A HEURISTIC APPROACH FOR INTERNATIONAL CRUDE OIL TRANSPORTATION SCHEDULING PROBLEMS

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Abstract

Nowadays the new trend of global economy has driven the business strategy from the local to the global supply chain planning. Comprehensive logistics solutions are critical to integrate supply chain management in the global landscape. In this paper, we propose a heuristic algorithm to solve the ship scheduling problem for international crude oil distribution. The problem is to find an optimal assignment, sequence and loading volume of demand simultaneously in order to minimize the total distance satisfying the capacity of the tankers. Computational results demonstrate the effectiveness of the heuristic algorithm.

Keywords: global supply chain, international logistics, crude oil transportation, heuristic algorithm.

1. Introduction

The global logistics strategy is driven by the new economic structure. Oil is considered as one of the most consumed energy resource in Japan. Due to lack of the domestic resource, Japan was the second-largest importer of oil in the world after the United States in 2009. This country is primarily dependent on the Middle East for its oil imports, as roughly 80 percent of Japanese crude oil imports originate in the region up from 70 percent in the mid-1980 (http://www.eia.doc.gov/cabs/Japan/Oil.html). In this paper, we propose an optimization approach to solve the international crude oil transportation problem.

In Japan, the demand of various types of crude oils is huge from Arabian countries while demands are given every month. In order to increase the efficiency, the assignment, the sequence and the loading volume of demands should be optimized simultaneously. In many practical situations, these decisions are executed manually by the negotiation between the human operators based on the contract with suppliers individually. In order to help the decision of human operators, the automatic generation of the practical ship scheduling is highly required to avoid the human errors and increase the efficiency of decision making.

The transportation problem of a fleet of vehicles for visiting customers can be modeled as vehicle routing problem with time window (VRPTW). However, the problem in this paper is different from VRP that the demand should be split into one or more than two deliveries. The difficulty is to determine the assignment and sequence but also the optimal loading volume. A generalized problem is a split delivery vehicle routing problem (Belenguer, Martinez, Mota 2000) (Jin, Liu, Eksioglu 2008). The demand of international maritime transport is increasing recently (Global Logistics 2010). An analytical model concerning the international maritime transport market has been studied (Kuruda, Takebayashi, Tsuji 2005). The ship scheduling problem has been studied widely. An optimization approach to solve the ship scheduling as a generalized set-packing model has been addressed (Kim and Lee 1997). They generate a feasible ship schedule by a directed acyclic graph. An optimization model as a multi-ship pickup and delivery is proposed in (Fagerholt 2001). The dynamic programming is used to solve the shortest path algorithm. A heuristic search algorithm for shipping and scheduling with split loads is introduced in (Korsvik, Fagerholt, Laporte 2011).

In this paper, we propose a solution approach to the international crude oil transportation problem. A heuristic algorithm is proposed to solve the problem. Computational results demonstrate the effectiveness of the proposed algorithm by comparing the results created by the human operators.

2. Ship scheduling problem for crude oil transportation

2.1 Problem description

The international ship scheduling problem for crude oil transportation mainly consists of two parts. The first part is the outbound ship loading planning problem that determines the visiting route for a fleet of tankers in Arabian countries. Another part is the inbound ship unloading raw materials into several factories in Japan considering both of inbound and outbound transportation simultaneously. However, the first step of automating procedure in this paper is to deal with the outbound international ship loading planning problem in order to simplify the problem.

Let L be the set of loading places where crude oils can be loaded. Each loading place has one or more than two type of crude oils. In order to visit loading places, an intermediate point should be visited first. The distances between load-
ing places denoted by \( d_{ij} \) are not symmetric (\( d_{ij} \neq d_{ji} \)) but satisfy the triangular inequality (\( d_{ij} + d_{jk} \geq d_{ik} \)). \( K \) is the set of available tankers whose capacity of loading volume is given. The total demand volume \( D_o \) is given by the contract from the suppliers. The problem is set to find an optimal assignment, routing and loading volume for a fleet of tankers in order to minimize the total costs.

The international crude oil transportation problem is characterized by the following constraints.

1. The number of countries visited by a tanker is at most two. The port charge is imposed if a tanker occupies one port. If one tanker visits one port, visiting time should be sufficient in order to complete loading operations.
2. The loading volume of a tanker should be nearly full and the number of tankers should be minimized. The reason is that the visit from Japan to Arabian countries is time consuming and requires lots of costs.
3. There is a constraint that some specific ports should be visited first. The loading condition is different for each loading place. Minimum and maximum loading volume, split or merger of volume constraints are given at each port in each country.

### 2.2 Problem formulation

The problem is formulated as a mixed integer linear programming problem in this section.

**Sets:**
- \( T \) is set of tankers, \( L \) is set of loading places, and \( O \) is set of crude oils

**Decision variables:**
- \( \delta_{k,i,j} \) binary variable that takes 1 when tanker \( k \) visits unloading place \( i \), and 0 otherwise,
- \( x_{k,i,j} \) binary variable that takes 1 when tanker \( k \) visits from loading place \( i \) to loading place \( j \), and 0 otherwise,
- \( y_{k,i,o} \) loading volume of crude oil \( o \) at loading place \( i \) for tanker \( k \),
- \( t_{k,i} \) loading date of loading place \( i \) for tanker \( k \).

**Parameters:**
- \( D_o \) demand of crude oil \( o \)
- \( \eta_{l,o} \) binary constraint that takes 1 if crude oil \( o \) can be loaded at loading place \( i \), and 0 otherwise,
- \( c_i \) charge cost imposed by visiting loading place \( i \),
- \( d_{i,j} \) distance between loading place \( i \) and loading place \( j \),
- \( y_{i}^{\min}, y_{i}^{\max} \) minimum and maximum loading volume at loading place \( i \)
- \( U_{k}^{\max} \) maximum loading volume for tanker \( k \)
- \( M \) sufficiently large positive constant
- \( \alpha_{\min} \) minimum loading volume ratio

The first objective is to minimize the sum of the volume loss from the minimum loading volume ratio for each tanker and the second objective is to minimize the total distances traveled by the tankers and the third is to minimize the total charge cost. These objectives can be represented by the weighted sum of the objective function.

\[
\begin{align*}
\min \ & w_1 \left( \sum_{k \in T} \max(\alpha_{\min} - \sum_{i \in L_o \cap O} y_{k,i,o}/U_{k}^{\max}, 0) \right) \\
\min \ & w_2 \left( \sum_{k \in T} \sum_{i \in L} \sum_{j \in L} d_{i,j} x_{k,i,j} \right) + w_3 \left( \sum_{k \in T} \delta_{k,i} \right)
\end{align*}
\]

**Constraints:**

The assignment constraints of loading places are denoted by

\[
\begin{align*}
\sum_{i \in L} x_{k,i,o} &= \delta_{k,i} \quad (\forall k \in T, \forall j \in L) \\
\sum_{j \in L} x_{k,i,j} &= \delta_{k,i} \quad (\forall k \in T, \forall i \in L)
\end{align*}
\]

Each tanker starts from the intermediate point \( s \) and return after visiting loading places.

\[
\begin{align*}
\sum_{i \in L} x_{k,s,i} &= 1 \quad (\forall k \in T) \\
\sum_{i \in L} x_{k,i,s} &= 1 \quad (\forall k \in T)
\end{align*}
\]

The number of visiting loading places should be three or less than three including the intermediate point.

\[
\sum_{i \in L} \delta_{k,i} \leq 3 \quad (\forall i \in L)
\]

The loading volume should be less than the capacity of a tanker.

\[
\sum_{i \in L \cap O} y_{k,i,o} \leq U_{k}^{\max} \quad (\forall k \in T)
\]

Total demand constraints:

\[
\sum_{i \in T} \sum_{i \in L \cap O} y_{k,i,o} = D_o \quad (\forall o \in O)
\]

Minimum and maximum loading volume constraints at each loading place:

\[
\delta_{k,i} y_i^{\min} \leq \sum_{o \in O} \eta_{l,o} y_{k,i,o} \leq \delta_{k,i} y_i^{\max} \quad (\forall k \in T, \forall i \in L)
\]

Estimated time related constraints:

\[
t_{k,i} - M(1 - x_{k,i,j}) \leq t_{k,j} \quad \forall k \in T, \forall i, j \in L
\]

**Variable constraints:**

\[
x_{k,i,j} \in \{0, 1\}, \quad y_{k,i,o} \geq 0, \quad \delta_{k,i} \in \{0, 1\}
\]

The difficulty of solving the model arises from the following characteristics.

- The model includes vehicle routing problem with time window. The assignment and the sequence of demand should be optimized simultaneously.
- The model includes set packing problem. The number of tanker should be minimized where the loading volume of tankers should be full with a minimum and maximum loading volume constraint.
- The model can be regarded as a set partitioning problem. The loading volume should be equal to the total demand. This means that the total demand should be split into disjoint sets.
3. Heuristic approach

After consulting with the operators in the industry, the data we use for the constraints in the model are formatted into database. Not only the general constraints state above, but also there are a lot of constraints depending on loading places and the types of crude oils. In order to solve the large scale problem efficiently, the heuristic approach is applied to this problem.

3.1 Savings-based algorithm

A well-known heuristic to solve the vehicle routing problem is savings algorithm (Paessens 1988). In the algorithm, the initial allocation of each customer to separate tour is generated. Then the cost-savings of visiting those customers on one tour is calculated. The pairs of the customers with maximum cost-saving are sequentially joined into tours till no more savings can be achieved.

In this problem, the savings value is to determine the optimal route, which is the combination of two loading places that we suppose the tanker will visit once. In another words, if the savings value is high, the visiting cost of the combination of loading places by one tanker is optimal. The savings distance for the combination of loading place \( i \) and \( j \) is calculated as

\[
s(i, j) = (d_{i,s}+d_{i,j}) + (d_{s,j}+d_{j,s}) - (d_{i,s}+d_{i,j}+d_{j,s})
\]

\[= d_{i,s}+d_{s,j} - d_{i,j}
\]

(13)

The savings value of (13) that is commonly used is not sufficient because the charge cost for visiting the port is neglected. The charge cost for joining two loading places is the same with a separate tour. However, due to the characteristic of split delivery of crude oil transportation problem, there is a possibility that the same loading place is visited more than two times. In order to consider the charge cost for visiting a port, the savings value is modified into

\[
s(i, j) = (d_{i,s}+d_{s,j}-d_{i,j})/(c_i+c_j)
\]

(14)

According to the savings value, the priority of the combination of two ports can be determined.

3.2 Lotsizing parameter

After the assignment and routing of loading places are determined, the loading volume of demands should be determined consisting of the split of delivery. We use the practical heuristic approaches which are applied by the human operator. The human operator has enough information for determining lotsizing of loading volume for each crude oil. The lotsizing parameter determines how to allocate the volume of crude oils in order to satisfy the demand since the demand of crude oil can be supplied from different loading places. The lotsizing parameter \( Q_b \) is specified for each crude oil. Based on the lotsizing and demand parameters, we use the heuristics that if a tanker visits loading places, the loading place that the tanker visit which has the largest parameters is prioritized. But the other types of oils which are demanded are also unloaded based on the volume of demands. The heuristic algorithm is as follows. Let \((o_1, o_2)\) be the pair of the first loading oil and the second loading oil that has the maximum savings value. \( l_1, l_2 \) is the first and second visiting loading place that has the crude oil \( o_1, o_2 \), respectively. \( n_{i1}, n_{i2} \) is the number of crude oils that has demand at the first and second loading place \( l_1, l_2 \), respectively.

[Volume Assignment Heuristic]

Step 1 Set the current demand as the total demand \( D_o = D_o \).

Step 2 Compute \( q_1 = \min(Q_{o_1}, D_{o_1}) \).

Step 3 The first loading quantity for tanker \( k \) at loading place \( l_1 \) is prioritized. The loading volume is determined by

\[
y_{k,l_1,o_1} = \max(y_{l_1}^{\min}, \min(q_1/n_{i1}, D_{o_1}, U_k^{\max}, y_{l_1}^{\max}))(j = 1, \ldots, n_{i1})
\]

\[
y_{k,l_2,o_2} = \max(y_{l_2}^{\min}, \min(q_2/n_{i2}, D_{o_2}, U_k^{\max} - \sum_{o \in O} y_{k,l_2,o}, y_{l_2}^{\max}))(j = 1, \ldots, n_{i2})
\]

Then go to Step 5.

Step 4 The second loading quantity for tanker \( k \) at loading place \( l_2 \) is prioritized.

\[
y_{k,l_2,o_1} = \max(y_{l_1}^{\min}, \min(q_1/n_{i1}, D_{o_1}, U_k^{\max} - \sum_{o \in O} y_{k,l_2,o}, y_{l_1}^{\max}))(j = 1, \ldots, n_{i1})
\]

\[
y_{k,l_2,o_2} = \max(y_{l_2}^{\min}, \min(q_2/n_{i2}, D_{o_2}, U_k^{\max} - \sum_{o \in O} y_{k,l_2,o}, y_{l_2}^{\max}))(j = 1, \ldots, n_{i2})
\]

Step 5 \( D_{o_1} \leftarrow D_{o_1} - \sum_{j=1}^{n_{i1}} y_{k,l_1,o_1} - \sum_{j=1}^{n_{i2}} y_{k,l_2,o_2} \). If \( D_o = 0 \ \forall o \in O \) then the algorithm is finished. Otherwise return to Step 2.

3.3 Optimization algorithm

First, parameters and variables are initialized. Then, read the demand of each crude oil, distance between each ports and assignment of crude oil. The initial lotsizing parameters for each crude oil are set. The saving value is calculated by distance parameters which are provided. The next step is to allocate requests by the assignment according to the priority. Finally, we use three indicators which are the average volume ratio, the number of tanks and total distance to evaluate the performance. The proposed optimization algorithm we apply is a greedy local search heuristic to optimize the lotsizing parameter. The heuristic algorithm consists of following steps.

[Heuristic algorithm]

Step 1 Set an initial lotsizing parameter.

An initial lotsizing parameter, the weight of the objective function and maximum number of iterations are set. The lotsizing parameter is determined according to history data.
Step 2 Generate an initial solution.
An initial solution is generated by the savings based on algorithm with the volume assignment heuristic.

Step 3 Evaluate the performance.
If the performance of the newly generated solution is better than that of the current solution, the newly generated solution is adopted.

Step 4 Update the lotsizing parameter.
The lotsizing parameter is updated according to the following equation where $r$ is an integer random number.

$$Q_o^\text{NEW} = \min(Q_o^{\text{OLD}} + r, y_{\text{max}}^{\text{OPT}}) \quad (o \in O) \quad (15)$$

Step 5 Evaluate the convergence.
If the current solution is not updated in the predetermined number of times or the maximum number of iterations is reached, the algorithm is terminated.

4. Computational experiments

4.1 Case study

In order to evaluate the performance of the heuristic algorithm, the real data is used. In the example problem, the number of loading places is 22 and the number of crude oils is 22. The distance matrix is taken from the real mile data. By using the data, computational experiments are executed. The maximum number of iterations is 10,000 times. An Intel Core i7 860 2.8GHz Processor with 4GB memory is used for computation. The total computation time was 25.7 sec. According to the algorithm mentioned above, we can obtain two results of the initial lotsizing parameter (Init) and the optimized lotsizing parameter (Opt). Operator is the actual results obtained by the human operators.

<table>
<thead>
<tr>
<th>Table 1 Computational results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tankers</td>
</tr>
<tr>
<td>Tankers</td>
</tr>
<tr>
<td>Volume ratio (%)</td>
</tr>
<tr>
<td>Distance (mile)</td>
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<tr>
<td>Charge cost</td>
</tr>
</tbody>
</table>

From the tables shown above, it is easy to observe that after the optimization, the number of tanks is reduced from 15 to 14, the total distance is reduced from 14,003 miles to 12,493 miles, and the charge cost is also reduced. Compared with the results of the human operators, the total distance is reduced. Meanwhile, the total charge cost and the average volume rate are larger than those of the human operators. In most cases, the volume rate should be nearly 100%. In this case the results after the optimization by the heuristic algorithm is comparable with those of human operators but the average volume ratio should be improved by setting the weights of the objective function. The priority of the optimization terms is still negotiable in the future. We should realize which terms are the more considerable among total distance, volume rate and the number of tankers in the practical cases.

5. Conclusion and future works

A heuristic approach to resolve the international crude oil transportation scheduling problem is introduced. The case study demonstrates the effectiveness of the proposed method compared with the results which are obtained by human operators. In the future, we should consider the improvement of the heuristic algorithm for the practical application. In the future works, we should start to consider a practical system development for the aid of human operation's decision.

References


