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OPTIMIZATION MODEL OF SHUTTLE TANKER SCHEDULING IN OFFSHORE OIL PRODUCTION SYSTEM

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Abstract. *In this paper, issues of shuttle tanker scheduling in offshore oil production system were addressed. A model of deployment and routing of shuttle tankers was developed. The model was to optimize the deployment and routing of shuttle tankers, the frequency of oil pick-up from FPSO (Floating Production Storage and Offloading) in a planning horizon. To solve the model, a heuristic algorithm was designed. Numerical experiments indicate that larger shuttle tankers and reasonable scheduling of shuttle tankers can effectively reduce the total cost and oil loss. Meanwhile, increasing of shuttle tankers will not significantly decrease the oil loss of FPSO.*

Keywords: Shuttle tankers, Ship allocation, Routing optimization

1. **Introduction.**

Offshore oil transportation is important to ensure the efficiency of offshore oil production system. Shuttle tankers are essential equipments to offloading oil from FPSO, connecting offshore drilling platforms, FPSO and shore storage bases. With the development of offshore oil industry, the scheduling of shuttle tankers has received increasing attention and has been extensively studied. The research topics include drilling platform design, connection and scheduling between FPSO and shuttle tankers, system design. Kim et al. [1] developed a vessel/mooring/riser coupled dynamic analysis model. Tahar and Kim [2] developed a computer program for hull/mooring/riser coupled dynamic analysis of a tanker-based turret-moored FPSO in waves, winds, and currents. Garrett [3] presented numerical models and procedures that provide accurate and efficient global modeling of the Floating Production System. Chen and Moan [4] developed a two-stage probabilistic model of FPSO and tanker collision in the tandem offloading operation. Li and Wang [5] used multi-body coupled method to analyze a soft yoke moored FPSO with an alongside moored shuttle tanker.

The scheduling of shuttle tankers includes the deployment of shuttle tankers, routing optimization, and frequency of oil pickup. Theoretically, it can be abstracted as a special VRP (Vehicle Routing Problem). VRP has been widely studied since it is proposed by Dantzig and Ramser [6]. Many models and algorithms were developed. It can be classified according to the different research emphases. According to the constraint conditions, there are Capacitated Vehicle Routing Problem (CVRP), Vehicle Routing Problem with Time Window (VRPTW). According to the information feature distribution, there are deterministic VRP and uncertainty VRP [7]. Moghaddam et al. [8], Goodson [9] developed methods for the multi-compartment vehicle routing problem with stochastic demands. Gauvin et al. [10] proposed a state-of-the-art branch-cut-and-price algorithm for the vehicle routing problem with stochastic demands (VRPSD). Mendoza [11], Dusan and Panta [12] developed a new type of the intelligent vehicle routing system and proposed a model based on the Fuzzy Arithmetic Rules, Fuzzy Logic and Ant System. Sungur et al. [13]

introduced a robust optimization approach to solve the VRP with demand uncertainty. Huisman et al. [14] developed a solution approach to the dynamic VRP.

Existing studies on VRP provide meaningful insights for shuttle tanker scheduling. However, the problem of shuttle tanker scheduling has its own characteristics comparing with VRP. For the shuttle tanker scheduling, the demand is changing with time, namely, crude oil in FPSO increases with the production of offshore drilling platform. Meanwhile, shuttle tanker scheduling needs to consider the influence of oil pickup frequency, the increased oil storage cost of FPSO and production suspending caused by pickup delay.

In this paper, the scheduling of offshore oil production and transportation system are addressed. An optimization model of shuttle tankers deployment and routing scheduling is developed considering the capacity constraints of FPSO and shuttle tankers, and the influence of shuttle tanker type. The objective is to minimize the total cost of offshore oil production and transportation. Compared with existing studies on scheduling of shuttle tankers, the proposed model considers the optimization of deployment and routing of shuttle tankers, which helps to realize the integrating optimization of offshore oil production system. Furthermore, the proposed model reflects the oil changing of FPSO, which helps to decrease the storage and production cost of offshore oil production system. It is a non-typical VRP problem, which helps to extend the studies on VRP. Meanwhile, an algorithm based on genetic algorithm is designed. The algorithm can tackle the complex constraints and solve the model effectively.

2. Model Formulation.

Offshore oil production and transportation system is composed of drilling platform, FPSO, shuttle tankers and oil storage bases. FPSO gets crude oil from drilling platform or undersea well via submarine oil pipeline, and processes the crude oil (e.g., filtering impurities like water and sand). The processed oil is stored in the tank, waiting to be transported to land oil storage base. Shuttle tankers transport oil from FPSO to the land oil storage base. In offshore oil production and transportation system, the scheduling of shuttle tankers affects transportation cost, storage cost of FPSO, and the continuity of oil production process. In this paper, the ship deployment (ship type and number), route selection and frequency of oil pickup, are optimized simultaneously.

To develop the model, we suppose: (1) Shuttle tankers departure from oil storage base, pickup oil of FPSO, and then back to the base. Each shuttle tanker serves several FPSOs, and each FPSO is served by one shuttle tanker each time; (2) FPSOs have different oil production rates and capacity limits. Transmission rate between one shuttle tanker and different FPSO, oil storage base is different; (3) Shuttle tankers are in the same type.

The parameters of this model are defined as follows. F is the set of FPSO, $F = \{1, 2, \ldots, n\}$, 0 denotes oil storage base, and $N = \{0, F\}$. S is the set of shuttle tankers; K is the number of shuttle tankers, $K = \{1, 2, \ldots, k\}$; cf^k denotes the fixed cost of shuttle tanker k; cv^k is unit transport cost of shuttle tanker k; c_1 is unit crude oil production cost; c_i is unit crude oil transmission cost; c_2 is unit time lost cost when exceeding FPSO capacity. T is planning horizon.

d_{ij} is the distance between nodes i and j. v^k is average speed from node i to j of shuttle tanker k, $k \in S$; t_{ij}^k is travel time from i to j of shuttle tanker k, $t_{ij}^k = d_{ij}/v^k$, $i, j \in N$, $k \in S$. u_i is oil transmission rate between shuttle tankers and FPSO; τ_i^{kr} is oil transmission time of rth pick-up oil at node i by shuttle tanker k, $\tau_i^{kr} = Q_i^{kr}/u_i$, $i \in N$, $k \in S$, $r \in R$; q^k is the capacity of shuttle tanker k, $k \in N$; ∂_i is the oil output rate at node i, $i \in F$; H_i^r denotes oil quantity of node i when the rth pick-up happening if there are no capacity constraints for FPSO; D_j^r is real oil quantity of node j considering the capacity limits of FPSO; L_i is FPSO capacity limits.

Decision variables are defined as follows. If shuttle tanker k passes node i at the rth pickup, $b_i^{kr} = 1$; otherwise, $b_i^{kr} = 0$. If shuttle tanker k travels from node i to j at the rth pickup, $a_{ij}^{kr} = 1$; otherwise, $a_{ij}^{kr} = 0$. Q_i^{kr} is picked-up quantity of shuttle tanker k at the rth pickup. R is the frequency that shuttle tankers serve an FPSO in planning horizon.

Thus, the model of shuttle tanker scheduling can be formulated as follows:

$$\begin{aligned} Min\,Z \;=\; & \sum_{r=1}^{R}\sum_{k\in S}\sum_{i\in N}\sum_{j\in N}\left(cf^k + cv^k d_{ij}\right)a_{ij}^{kr} + \sum_{r}^{R}\sum_{j\in F} c_1 D_j^r \\ & + \sum_{r}^{R}\sum_{k\in S}\sum_{j\in F} 2c_j Q_j^{kr} + \sum_{r}^{R}\sum_{j\in F} c_2\left(H_j^r - L_j\right)/\partial_j \end{aligned} \tag{1}$$

$$\begin{aligned} \text{s.t.}\qquad & H_j^r - \Bigg\{\partial_j\Bigg(\sum_{r=1}^{r}\sum_{k}^{K}\sum_{i=0}^{j-1}\sum_{j=0}^{j} t_{ij}^k a_{ij}^{kr} + \sum_{k}^{K}\sum_{i=1}^{j-1}\tau_i^{kr} b_i^{kr} + 2\sum_{r=1}^{r-1}\sum_{k}^{K}\sum_{i\in F}\tau_i^{kr} b_i^{kr} \\ & + \sum_{r=1}^{r-1}\sum_{k}^{K}\sum_{j\in F/\{1,\ldots,j-1\}}\;\sum_{i\in N/\{1,\ldots,j\}} t_{ji}^k a_{ji}^{kr}\Bigg) - \sum_{r=1}^{r-1}\sum_{k=1}^{K} Q_j^{kr} b_j^{kr}\Bigg\} = 0 \end{aligned} \tag{2}$$

$$D_j^r - \min\left\{L_j, H_j^r\right\} = 0 \tag{3}$$

$$0 \le Q_j^{kr} b_j^{kr} \le \min\left\{D_j^r, q^k\right\} \quad \forall k \in S, r,\ j \in F \tag{4}$$

$$\sum_{j\in F} Q_j^{kr} b_j^{kr} \le q^k, \quad \forall k \in S, r \tag{5}$$

$$\sum_{r=1}^{R}\sum_{k}^{K}\sum_{j\in F}\left(\sum_{i=0}^{j-1} t_{ij}^k a_{ij}^{kr} + 2\tau_j^{kr} b_j^{kr} + \sum_{i\in N/\{1,\ldots,j\}} t_{ji}^k a_{ji}^{kr}\right) \le 24 * T \tag{6}$$

$$\sum_{j\in F} a_{0j}^{kr} = 1, \quad \forall k \in S, r \tag{7}$$

$$\sum_{i\in F} a_{i0}^{kr} = 1, \quad \forall k \in S, r \tag{8}$$

$$\sum_{k\in S}\sum_{j\in N} a_{ij}^{kr} = 1, \quad \forall i \in N, r \tag{9}$$

$$\sum_{k\in S}\sum_{i\in N} a_{ij}^{kr} = 1, \quad \forall j \in N, r \tag{10}$$

$$\sum_{k\in S} a_{ii}^{kr} = 0, \quad \forall i \in F \tag{11}$$

$$\sum_{k\in S} a_{ij}^{kr} = 1, \quad \forall i, j \in N, r \tag{12}$$

$$\sum_{i\in N} a_{ij}^{kr} - \sum_{j\in N} a_{ji}^{kr} = 0, \quad \forall k \in S, r \tag{13}$$

$$\sum_{k\in S}\sum_{i\in N}\sum_{j\in N} a_{ij}^{kr} \le n, \quad \forall i, j \in N, r \tag{14}$$

$$\sum_{i\in F} a_{ij}^{kr} = b_j^{kr}, \quad \forall r, j \in F,\ \ k \in S \tag{15}$$

$$\sum_{i\in F} a_{ji}^{kr} = b_j^{kr}, \quad \forall r, j \in F,\ \ k \in S \tag{16}$$

$$a_{ij}^{kr} = b_i^{kr} b_j^{kr}, \quad \forall r, i, j \in F,\ \ k \in S \tag{17}$$

$$a_{ij}^{kr} = \{0, 1\}, \quad \forall i, j \in F,\ \ k \in S \tag{18}$$

$$b_i^{kr} = \{0, 1\}, \quad \forall r, i \in F,\ \ k \in S \tag{19}$$

The objective (1) is to minimize the total cost, including transportation cost and fixed cost of shuttle tankers, storage cost of FPSO, oil transmission cost between shuttle tankers and FPSO, and oil production loss cost caused by pickup delay of shuttle tankers. Equation (2) and Equation (3) denote the oil quantity of FPSO without and with capacity limits respectively. Equation (4) and Equation (5) are the shuttle tanker capacity constraints. Equation (6) is the constraint of shuttle tanker pickup frequency in planning horizon. Equation (7) and Equation (8) denote that all shuttle tankers departure from oil storage base and return after serving FPSOs. Equation (9) and Equation (10) denote that each FPSO is served by one shuttle tanker, and each FPSO has at most one predecessor and successor node. Equation (11) ensures that shuttle tankers do not stop at FPSO all time. Equation (12) ensures that different shuttle tankers cannot serve the same FPSO in one pickup process. Equation (13) is flow balance constraints ensuring that all FPSOs are performed in well-defined sequences. Equation (14) ensures that all shuttle tankers are in use. Equations (15)-(17) denote that all the node are served by shuttle tankers. Equations (18) and (19) are binary constraints for variables.

3. **Solution Algorithm.** The scheduling of shuttle tankers can be classified as a special VRP. VRP has been proved to be an NP-hard problem. Here, an algorithm based on genetic algorithm is designed, and the main process is illustrated as follows.

(1) Chromosome representation. We code the decision variables a_{ij}^{kr}, Q_j^{kr}, and design two chromosomes that chromosome 1 represents oil pick-up route a_{ij}^{kr}, and chromosome 2 represents oil quantity of Q_j^{kr}. For chromosome 1, the number of columns is $F + K - 1$, and the number of rows is R^u. Each genetic value represents a node type, and each row of chromosome represents shuttle tanker's oil pick-up route each time. Chromosome 2 has the same dimensions with chromosome 1. Each genetic value is oil pickup quantity of the same node in chromosome 1.

(2) Population Initialization. Randomly generate the initial population, and ensure the feasibility of chromosomes. First, calculate the upper bound R^u of oil pickup frequency according to the planning horizon, and use it as the row number of chromosome 1 and chromosome 2.

(3) Fitness function. The objective is the proposed model to minimize the transportation cost of offshore oil production system. The lower the optimal results, the larger the fitness function values. Thus, the reciprocal of the objective function is treated as the fitness function. The fitness function $f(x)$ is formulated as: $f(x) = 10^7/y(x)$, where, $y(x)$ represents objective function. When we get the decision variables in the model, we can get the value of $y(x)$, and then we get the fitness value.

(4) Genetic operations.

Selection: The method of roulette is used to process selection operations, putting individual with high fitness into new population.

Crossover: To avoid too many unfeasible chromosomes in crossover process, single crossover method is used. Randomly generate two crossover position, reverse the gene order of two crossover position, and generate new chromosomes.

Mutation: Use irregular code mutation to generate two mutation positions, and then exchange the gene value of two gene bits.

4. **Numerical Experiments.** Data of an oil firm in Bohai Bay, China is used for numerical experiments. Since the longest time oil stored in FPSO is 2.86 days, and the shortest is 0.86 days, we assume the planning horizon is a week (7 days). Based on the geographical coordinates, we can calculate the distance between FPSO and the oil reserve base.

Four types of shuttle tankers A, B, C, D are selected. Let 0 represent oil storage base, $F = \{1, 2, \ldots, 7\}$ denote the set of FPSO, and $N = \{0, 1, 2, \ldots, 7\}$ denote all the nodes

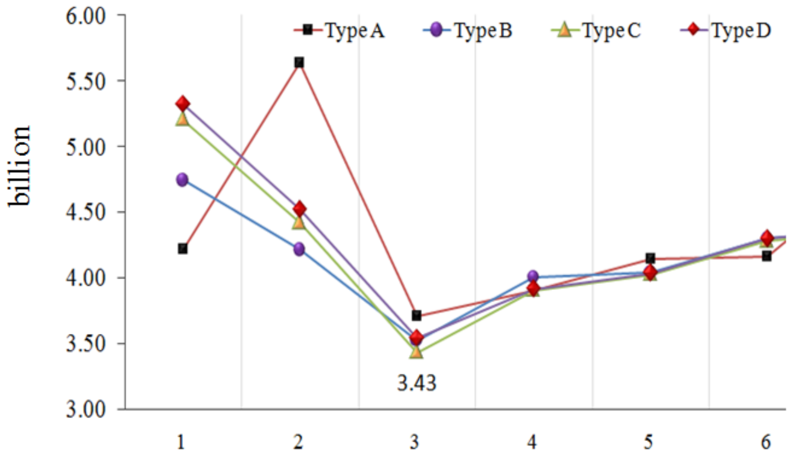

Figure 1. The total cost with different shuttle tankers

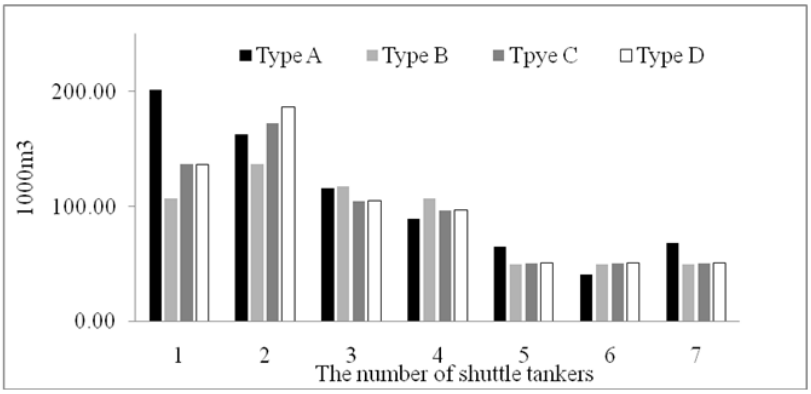

Figure 2. FPSO oil-loss volume with different tanker types and numbers

of the oil production network. cf^k is the fixed cost of shuttle tankers, and cv^k is the unit travel distance. We can get t_{ij}^k, H_i^r, D_i^r, b_i^{kr} and a_{ij}^{kr}.

Figure 1 and Figure 2 illustrate the total cost with different ship types and crude oil loss cost of FPSO. Oil production and transportation cost is the lowest when the number of shuttle tankers is three. The total cost is the lowest when three shuttle tankers of type C are used. For different shuttle tanker types, the oil loss volume of the system decreases with the increasing of ship number. With the increase of shuttle tankers number, the loss volume reduction is not obvious.

When deploying 3 type C shuttle tankers, the system cost is the lowest, and route optimization results are as Table 1 shows. It is obvious that, it takes oil 3 times in total, and there is the same route but different volume for the first time and the second time. As tanker C-2 cannot serve other FPSO after serving FPSO 4 and 5 in planning horizon, thus FPSO 4 and 5 are served by tanker C-3 in the third time so that the oil-taken route is different from the first two times.

5. **Conclusions.**

In this paper, a model of deployment and routing of shuttle tankers was developed to optimize the deployment and routing of shuttle tankers, the frequency of oil pick-up from FPSO. A heuristic algorithm was designed to solve the model, and numerical experiments were provided. Results indicate that, larger shuttle tankers and reasonable number of shuttle tankers deployed in the shipping network can effectively reduce the total system cost and oil loss volume, and also increasing the number of shuttle tankers will not obviously decrease the oil loss of FPSO greatly.

Table 1. The optimization result of shuttle tankers

FPSO	Offshore oil 112	Offshore oil 113	Mingzhu	Offshore oil 117	Bohai Century	Changqing	Youyi
Real node	6	7	4	5	3	1	2
Visual node	1	0	1	0	1	1	0
Pickup quantity (m^3)	0.804	1.716	0.462	4.879	1.556	0.314	0.412
Oilloss (m^3)	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1st oil-taken route	0-6-7-0		0-4-5-0		0-3-1-2-0		
FPSO	Offshore oil 112	Offshore oil 113	Mingzhu	Offshore oil 117	Bohai Century	Changqing	Youyi
Real node	6	7	4	5	3	1	2
Visual node	0	1	1	0	1	1	0
Pickup quantity (m^3)	6.133	7.656	3.104	26.000	5.891	0.937	1.130
Oilloss (m^3)	3.590	0.000	6.030	25.603	0.000	0.000	0.000
2nd oil-taken route	0-6-7-0		0-4-5-0		0-3-1-2-0		
FPSO	Offshore oil 112	Offshore oil 113	Bohai Century	Changqing	Youyi	Mingzhu	Offshore oil 117
Real node	6	7	3	1	2	4	5
Visual node	0	1	1	1	1		
Pickup quantity (m^3)	15.000	16.000	12.870	1.902	2.255	5.200	26.000
Oilloss (m^3)	12.013	6.570	4.799	0.000	0.000	0.000	46.088
3rd oil-taken route	0-6-7-0		0-3-1-2-4-5-0				

The scheduling of shuttle tanker is a special VRP with changing demand, which is an NP-hard problem. Efficient algorithms are needed to improve the computation efficiency, and benchmarks are needed to compare different algorithms. These issues need further studies.

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