 4) is the only row with dual price.

Tables 4.8 and 4.9 are for the sensitivity analysis of the model. From Table 4.8, it can be seen that X4 is the only variable which has a valid maximum cost of $2184, a current cost of$440 and a minimum cost of 0, all other variables have positive-infinite maximum cost. From Table 4.9, it can be seen that it is only Row 4 that has a valid maximum RHS value of 200. Current RHS value of 10 and minimum RHS value of 0; all other Rows have positive-infinite values.

Validation of the Model

From Table 2 (Per Unit Oil Spill Cleanup Cost by Oil Type), the average cleanup cost for crude oil is given as presented below;

Table 4.8: summary of per unit oil spill cleanup cost by oil type and the model cost

Oil Type	**US Spills (USD/ton)**	**Non-US Spills (USD/ton)**	**All Spills(USD/ton)**	**From The Model (USD/ton)**
Crude Oil	14,520.66	3,963.12	7,250.04	4,400.00

From Table 3 (Per Unit Oil Spill Cleanup Cost by Degree of Shoreline Oiling), the average cleanup cost between 0km to500km is given as presented below;

Table 4.9: Summary of per unit Oil Spill Cleanup Cost by Degree of Shoreline Oiling and the model cost

Shoreline Oiling	**US Spills (USD/ton)**	**Non-US Spills (USD/ton)**	**All Spills(USD/ton)**	**From The Model (USD/ton)**
Okm-500km	18,934.83	7,385.73	8,534.67	4,400.00

From Table 4 (Per Unit Marine Oil Spill Cleanup Cost by Location Type), the average cleanup cost is given as presented below;

Table 4.10: Summary of per unit Marine Oil Spill Cleanup Cost by Location Type and the model cost

Location	**US Spills (USD/ton)**	**Non-US Spills (USD/ton)**	**All Spills(USD/ton)**	**From The Model (USD/ton)**
Offshore	6,873.72	8,570.10	8,292.94	4,400.00

From Table 5 & 6 (Per Unit Marine Oil Spill Cleanup Cost by Spill Size), the average cleanup cost between 0.00tons to 5000tons is given as presented below;

Table 4.11: Summary of per unit Marine Oil Spill Cleanup Cost by Spill Size and the model cost

Spill Size	**US Spills (USD/ton)**	**Non-US Spills (USD/ton)**	**All Spills(USD/ton)**	**From The Model (USD/ton)**
0tons – 5000tons	20,260.37	34,172.93	-	4,400.00

From Table 9 (Per Unit Oil Spill Cleanup Cost by Nation/Region), the overall average cleanup cost of all the countries/ Regions provided is given as presented below;

Table 4.12: Comparison between Summarized clean-up cost for Nigerian Spills, African Spills, All Nation Spills and The Model Spill

Nation/Region	**Overall Average Cost/ ton (USD/ton)(1999)**	**Cost From The Model (USD/ton)**
All Nation/Region	8,072.83	4,400.00
African Spills	3,163.93	4,400.00
Nigerian Spills	1,766.75	4,400.00

From the extract of Table 2.9 above, the current value of the per unit spill is given by

(1999 rate/2015 rate) * (1999 Average cost/ Y) where 'Y' represents the current per unit cost of mitigating spills per tonne in Nigeria. By applying this formula, we have

Y = $16061.36/ton

Table 4.13: Comparison between per unit cost of Nigerian Spill and the model cost

Nigerian Spills (USD/ton)(1999)	**Nigerian Spills (USD/ton)(2015)**	**From The Model (USD/ton) (2015)**
1,766.75	16061.36	4,400.00

The comparisons above (Table 4.11) show that using the optimization model, the mitigation cost of oil spill can be greatly reduced for Nigerian Spills, considering the present dollar rate.

Details of these are shown in the figures below (Figs: 4.4) for US, Non US and All Spills.

Finding the percentage increase of the current Nigerian cost of mitigating spills as compared with the model cost, we have:

(16,061.36 – 4400)/16,061.36*100% = 72.61%

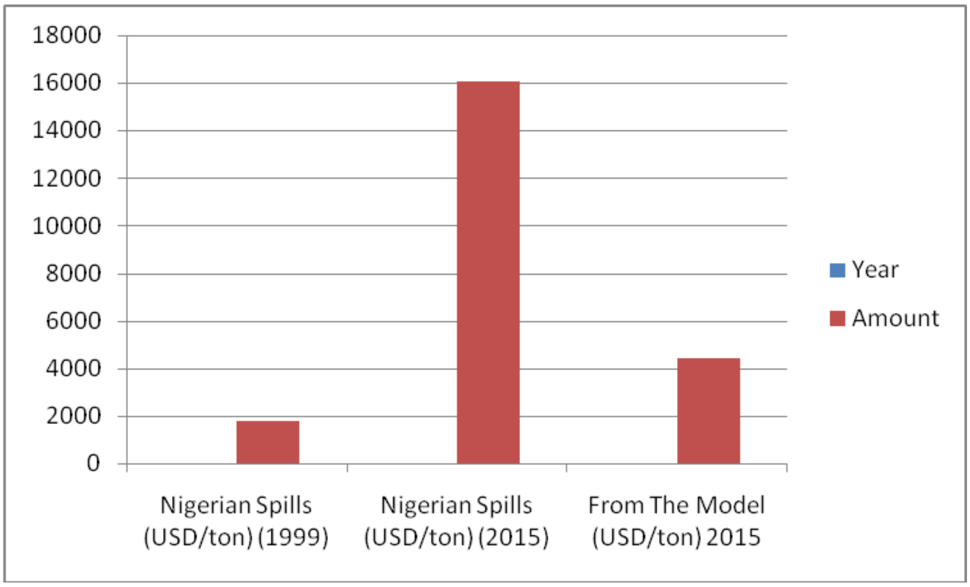

Figure 4.1: Comparison between Nigerian spill costs and the model cost

The figure 4.1 above shows that the optimized cost is lesser than the present cost of mitigating oil spill in Nigeria. The X axis(horizontal) shows the year while the Y axis (vertical) shows the amount in dollars.

Table 4.10: Summary of different per-unit cost of Crude Oil Spill and the Model Cost

ITEM	US Spills (USD/ton)	Non-US Spills (USD/ton)	All Spills(USD/ton)	From The Model (USD/ton)
Crude Oil	14,520.66	3,963.12	7,250.04	4,400.00
Okm-500km	18,934.83	7,385.73	8,534.67	4,400.00
Offshore	6,873.72	8,570.10	8,292.94	4,400.00
0tons – 5000tons	20,260.37	34,172.93	0	4,400.00

The comparisons above (Table 4.10) shows that using the optimization model, the mitigation cost of oil spill can be greatly reduced for US, Non US, and All Spills costs for crude oil, spills of 0km – 500km, Offshore Spill, and Spills of 0tons – 5000tons. Details of these are shown in the figures below (Figs: 4.1 – 4.3) for US, Non US and All Spills respectively.

Also from the table Summary of different per-unit cost of Crude Oil Spill and the Model Cost above,
Total Number of Entries = 16
Mean (Average) Cost = $9772.444
Standard Deviation = $8493.938

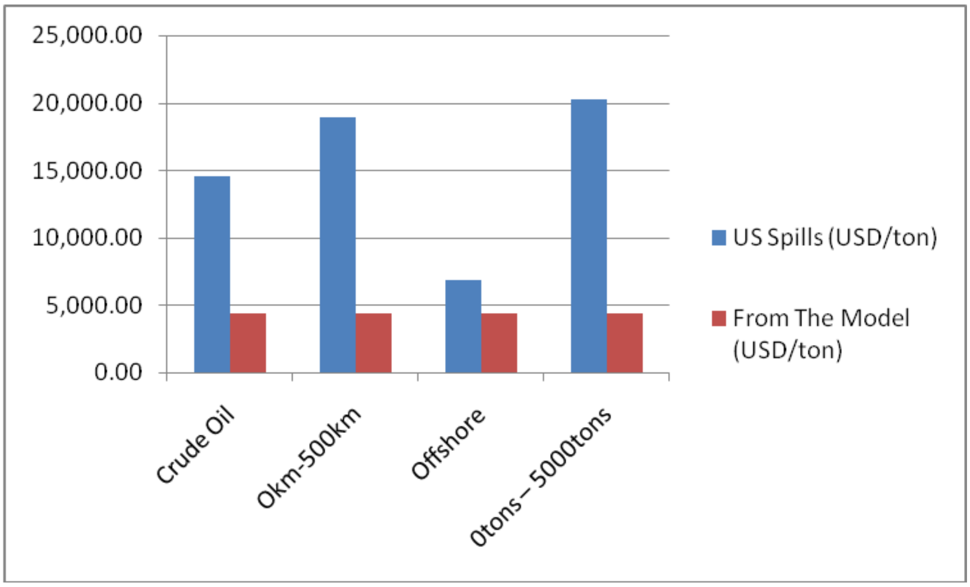

Fig 4.2: Comparison between Model Cost and US Spill Costs

The figure above shows the comparison between Model Cost and US Spill Costs**.** The X axis (horizontal) shows the oil type, the distance of spill from the shore, offshore spills and different quantity of spills from zero to five thousand tons while the Y axis (vertical) shows the amount in dollars.

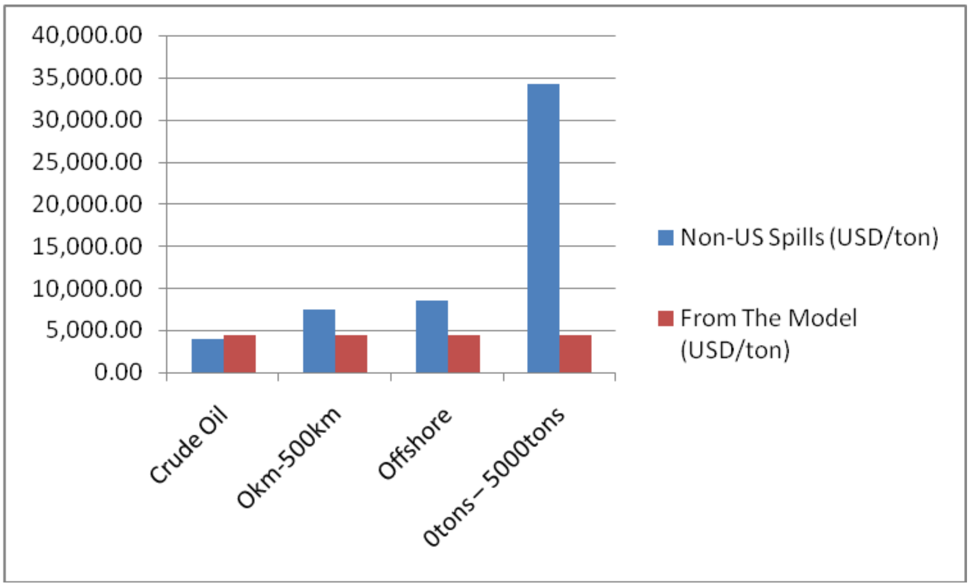

Fig 4.3: Comparison between Model Cost and Non-US Spill Costs

The figure above shows the comparison between Model Cost and Non US Spill Costs**.** The X axis (horizontal) shows the oil type, the distance of spill from the shore, offshore spills and different quantity of spills from zero to five thousand tons while the Y axis (vertical) shows the amount in dollars.

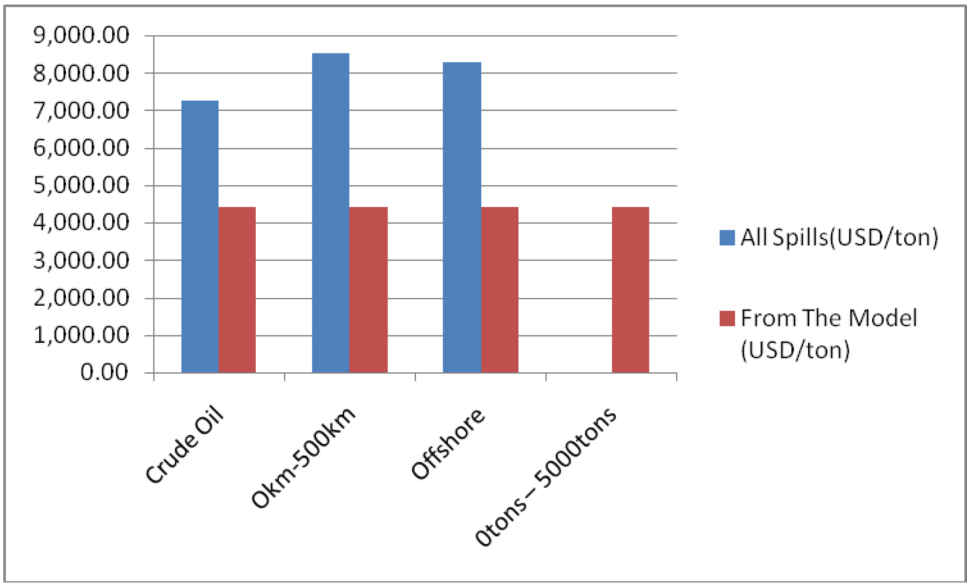

Fig 4.4:Comparison between Model Cost and All Spill Costs

The figure above shows the comparison between Model Cost and US Spill Costs**.** The X axis (horizontal) shows the oil type, the distance of spill from the shore, offshore spills and different quantity of spills from zero to five thousand tons while the Y axis (vertical) shows the amount in dollars.

Acceptance of Hypothesis

The hypothesis proved positive because after the formulation of the systematic model aimed at minimizing cost, the equations of the model were analyzed and the model yielded a result that is less than the current cost of mitigating oil spill both in Nigeria and other parts of the world.

III. CONCLUSION

Different methods of oil spill clean-up were investigated to know there advantages and disadvantages as well as the cost of using or applying each of them. Afterwards, data of the cost of mitigating past oil spill incidents were collected as well as the current cost of materials used in the mitigation (which was used to derive the input variable data and state variables from the model as shown in the appendix)

Optimization equation was formed to minimize the cost of mitigating the clean-up costs and the optimization equation formed after the collection of data from relevant sources was analyzed using the Linear Programing Software. The result ($4400) obtained after the analysis was satisfactory as it gave a result that is lesser than the current costs of mitigating offshore oil spills from historical records as summarized in Table 4.10.

Implementation of the model result gave a 72.61 percentage reduction to the current average per unit cost of mitigating oil spill in Nigeria as seen in Table 4.11.

Contribution to Knowledge

This model is an improvement over universal per-unit spill cost estimate models for planning or evaluation purposes which will be very useful in mitigating offshore oil spillage around the world. The model can be applied to any country or region of the world as long as the assumptions in the model are kept constant. Most importantly, the Model is very beneficial to Contingency Planners, Response Officials, Government Agencies, Oil Transporters, oil and Gas Companies for easy and quick estimation of the anticipated cost of mitigating spilled oil offshore.

It is also worthy of note that applying the model in any offshore oil spill cleanup will greatly reduce the cost of mitigating the said spill. This has been demonstrated using available data of the Nigeria per unit cost of mitigating oil spill (Table 4.14 and Figure 4.4). From 4.4, it can be seen that using the Model, the per-unit cost of Mitigating oil spill in Nigeria can be reduced to 72.3%.

IV. RECOMMENDATIONS

Further studies/research is recommended to be done to take care of other types of spilled oil; oil spills exceeding 5000tons; Onshore spills; and to take care of other associated costs of mitigating spilled oil like costs of 'loss of Cargo', 'death of fishes and other organisms', 'death or injuries to humans', 'levies', etc.

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