Journal of
Marine Science
and Engineering

Article

Optimization on Emergency Materials Dispatching Considering the Characteristics of Integrated Emergency Response for Large-Scale Marine Oil Spills

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Received: 27 May 2019; Accepted: 9 July 2019; Published: 12 July 2019

Abstract: Many governments have been strengthening the construction of hardware facilities and equipment to prevent and control marine oil spills. However, in order to deal with large-scale marine oil spills more efficiently, emergency materials dispatching algorithm still needs further optimization. The present study presents a methodology for emergency materials dispatching optimization based on four steps, combined with the construction of Chinese oil spill response capacity. First, the present emergency response procedure for large-scale marine oil spills should be analyzed. Second, in accordance with different grade accidents, the demands of all kinds of emergency materials are replaced by an equivalent volume that can unify the units. Third, constraint conditions of the emergency materials dispatching optimization model should be presented, and the objective function of the model should be postulated with the purpose of minimizing the largest sailing time of all oil spill emergency disposal vessels, and the difference in sailing time among vessels that belong to the same emergency materials collection and distribution point. Finally, the present study applies a toolbox and optimization solver to optimize the emergency materials dispatching problem. A calculation example is presented, highlighting the sensibility of the results at different grades of oil spills. The present research would be helpful for emergency managers in tackling an efficient materials dispatching scheme, while considering the integrated emergency response procedure.

Keywords: waterway transport; marine oil spills; integrated emergency; dispatching optimization model

1. Introduction

The rapid increase of sea oil transportation and the trend of larger ship size have caused the marine environment and marine economic activities to be threatened by large-scale marine oil spills. For instance, a severe environmental impact was caused by the oil spill of tanker *Prestige* in 2002 [1] and the tanker *Sanchi* in 2018 [2], and more than 50 similar serious accidents have occurred since 1967 around the world. The capacity of an oil tanker is basically higher than 100,000 tons, and very large crude carriers (VLCCs) have become the leader of the world's tanker fleet, taking up approximately 60% of the global transportation capacity [3]. A typical VLCC tanker carries 300,000 tons of crude oil with 15 cargo oil tanks. If half of this cargo oil tank is spilled, 10,000 tons of oil will be spread over a large area of the sea. In addition, large-scale containers and bulk carriers that carry thousands of tons of fuel oil are also a significant source of oil spill risk.

Oil spill response is dictated by many factors. However, the type of oil (i.e., heavy crude oil, light oil, etc.) and the amount of oil are the most important factors in oil spill analysis [4]. Light oil is volatile and flammable, making it easier to handle. Therefore, this contribution takes the heavy oil spills as the research goal. Spilled oil is rapidly spread under the effect of wind, waves and currents at the sea [5]. The emergency response of marine oil spills requires high timeliness. Otherwise, it will greatly increase the diffusion area and cost of oil spills alleviation measures. It is often necessary for the emergency response to dispatch a large amount of resources, and take multiparty, cross-region, and rapid emergency action [6]. Many governments have increased their investment in the construction of oil spill response capability in the past several years, especially some developing countries. Taking China as an example [7], as of 2017, 16 national large offshore oil spill emergency equipment warehouses have been built along the coast of China, among which the largest three (Dalian, Ningbo, and Zhujiangkou) can merely confront 1000 tons of oil spills. A total of 13 oil spill emergency equipment warehouses have been set up on the trunk line of the Yangtze River. Among these, the largest warehouse is medium-scale (confronting oil spills of 500 tons), while seven warehouses are small scale (confronting oil spills of 200 tons) and the other five warehouses are merely equipment points (confronting oil spills of 50 tons). In addition, approximately 150 medium- and small-scale oil spill emergency equipment warehouses and more than 200 oil spill emergency disposal vessels have been built by social oil spill emergency forces similar to professional marine pollution removal and port enterprises, especially oil facilities and other large-scale terminals [8]. Furthermore, there are national oil spill emergency equipment warehouses (sea area level), professional marine pollution removal enterprises (port level), and the large-scale port enterprises (wharf level). The structure of China's oil spill emergency hardware facilities and equipment is, in fact, a summation of the aforementioned infrastructures.

Hence, the integrated emergency response procedure refers to the joint operation of emergency materials dispatching in different kinds, different storage places, and different quantity demanded, according to the specific circumstances of different accidents [9]. Studies on marine oil spills usually focus on clean-up measures [10], environmental impact [11], research and development of oil absorbing materials [12], support systems for monitoring and forecasting oil spills [13–16]. In addition, many researchers have also attained well-academic research achievements on oil spill emergency response and the emergency materials dispatching. Most of the relevant literature that was surveyed aimed at optimizing the materials dispatching and the improvement of the optimization algorithm accuracy. Unfortunately, these contribution do not have a detailed description of the actual operation of integrated emergency response. For instance, Zhen Li et al. generates the probability of oil spill contact maps by initiating trajectories from hypothetical oil spill points over the entire planning areas in the U.S. Gulf of Mexico (GOM) OCS and tabulating the contacts over the entire waters in the GOM [17]. Costa et al. describe a model to deal with oil spills clean-up requirements, considering the location of the protection systems that must be immediately deployed to the priority areas associated with spills scenarios [18]. Wang Jun et al. reported the mechanism of the greedy algorithm used to solve a model [19], which includes the nearby navigating ships, coastal rescue bases, and inland depots of contingent commodities, under the constraints of requirements of demand and time limit. Manish Verma etal. present a two-stage stochastic programming approach which tackles both the location and stockpile of equipment at the emergency response facilities [20]. Najmedin Meshkatiet et al. propose a generic integrated system-oriented model [21]. That is, an essential need for effective integration and interoperability among multiple emergency response agencies, possibly from different countries, in the case of an accident in a safety sensitive industry that would cause the release of hazardous materials or contaminants. An emergency material scheduling model (EMSM) with time-effective and cost-effective objectives is developed to coordinate both allocation and scheduling of the emergency materials [22].

At the same time, due to the increasing maturity of optimization algorithms and software, solving the optimization model with high accuracy and efficiency is not a major difficulty. The emergency materials dispatching optimization model combined with emergency materials construction characteristics and the integrated emergency response procedure of China deserve further research. This represents a step forward in establishing strategies for fighting against large-scale oil spills when compared to other contributions. Hence, the present study intends to establish an emergency materials dispatching optimization model for large-scale marine oil spills along the Chinese coast, with the consideration of the construction achievements of oil spill response capability, the allocation and status of emergency materials, the actual integrated emergency response process, and so on. The constraint conditions of the model are mainly about the demands of emergency materials, cargo holds, and the speed of the vessels, sailing distance, etc. In addition, the objective function of the model is formulated with the aim of minimizing the largest sailing time of all oil spill emergency disposal vessels, and the difference in sailing time among vessels that belong to the same emergency materials collection and distribution point. Finally, the present study applies the *YALMIP* toolbox (Introduced by Professor Johan Lofberg, Linkoping University, Linkoping, Sweden) and *CPLEX* optimization solver (IBM, Armonk, NY, USA) on the Matlab R2017a (MathWorks, Natick, The United States) software platform to optimize the emergency materials dispatching problem.

The main objective target of the contribution is to establish an emergency materials dispatching optimization model for large-scale marine oil spills, based on the characteristics of integrated emergency response procedure and the construction achievement of Chinese oil spill response capacity. Equivalent volume of different kinds of materials, the building of dispatching optimization model, and a case study implementation and analysis are shown in this contribution. The present research would be helpful for emergency managers to develop more efficient dispatching schemes for scattered emergency materials, and mitigate the harmful consequences of marine oil spills.

This contribution is organized as follows: After the introduction (Section 1), Section 2 will present the model assumptions and related descriptions. Then, the building optimization model is shown in Section 3, achieving a model implementation based on a semi-definite programming solver (Section 4). The model example results and subsequent analysis are discussed in Section 5. Finally, a conclusion is presented in Section 6.

2. Model-Related Descriptions and Assumptions

The optimization of the material dispatching problem requires several assumptions and constraints that consider the characteristics of oil spill accidents and operational procedures. These descriptions and assumptions are presented, as follows.

2.1. Model Related Descriptions

Description 1. *The primary purpose of marine oil spills emergency response is to quickly reach the accident scene with emergency materials and immediately take effective measures. Partial emergency materials, such as dispersants and oil containment booms, have an expiration date and needs to be regularly updated. The probability of large-scale marine oil spill accidents is relatively small. Therefore, the model does not consider the minimum economic cost of the integrated emergency response.*

Description 2. *Affected by island topography, and for the convenience of communication drills and quick emergency response, the emergency materials collection and distribution point usually has a group correspondence with neighboring port companies. This means that an integrated emergency response system in the local water area has been established. In general, the collection and distribution point is equipped with oil spill emergency disposal vessels, while the port enterprises are not equipped with vessels.*

Description 3. *Emergency vessels are mainly divided into two categories: oil spill emergency disposal vessels and oil wastewater storage vessels. Oil emergency disposal vessel loading capacity is considered to be limited by storage capacity, in which different types of emergency materials can be mixed, such as oil containment booms, emergency unloading pumps, oil skimmers, oil spill dispersants, oil absorbing materials, etc. The speed of these vessels range within 10–22 kn. In addition, depending on the characteristics of the accident, these emergency vessels may also include fireboats, transport flat barges, etc.*

Description 4. *Oil spills emergency materials have a general working procedure at the scene of the accident. For example, a large number of oil containment booms are needed to control the oil spills for further diffusion. Emergency unloading pumps discharge the residual oil from the leak tank to the other oil tanks, ballast tanks, or storage vessels. Then, an oil skimmer is used to recover the spilled oil. Finally, the sporadic marine oil spill is treated with oil dispersant and an oil absorbing blanket. The above emergency response procedure can be flexibly commanded, according to the specific situation of the dangerous situation [23].*

Description 5. *The loading of oil spills emergency disposal vessels is mainly limited by storage capacity. Combined with Description 4, the stowage factors (the volume of per ton cargo in the hold when it is normally stacked) of emergency materials are considered. The amount of different kinds of materials can be converted into volume, which can simplify the model building and solving. In consequence, the values considered in the model would be the following: oil containment booms of 45 m^3/100 m (typical value), emergency unloading pump of 10 m^3/set, medium oil skimmer of 10 m^3/set, oil spill dispersant of 1.5 m^3/ton, and oil absorption material of 5 m^3/ton [24,25].*

Description 6. *According to the survey, oil spills emergency disposal vessels are mainly medium and small size vessels, and the cargo capacity is considered to be 200 m^3 and 100 m^3, respectively. Furthermore, the oil storage tanks range approximately from 300 m^3 and 700 m^3. As an example, a medium-sized oil spills emergency disposal vessel has a length of approximately 60 m, and the cargo volume can be loaded with 400 m oil containment booms and two emergency unloading pumps for each voyage.*

The sketch map of the emergency materials dispatching scheme is presented in Figure 1.

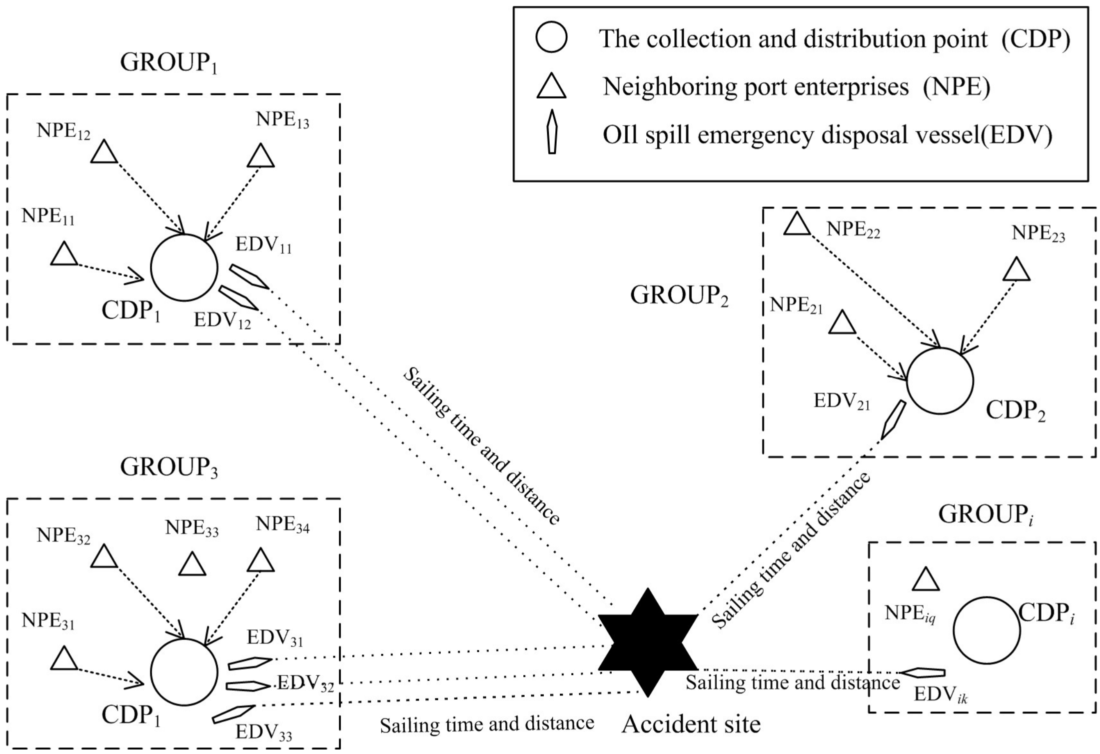

Figure 1. Sketch map of the emergency materials dispatching scheme.

2.2. Model Assumptions

Assumption 1. *The amount of oil spilled is basically given and unchanged.*

Assumption 2. *The analysis does not consider the route selection from the collection and distribution point to the accident site. The distance between these two places is known and minimized.*

Assumption 3. *The types and quantities of emergency materials in each collection and distribution point are known, including those that can be collected from neighboring port enterprises through the integrated emergency response system.*

Assumption 4. *Oil spill emergency disposal vessels that belong to a collection and distribution point may perform several round trips between the collection and distribution point and accident site to carrying the materials for the emergency response. The model does not account for the time consumed at the accident site. It was considered that the sailing time of departure is the same as the sailing time for the return.*

Assumption 5. *The loading time of emergency materials was considered negligible. First, the tonnage of oil spill emergency disposal vessels is generally small, and the overall loading time is not significantly different. Second, in most cases, the emergency disposal vessel is docked near the materials warehouse. Third, it can be predicted when the materials of a collection and distribution point's warehouse are not sufficient. The supplementary materials from other port enterprises can be timely and synchronously transported to the collection and distribution point by road or water.*

Assumption 6. *Since fireboats and oil waste water storage vessels can be self-propelled to the accident site, the demand quantity is mainly affected by the speed, distance and scale of the accident. If the transportation capacity of oil wastewater storage vessels fits the specified requirements, it can be considered that the recovery rate of sewage oil meets the necessary transportation capacity. The scheduling of oil wastewater storage vessels was not included in the optimization model.*

Assumption 7. *In the case of large marine oil spills, due to the limited capacity of oil spills emergency disposal vessels, there is the possibility of calling a barge to temporarily transport a large amount of oil containment booms. In the example section, a collection and distribution point was set up with a barge, and its transportation capacity was established to be at 800* m^3.

Assumption 8. *Considering the particularity of emergency transportation, the actual transportation of emergency materials can be greater than the estimated demands. Hence, it was assumed that the cargo holds of the transport vessel are full during each trip, not partially filled.*

Assumption 9. *Large marine oil spills may also be temporarily collected by a certain number of small vessels, such as tugs and fishing boats, in order to participate in the emergency response. The model does not consider these emergency forces.*

3. Model Building

According to the analysis of the above assumptions, the decision variables, constraints and objective function of the optimization model are set as follows:

3.1. Decision Variables

f_{ij} is the number of the *j* emergency materials (e.g., oil containment booms, unloading pump, oil absorption material, etc.) transported at the *i* collection and distribution point.

y_{ik} is the total trips of the *k* vessel of the *i* collection and distribution point.

Therefore, f_{ij} and y_{ik} are the two decision variables, meaning that at every point (*i*) there are (*k*) vessels representing how many trips of every vessel and how many materials of every kind have to be transported.

3.2. Model Parameter

A is the amount of the marine oil spill in tons.

E_j is the demand of j—the emergency materials category—in m^3.

F_{ij} is the amount of j—the emergency materials category—that can be dispatched from the i collection and distribution point, in m^3.

v_{ik} $\in${200, 100} is the capacity of k vessel's cargo holds (in m^3) of the i collection and distribution point.

s_{ik} $\in$ {10, 22} is the range of the speed of the k vessel of the i collection and distribution point, in kn.

Here, the data is standardized, and the number of vessels from each collection and distribution point is up to the maximum number of vessels at each point. The speed and cargo hold values are small, such as 0.1 (in kn or m^3), allowing that a symmetric array is obtained, which is convenient for optimization calculation [26].

Considering the distance and time sailed, the following parameters are defined:

$$t_{ik} = \frac{2 \cdot D_i}{s_{ik}} \qquad i = 1, 2 \ldots, n; \; k = 1, 2 \ldots, P_i \tag{1}$$

$$TB_{ik} = y_{ik} \cdot t_{ik} \qquad i = 1, 2 \ldots, n; \; k = 1, 2 \ldots, P_i \tag{2}$$

D_i is the distance (in nautical miles) between the accident site and the $i$collection and distribution point. t_{ik} in Equation (1) is the round trip travel time of the k vessel from the accident site to the i collection and distribution point, in hours. TB_{ik} is the total sailing time of each emergency vessel given by Equation (2). Finally, the sum of the differences in sailing time between vessels of each collection and distribution point (TC) and the longest sailing time for each emergency vessel (MTB) is defined as:

$$TC = \sum_{i=1}^{n} \sum_{k=1}^{p-1} \left(\left| TB(i,k) - TB(i,k+1) \right| \right) \tag{3}$$

$$MTB = \max(\max(TB)) \tag{4}$$

3.3. Objective Function

The objective function to minimize is given by the minimum value of the differences in sailing time among vessels of the corresponding collection and distribution point (TC and MTB, respectively), and this is given by Equation (5):

$$\min(TC + MTB) \tag{5}$$

The objective function has two implicit contents: First, vessels that belong to the collection and distribution point can time the synchronous sailing, and achieve the minimization of MTB. Second, the minimum of TC can allow the maximum sailing time to be used for each point to be equal. That is, the optimization of the total emergency time.

3.4. Constraints

Several constraints are established in the model. The first constraints (Equation (6)) show that the sum of the actual shipment of the kind of j material from each emergency material distribution point is not less than the total demand for the kind of j material in the accident. Equation (7) formulates that the sum of the actual shipment of category j materials from the emergency materials distribution point is not higher than the total amount of the kind of materials that can be dispatched from the corresponding collection and distribution point. The constraint shown in Equation (8) states that the sum of the actual shipment of each vessel belonging to the emergency material distribution point cannot be higher than the total amount of materials potentially dispatched from the corresponding collection and distribution point. The constraint shown in Equation (9) is correlated with the sum of the actual shipment of each vessel that belongs to the emergency material distribution point, which must be equal to the sum of the actual shipment of the corresponding collection and distribution point [27]:

$$\sum_{i=1}^{n} f_{ij} \geq E_j \qquad j = 1, 2 \ldots, m \tag{6}$$

$$f_{ij} \leq F_{ij} \qquad i = 1, 2 \ldots, n;\ j = 1, 2 \ldots, m. \tag{7}$$

$$\sum_{k=1}^{p} y_{ik} \cdot v_{ik} \leq \sum_{j=1}^{m} F_{ij} \qquad i = 1, 2 \ldots, n; v_{ik} \in \{200, 100\} \tag{8}$$

$$\sum_{k=1}^{p} y_{ik} \cdot v_{ik} = \sum_{j=1}^{m} f_{ij} \qquad i = 1, 2 \ldots, n. \tag{9}$$

4. Model Implementation

4.1. Estimation of the Demand Equivalent of Emergency Materials for Large Oil Spills

The volume of the oil spill is considered unchanged after the accident according to Assumption 1. According to the equipment configuration requirements of the Chinese regulation (refer to the offshore oil spill emergency equipment warehouse management regulations from the Ministry of Transport of China, 2009), the total amount of emergency materials required for different grades of accidents can be estimated. In this sense, the large-scale warehouse (fighting against 1000-ton oil spills) has a decontamination capacity of 1000 tons, with an emergency service radius of 350 nautical miles. These warehouses are equipped with 4–6 emergency unloading pumps, not less than 2200 m of oil containment booms, 4–6 oil skimmers, not less than 200 tons of oil spill dispersant, an oil absorption material larger than 80 tons, and an appropriate amount of dispersant spray device.

In combination with the actual research, a large-scale warehouse generally configures two medium (or small) emergency disposal vessels. These vessels have a cruising capacity of approximately five days, approximately 700 m^3 of oil wastewater storage, and 200 m^3 of cargo holds, which can load 400 m of oil containment booms and two emergency unloading pumps. These large-scale warehouses also have at least three oil wastewater storage vessels, and a total storage capacity greater than 2000 tons. In addition, there are generally auxiliary vessels, such as self-propelled skimmers, tugs, etc. [28].

According to administrative regulations, Table 1 shows the requirements for the configuration of equipment warehouses of 1000, 500, and 200 tons. On this basis, the estimated amount of emergency materials required for 5000, 10,000, and 20,000 tons in accidents is inferred.

Table 1. Estimationof emergency materials required for accidents with different offshore oil spill grades.

Kinds	Stowage Factor	20,000 tons		10,000 tons		5000 tons		1000 tons		500 tons	
		Num	Equivalent Volume m^3	Num	Equivalent Volume m^3	Num	Equivalent Volume m^3	Num	Equivalent Volume m^3	Num	Equivalent Volume m^3
E_1/Containment booms	45 m^3/100 m	8000 m	3600	6000	2700	4000	1800	2200	990	1600	720
E_2/unloading pump	10 m^3/set	12	120	9	90	7	70	5	50	4	40
E_3/Oil skimmer	10 m^3/set	15	150	9	90	7	70	5	50	4	40
E_4/Spill dispersant	1.5 m^3/t	2000 t	3000	1400	2100	800	1200	200	300	100	150
E_5/Absorption material	5 m^3/t	800 t	4000	500	2500	320	1600	80	400	40	200
E_6/Oilwastewater storage	——	20,000 t	——	16,000	——	8000	——	2000	——	1000	——

4.2. Model Key Code

The main feature of this paper is that it is really closer to the actual emergency integrated response process. The complexity of the model building and solving is not very high, when compared with other optimization problems with higher complexity, and there is also a certain degree of error tolerance for the optimization solution in this contribution. At the same time, the functions of various optimization solution software was used in the literature, such as Lingo, 1stOpt, Matlab, SPSS, and Data Fit. Additional toolboxes and optimization solvers, such as YALMIPand CPLEX, provide solvers for model algorithm optimization. In this contribution, the Matlab R2017a software platform and YALMIP toolbox were used to call the CPLEX optimization solver to optimize the oil spill emergency materials dispatching problem [29]. YALMIP is a modeling tool kit for Matlab, the most significant feature being an integration and callable external optimization solver, such as Gurobi, CPLEX, etc. Although different solvers use different specialized languages, YALMIP can convert the simple and efficient YALMIP modeling solution language into other solver languages, which can be simply and conveniently applied for the problem optimization. The four main processes of YALMIP are setting decision variables, objective functions, constraints, and the use of the toolbox. The key code of model solving are shown in Table 2.

Table 2. The key code of model solving.

Input Parameters: D_i, E_j, F_{ij}, v_{ik}, S_{ik} Output Value: Optimal Solution f_{ij} , y_{ik}, t_{ik}	 Optimal Value T
D_i= ;E_j= ; F_{ij}= ; v_{ik} = ; S_{ik} =	%Input known value
F = intvar(i,j); y = intvar(i,k);	% Decision variables
T = 2*D./S;	% Round trip time ofevery vessel
TB = y.*T;	% The sailing time of every vessel
MTB = max(max(TB));	% The largest sailing time
TC = abs(TB(1,1)−TB(1,2)− …)+ …	% The sum of the differences sailing time
C = [sum(f)> = E,f< = F,sum(y.*v,2)<=sum(F,2),sum(y.*v,2)==sum(f,2),f >= 0, y >= 0];	% Constraints
Mu = TC+MTB	% Objective functions
ops =sdpsettings('solver','cplex','verbose',2);	% Solver parameter configuration
Result = solvesdp(C,Mu,ops);	% Find the minimum
TB = double(TB); f= double(f); y = double(y); MTB = double(MTB);	
disp(TB); disp(x); disp(y); disp(MTB)	% Output optimal solution

5. Case Study Implementation and Analysis

The case study corresponds to an extraordinary oil spill as an example of a good reference for oil spill accidents. If the accident tonnage is small (less than 1000 tons), it will be convenient to provide enough emergency materials nearby. In order to test the sensitivity to the results for oil spill tonnage, different volumes are taken: 20,000, 10,000, 5000, and 1000 tons.

5.1. Known Parameters

The parameters were achieved according to the Chinese program of the offshore oil spill emergency equipment warehouse management regulations. The matrix in Equation (10) shows the amount of emergency materials that can be dispatched, previously converted into equivalent volume (m^3). The row indicates each collection and distribution point. The column indicates the kinds of emergency materials in the following order: oil containment boom, emergency unloading pump, oil skimmer, oil spill dispersant, oil absorption material, and oil wastewater storage vessel.

Equation (11) presents the vector distance from each collection and distribution point to the accident site, while Equation (12) presents the speed and capacity parameters of each vessel considered in the test case.

$$F[12]\ [6] = \begin{bmatrix} 720 & 60 & 60 & 210 & 180 & 1600 \\ 820 & 40 & 40 & 255 & 300 & 2000 \\ 990 & 50 & 50 & 600 & 500 & 2000 \\ 720 & 40 & 40 & 150 & 200 & 1400 \\ 540 & 30 & 30 & 120 & 80 & 1200 \\ 540 & 30 & 30 & 180 & 200 & 1400 \\ 450 & 60 & 50 & 120 & 200 & 1200 \\ 1125 & 50 & 50 & 570 & 400 & 2800 \\ 540 & 30 & 30 & 360 & 300 & 1200 \\ 810 & 70 & 70 & 360 & 600 & 2000 \\ 810 & 70 & 70 & 570 & 600 & 2000 \\ 1125 & 70 & 70 & 570 & 700 & 2800 \end{bmatrix} \tag{10}$$

$$D[1][12] = [120\ 80\ 150\ 140\ 60\ 98\ 110\ 200\ 30\ 160\ 320\ 260] \tag{11}$$

$$\begin{gathered} V_1 = [12{,}100]; V_2 = [12{,}200;15{,}100];\ V_3 = [22{,}200;15{,}100;10{,}100];\ V_4 = [18{,}100;15{,}200;12{,}100]; \\ V_5 = [18{,}100;12{,}100];\ V_6 = [18{,}200;12{,}100];\ V_7 = [18{,}200;12{,}100];\ V_8 = [22{,}200;15{,}100;10{,}800;12{,}100]; \\ V_9 = [18{,}100;12{,}100];\ V_{10} = [12{,}100];\ V_{11} = [18{,}200;12{,}200];\ V_{12} = [18{,}200;12{,}200] \end{gathered} \tag{12}$$

5.2. Case Test Results

Tables 3 and 4 shows the case test results after the optimization calculations. The emergency materials dispatching optimization schemes are considered in the function of the four different levels of accidents previously mentioned (i.e., 20,000, 10,000, 5000, and 1000 tons) at the same accident site.

5.3. Analysis of Results

From the examples of four different grades of oil spills, it can be observed that the shipment of emergency materials and the calculation result for trips and sailing time are more reasonable and balanced. The maximum sailing time of each vessel can represent the total time of emergency materials transportation. The model and optimization calculation results also reflect the characteristics of the parallel operation of each emergency collection and distribution point, and each vessel.

The amount of emergency materials shipment in Tables 3 and 4 was compared with the demand in Table 1, and the number of materials per trip and the total amount of shipments are slightly larger than the total number of demands. The calculation results are in line with the model expectations, as shown in Figure 2.

The traditional methods merely based on the distance between the collection and distribution points and the accident site. The materials were dispatched from near to and far from the collection and distribution points, until the total demand is met. The traditional method trip time of each point under different accident grades is shown in Figure 3 by dotted bars. Compared with the square optimization time data, the peak value is obviously high, and the overall connection is above the optimized line. As a consequence, the results provided by the model optimized results achieve better performance.

Table 3. Optimized dispatching schemes of emergency materials for 20,000 tons and 10,000 tons.

	20,000 tons of Oil Spills										10,000 tons of Oil Spills									
Point	**Emergency Material (m^3)**					**Voyage Times and Sailing Time (h)**					**Emergency Material (m^3)**					**Voyage Times and Sailing Time (h)**				
	F1	**F2**	**F3**	**F4**	**F5**	**Y1/TB1**	**Y2/TB2**	**Y3/TB3**	**Y4/TB4**	**Max Sailing Time (h)**	**F1**	**F2**	**F3**	**F4**	**F5**	**Y1/TB1**	**Y2/TB2**	**Y3/TB3**	**Y4/TB4**	**Max Sailing Time (h)**
1	110	0	0	210	180	5/100	—	—	—	100	0	20	0	210	170	4/80	—	—	—	80
2	745	0	0	255	300	4/54	5/54	—	—	54	745	0	0	255	300	4/54	5/54	—	—	54
3	525	0	0	275	500	4/55	3/60	2/60	—	60	348	0	0	582	370	4/55	3/60	2/60	—	60
4	470	40	40	150	200	3/47	2/38	2/47	—	47	10	40	0	150	200	1/16	1/19	1/24	—	24
5	240	30	30	120	80	3/20	2/20	—	—	20	240	30	30	120	80	3/20	2/20	—	—	20
6	390	30	0	180	200	3/33	2/33	—	—	33	420	0	0	180	200	3/33	2/33	—	—	33
7	410	20	50	120	200	3/37	2/37	—	—	37	430	0	50	120	200	3/37	2/37	—	—	37
8	430	0	0	570	400	2/37	1/27	1/40	1/34	40	0	0	0	0	0	0/0	0/0	0/0	0/0	0
9	280	30	30	360	300	6/20	4/20	—	—	20	340	0	0	360	300	6/20	4/20	—	—	20
10	0	0	0	0	400	4/107	—	—	—	107	0	0	0	0	0	0/0	—	—	—	0
11	0	0	0	460	540	3/107	2/107	—	—	107	0	0	0	0	0	0/0	0/0	—	—	0
12	0	0	0	300	700	3/87	2/87	—	—	87	167	0	10	123	700	3/87	2/87	—	—	87
Subtotal	3600	150	150	3000	4000	Max time				107	2700	90	90	2100	2520	Max time				87

Table 4. Optimized dispatching schemes of emergency materials for 5000 tons and 1000 tons.

	5000 tons of Oil Spills										1000 tons of Oil Spills									
Point	**Emergency Material (m^3)**					**Voyage Times and Sailing Time (h)**					**Emergency Material (m^3)**					**Voyage Times and Sailing Time (h)**				
	F1	**F2**	**F3**	**F4**	**F5**	**Y1/TB1**	**Y2/TB2**	**Y3/TB3**	**Y4/TB4**	**Max Sailing Time (h)**	**F1**	**F2**	**F3**	**F4**	**F5**	**Y1/TB1**	**Y2/TB2**	**Y3/TB3**	**Y4/TB4**	**Max Sailing Time (h)**
1	0	0	0	0	100	1/20	—	—	—	20	0	0	0	0	0	0/0	—	—	—	0
2	80	20	40	260	300	2/27	3/32	—	—	32	0	0	0	0	300	1/14	1/11	—	—	14
3	0	0	0	180	420	2/28	1/20	1/30	—	30	0	0	0	0	0	0/0	0/0	0/0	—	0
4	0	0	0	0	0	0/0	0/0	0/0	—	0	0	0	0	0	0	0/0	0/0	0/0	—	0
5	540	30	30	120	80	5/34	3/30	—	—	30	460	20	20	120	80	3/20	2/20	—	—	20
6	420	0	0	180	200	3/33	2/33	—	—	33	0	0	0	0	0	0/0	0/0	—	—	0
7	450	30	0	120	200	3/37	2/37	—	—	37	0	0	0	0	0	0/0	0/0	—	—	0
8	0	0	0	0	0	0/0	0/0	0/0	0/0	0	0	0	0	0	0	0/0	0/0	0/0	0/0	0
9	310	0	30	360	300	6/20	4/20	—	—	20	540	30	30	300	100	6/20	4/20	—	—	20
10	0	0	0	0	0	0/0	—	—	—	0	0	0	0	0	0	0/0	—	—	—	0
11	0	0	0	0	0	0/0	0/0	—	—	0	0	0	0	0	0	0/0	0/0	—	—	0
12	0	0	0	0	0	0/0	0/0	—	—	0	0	0	0	0	0	0/0	0/0	—	—	0
Subtotal	1800	80	100	1220	1600	MAX time				37	1000	50	50	420	480	MAX time				20

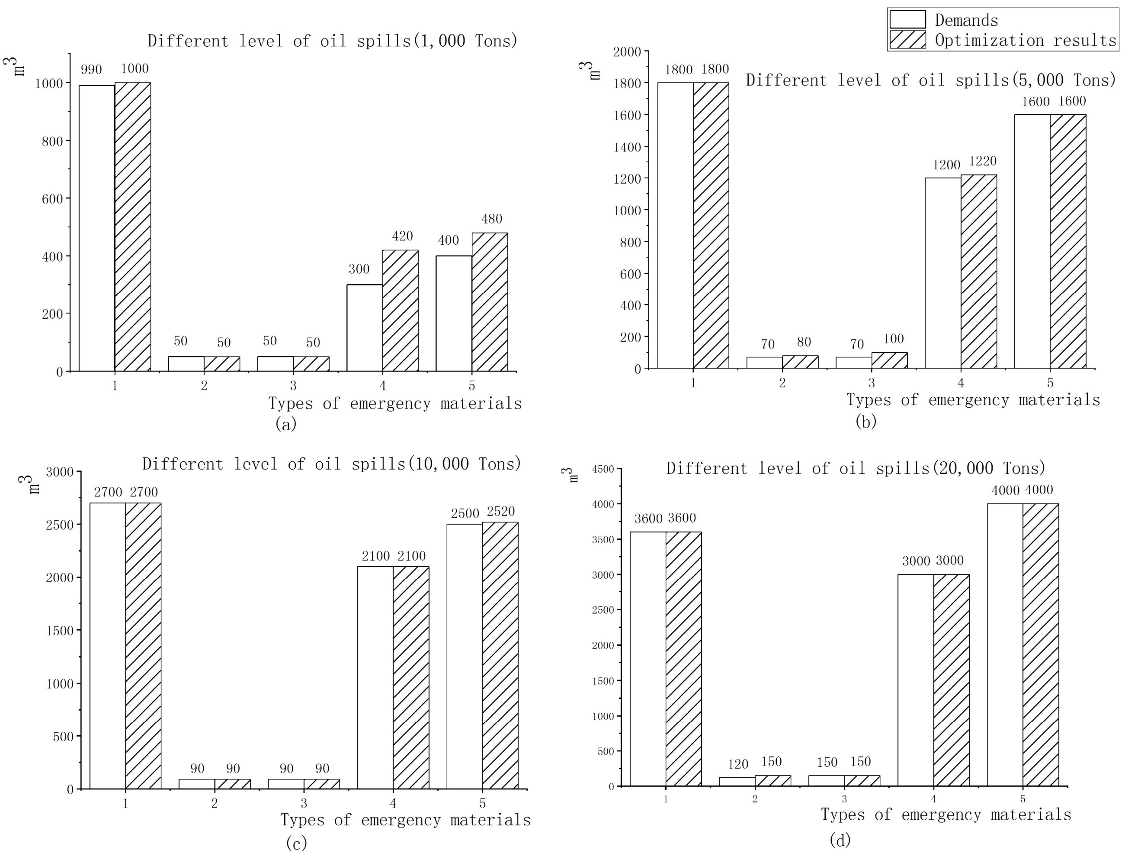

Figure 2. Thecomparison of the amount of emergency materials shipment with the demand (in m^3).

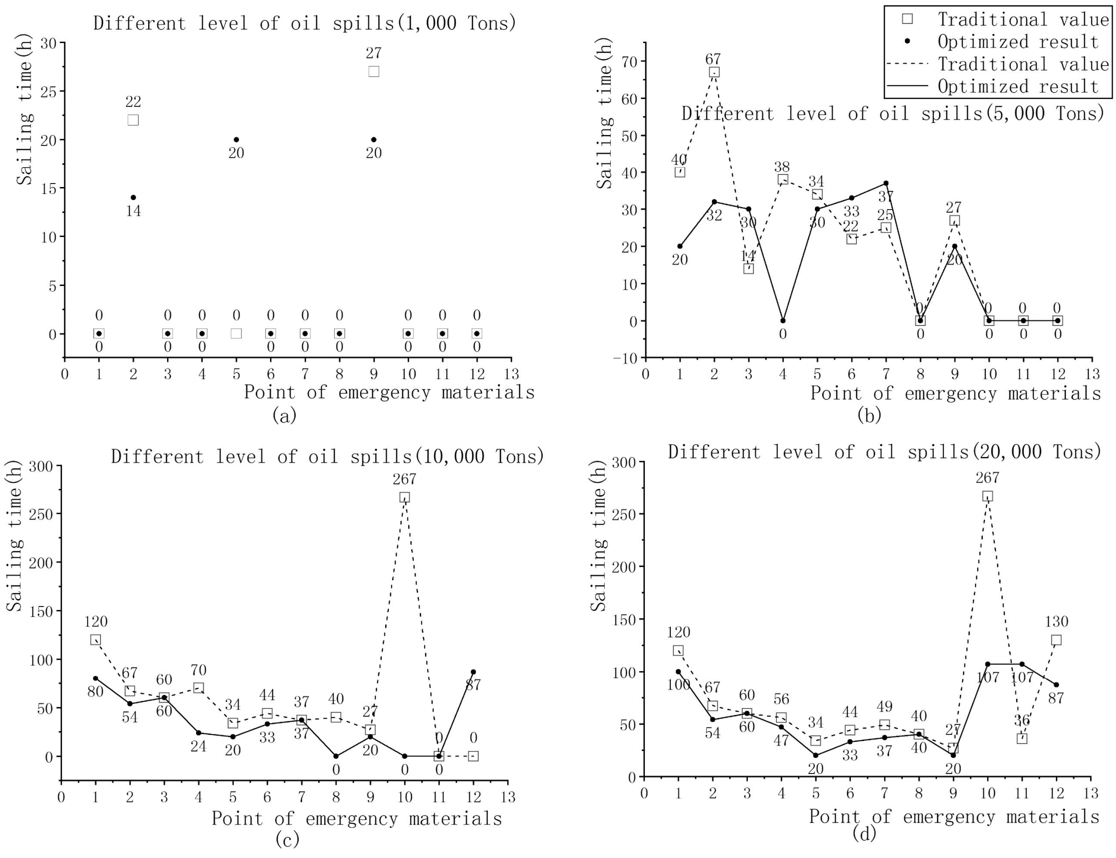

Figure 3. Traditional method compared with the optimization results for different oil spills in tons.

It can be observed from Table 3 that the barge of the 8th point was used for the transportation of 20,000 tons from the accident site. This is because it is far away from the accident site, and the navigation speed is low.

In the emergency response of small and medium oil spill incidents, the materials of several collection and distribution points near the accident site can often meet the demand. Comparing Tables 3 and 4 with Figure 3, the model can play a better role of integrated emergency response in an extraordinarily severe oil spill accident.

The oil wastewater storage vessel generally has a self-propelled capability. According to Table 1 and Equation (10), when taking an oil spill accident of 10,000 tons as an example, the capacity of the oil wastewater storage vessel is 16,000 tons, and the storage capacity of the collection and distribution points (1–10) from near to far is 16,800 tons.

6. Final Remarks

Combined with the emergency materials dispatching characteristics and integrated emergency response process of large-scale marine oil spills, an emergency materials integrated optimization model was presented. The validity of the model was analyzed through several examples. This contribution would help to optimize the coordinated dispatch of emergency materials for marine oil spills, improve the timeliness of emergency response, and mitigate the consequences of accidents. In addition, the methodology presented in the present study may be helpful for resource managers and technical decision makers for implementing efficient materials dispatching system under emergency response conditions in large oil spills.

For future works, there are still many areas in the integrated emergency optimization model that needs further improvement, such as considering the spread and movement of oil spills, in which oil spill emergency disposal vessels can dock to other collection and distribution points according to emergency needs. On the basis of the distribution of waters with a high probability of oil spill accidents, the distribution of emergency materials distribution points and allocation of material storage capacity are further optimized. The methodology could be also applied to develop software of emergency materials automatic dispatching system based on the platform of ECDIS (Electronic Chart Display and Information System) and AIS (Automatic Identification System).

Author Contributions: S.L. is responsible for the model construction. M.G. is responsible for manuscript structure construction and data analysis. Improving the english grammar of the paper helped by M.E. P.Z. gives guidance on the technical route of the paper. H.F. participates in the compilation of basic data.

Funding: This research was sponsored by Humanity and Social Science Youth foundation of Ministry of Education (14YJCZH081), Basic Public Welfare Research Project of Zhejiang Province, 2018 (LGF18E090005 and 2016C31111), and the K.C.Wong Magna Fund at Ningbo University, China.

Conflicts of Interest: The author declares no conflict of interest.

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