A Multiobjective Maritime Risk-Based Oil Transportation Model

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Abstract

A high level strategic problem faced by both regulatory agencies and commercial shippers is evaluating the merit and risks of various alternative policies for the transportation of crude oil and petroleum products To address this problem, we present a network flow model with multiple objectives, commodities, modalities and origin-destination pairs. The development of an interactive solution methodology is presented, followed by its implementation via a web-based software package. Finally, the application of the solution methodology is demonstrated within a case study.

1. Introduction

Significant demand for crude oil and petroleum products have led to increased□shipments [10]. Based on this trend, oil spill□ are now more probable and prevalent. Oil spills such as the *Exxon Valdez* in 1989, the *North Cape* barge, and the *Sea Empress* in 1996, are just a few of the major incidents that have brought these accidents and the associated risks to the forefront of public attention.

Currently, there are few quantitative risk analysis models for marine transportation, most are generally qualitative examinations [5]. However, recent quantitative efforts by Li et al. [4] and Iakovou et al. [3] have tackled the marine transportation of hazardous materials (hazmats), and specifically oil products. NMOTSM [1] quantifies many important factors: it quantifies and models the oil transported within the United States' boundaries; analyzes the risks and effects of oil spills; determines technologies to intervene and mitigate by reducing the damages from spills in high-risk areas. These points aside, a serious gap in the literature concerning marine oil transportation models is the estimation and assignment costs of the network links. Douligeris et al. [2] and Yudhbir [11] have tackled the issue of first quantifying risk associated with the marine transportation of oil products and, then, allocating and assigning risk cost estimates of the routes employed by the different maritime oil transportation networks

In this paper, we present the development of a comprehensive maritime oil transportation model that integrates the risk assessment methodology of Douligeris et al. [2] and Yudhbir [11]. We further present the development of an interactive solution methodology, along with its implementation via **IOTS**, an internet-based software package. This methodological implementation is then applied to a case study based within the marine network of the Gulf of Mexico.

2. The Risk Based Maritime Oil Transportation Problem

The maritime oil transportation problem is a multiobjective, multiple source-destination, multinodal problem faced by commercial shippers and regulatory agencies. Given a fleet of vessels servicing specific routes (over a long planning horizon), a modeler needs to efficiently ship different products using fleet vessels to-and-from several ports, satisfying the ports supply/demand at a minimal transportation (voyage) cost, but also at the minimal risk cost (due to oil spills). A number of policy-related issues are considered throughout this study

The decision-making process for the above oil routing problem is a medium-range strategic problem with a quarterly, semi-annual or annual planning horizon [8]. These planning horizons are predicated on the voyage legs of tankers between any two ports, lasting anywhere between two days to two months. For time periods of such length, supply and demand at each port are critically based on existing contracts. The vessels that are considered in this model are tankers and tank-barges (typical tanker types include Afromax, Suezmax, VLCC, and ULCC). The products being considered here are crude oil and petroleum products such as kerosene, diesel, lubricants, jet fuel, hydraulic oils, etc.

2.1 Problem Formulation

We consider a transportation network G = (N, E), where N is the set of nodes that includes origins, destinations and junctions (ports/port groups, import/export points), and E is the edge set used by the modalities. The arcs connecting the nodes of the network may correspond to tanker routes, waterways, and other coastal navigational channels. An arc is characterized by its length, transport rate per ton-mile, risk cost, capacity, etc. We concentrate on the five types of vessels (tank-barges and the four types of tankers) mentioned earlier. Each route is assigned an expected risk cost based on historical spills, that can be determined by the risk assessment and allocation methodologies provided by Douligeris et al. [2] and Yudhbir [11]. Specifically, the risk methodology accommodates for damages due to historical spills that have occurred within a properly defined spatial area around a shipping lane.

The following nomenclature is used:

A: Set of all port nodes (producers) from which a product is shipped.

B: Set of all port nodes (consumers) from where a product is received.

C: Set of all transferring nodes (transshipment points).

p: Types of products, p = 1, …, P.

k: Types of oil transporting vessels operated by a shipper, k = 1, …, K.

X_{ij}^{pk}: Amount (barrels; bbls – from now on) of product p which will be transported from node i to node j via vessel type k.

C_{ij}^{pk}: The transportation cost of one unit of volume (bbls) of product p from node i to node j via vessel type k.

R_{ij}^{pk}: Expected risk cost for transporting one unit of volume (bbls) of product p from node i to node j via vessel type k. (See [2] and [11]).

S_{jp}: Amount of product p required at node j.

$$S_{jp} = \begin{cases} S_{jp} > 0, \text{ if } j \in A \\ S_{jp} < 0, \text{ if } j \in B \\ S_{jp} = 0, \text{ if } j \in C \end{cases}$$

U_{ij}^{k}: Aggregate flow capacity for link (i, j) employing vessel type k.

Capacity U_{ij}^{k} is related to the total number of voyages that could serve arc (i, j) by the existing fleet of the k^{th} type vessels over the planning period. Note that U_{ij}^{k}'s are simply aggregate measures of capacity, since the problem under study is a strategic one (the impact of the choice of various levels of U_{ij}^{k}'s on the decision-making process will be discussed below). Problem **(P)** is then:

$$\textbf{(P)} \ \min z_1 = \sum_{(i,j)\in E} \sum_{p\in P} \sum_{k\in K} C_{ij}^{pk} X_{ij}^{pk} \tag{1}$$

$$\min z_2 = \sum_{(i,j)\in E} \sum_{p\in P} \sum_{k\in K} R_{ij}^{pk} X_{ij}^{pk} \tag{2}$$

subject to:

$$\sum_{k\in K} \sum_{i:(i,j)\in E} X_{ij}^{pk} - \sum_{k\in K} \sum_{l:(j,l)\in E} X_{jl}^{pk} = S_{jp}, \ \forall j \in N, \forall p \in P \tag{3}$$

$$\sum_{p\in P} X_{ij}^{pk} \le U_{ij}^{k}, \ \forall (i,j) \in E, \forall k \in K, \tag{4}$$

$$X_{ij}^{pk} \geq 0, \ \forall (i,j) \in E, \forall p \in P, \forall k \in K, \qquad (5)$$

Equations (3) are balance equations, while equations (4) ensure that the total flow p on link (i, j) being transported via vessel of type k does not exceed the appropriate capacity. A commercial shipper would be interested in finding satisfactory/improved transportation policies that minimize both the transportation (voyage) costs and the risk costs (since the shipper is liable for environmental damages [6]). However, a regulatory agency's motivation to solve these issues **(P)** is somewhat different from a shipper's. A regulatory agency must take into account all oceanborne traffic, and, thus, consider the risk of oil spills due to all vessels-- not just to tankers and tank-barges. Therefore, a regulator has to solve **(P)** for K>5. Thus, aside from generating tradeoffs between the expected risk cost and the transportation cost, a regulator may utilize **(P)** to further enforce an equitable distribution of risk as the third objective. By setting appropriate values for U_{ij}^{k}; this can be achieved by examining the impact many alternative levels of the link capacities U_{ij}^{k}, as part of a sensitivity type of an analysis. Such an analysis could further aid in the identification of overloaded links, and subsequently in the identification of potential countermeasures.

3. Solution Methodology

Maritime oil transportation problem is a multiobjective problem that can be solved by most standard techniques used to solve multiobjective problems, such as goal programming, single objective approach, interactive approach, etc. While these techniques may be used to solve the oil transportation problem, interactive solutions are critical for transportation problems, where an end-user plays an integral role in obtaining a satisfactory solution [9].

The oil transportation problem considers both transportation and "expected" risk cost on each link of the maritime network. This problem could be reduced into a single objective problem obtained by assigning weights to the two objectives. Solving such a single objective problem implies that the same weights are assigned for every link, irrespective of the links location, the environmental sensitivities□surrounding the link, etc. However, this could be rather limiting, since the links of a maritime oil transportation network are spread throughout a large area with varying environmental sensitivities, and, hence, have radically different damage/impact costs. A more desirable choice would be to solve the problem in a manner that would apply appropriately customized tradeoffs between the transportation and risk costs for each link. We developed an interactive solution methodology, similar in principle to the one solve the maritime oil transportation problem. This solution methodology (*Interact*) will serve as the engine of the internet-based software package **IOTS**, described in the next section.

Let us define the following two subproblems:

Subproblem 1 ... **min** $z_1 = \sum_{(i,j)\in E} \sum_{p\in P} \sum_{k\in K} C_{ij}^{pk} X_{ij}^{pk}$, subject to (3), (4), & (5), whereas

subproblem 2 ... **min** $z_2 = \sum_{(i,j)\in E} \sum_{p\in P} \sum_{k\in K} R_{ij}^{pk} X_{ij}^{pk}$, subject to (3), (4), and (5).

An *ideal solution* to **(P)** would result in each objective simultaneously realizing its minimum. This is quite unlikely in practice, thus a compromise solution must be obtained. The *best compromise solution* can be defined as a one obtained at a feasible vector, which is considered to be 'closest' to the ideal solution by the decision-maker. This compromise solution must however be *nondominated*. A feasible vector $\hat{X}$ yields a nondominated solution to **(P)** if, there is no other feasible vector X such that

$$\sum_{(i,j)\in E} \sum_{p\in P} \sum_{k\in K} d_{ij}^{mpk} X_{ij}^{pk} \le \sum_{(i,j)\in E} \sum_{p\in P} \sum_{k\in K} d_{ij}^{mpk} \hat{X}_{ij}^{pk}, \quad m = 1,2 \qquad (7) \text{ and}$$

$$\sum_{(i,j)\in E} \sum_{p\in P} \sum_{k\in K} d_{ij}^{mpk} X_{ij}^{pk} \ne \sum_{(i,j)\in E} \sum_{p\in P} \sum_{k\in K} d_{ij}^{mpk} \hat{X}_{ij}^{pk}, \quad m = 1,2. \qquad (8)$$

where the penalty coefficients are: $d_{ij}^{mpk} = \begin{cases} C_{ij}^{pk} & m = 1 \\ R_{ij}^{pk} & m = 2. \end{cases}$

The decision-maker must follow the algorithmic steps of *Interact* are listed below:

1. Solve the two single objective subproblems and compute the two initial nondominated basic solutions of the form

$z_m = [z_1(x^*_m), z_2(x^*_m)]$ for m = 1,2

where x^*_m is the optimal extreme point for the mth subproblem.

2. Ask the decision-maker to decide upon the most preferred nondominated solution.

3. Decide if the solution obtained in the previous step is satisfactory.

If it is satisfactory, **STOP**.

Else proceed to Step 4.

4. Construct a compromise function $z'(x)$ as follows:

4a. Create a new penalty matrix (M_{ij}^{pk}) by:

$$M_{ij}^{pk} = w_{ij}C_{ij}^{pk} + (1-w_{ij})R_{ij}^{pk} \qquad \forall \text{i, j, p, k}$$

4b. Then $z'(x)$ is:

$$z'(x) = \sum_{(i,j)\in E}\sum_{p\in P}\sum_{k\in K} M_{ij}^{pk} X_{ij}^{pk}, \qquad (9)$$

The coefficients w_{ij} capture the relative weight that the user may want to place on the transportation and risk link costs; these coefficients are unique for each link of the network.

5. Determine the vector x' that minimizes (9) subject to (3), (4) and (5). This is a single objective transportation problem and can be solved by any standard algorithm.

6. If the decision-maker prefers $z(x')$ to at least one solution in the current set of nondominated solutions and x' is new, proceed to **Step 6a**, else proceed to **Step 6b**.

6a. Add $z(x')$ to the set of nondominated solutions, while deleting the least preferred solution from this set, and return to **Step 4**.

6b. The decision-maker identifies the most preferred solution from the set of nondominated solution, **STOP**.

Interact allows for this multiobjective problem to be solved by calling on CPLEX libraries, every time a linear problem needs to be solved. CPLEX is a commercially available optimization software package. The solution obtained in **Step 1** serves as a starting point for the overall solution by determining an initial set of nondominated solutions. The decision-maker then identifies a linear combination of the two objectives in **Steps 4** and **5**. **Steps 4-6** are iteratively repeated until the most preferred solution is identified. The methodology is capable of backtracking, since it can return the solutions that may have been removed in previous steps.

In order for the decision-maker to solve instances of **(P)**□ or quite possibly other multiobjective problems via *Interact*, an internet-based software tool□was developed known as **Interactive Oil Transportation Model (IOTS)**. The URL for **IOTS** is http:// hercules.eng.miami.edu/~yudhbir/iots.html. The software is written in *C* and runs on a Sun workstation running SunOS 4.1.3. The end-user/decision-maker has the flexibility of running the program over the World Wide Web site using any standard browser.

4. The Gulf of Mexico: A Case Study

An instance of the maritime oil transportation problem **(P)** for the Gulf of Mexico (Figure 1) is presented here for the representative year of 1996 as an exemplification. Risk and transportation costs are calculated for each arc of the maritime transportation network in the Gulf of Mexico. The spill data-set chosen here encompasses the time period of 1991-1995. This instance of problem **(P)** considers a shipping company with a fleet of 43 tank vessels (11 Afromax tankers, and 32 Suezmax tankers). A hypothetical schedule is further generated. Supply and demand data are collected for all of the appropriate ports in this network (Details are provided in Yudhbir[11]).

The problem was solved via **IOTS**. Simulating the role of a "regulator", a number of solutions were generated by choosing different weights to reflect the various tradeoffs between the transportation and risk costs for each arc on the network. Finally, a solution that best represents these tradeoffs is chosen by the regulator Using **IOTS**, several hypothetical scenarios were further generated to aid the regulator in understanding and improving the shipping operations. One such scenario is briefly presented below.

On August 10, 1993, a collision occurred at 6:00 A.M. in Tampa Bay between two inbound fuel barges and an outbound phosphate freighter. One of the barges leaked No. 6 fuel into the water, eventually spilling 300,000 gallons. The prevailing winds (S-SE up to 23 knots), combined with certain water conditions, drove the oil slick towards the shallow seagrass and mangrove islands. In order to account for the effects of this accident, risk contribution was calculated and incorporated into the risk costs of all the arcs of the transportation network in the Gulf of Mexico. Link (25,15) was the primary link affected by the accident. The spill effects on the link (25,15) are recalculated using the risk assessment methodology (Douligeris et al. [4] and Yudhbir [11]). A policy maker would potentially like to resolve **(P)**, taking into account the increase of risk cost on link (25,15). This new problem is then resolved using **IOTS**. In this post-spill solution, there is a considerable increase in the overall cost in the routing of the petroleum products, as compared to the overall cost of the routing prior to the spill. This increased link risk results in the significant rerouting of the products, as seen from the greater flows on links (14,25), (60,14) and (14,15) (Please refer to Yudhbir[11] for the detailed flows of petroleum products and crude oil).

The Tampa Bay area is a focal point for imports in Florida, with its share of spills in the past. The potential of spills remains high with an increase in demand. Problems are further aggravated by the limited number of links available to transport crude oil and petroleum products A major spill can potentially bring shipping operations to a halt in this area. Thus, a better understanding of the routing strategies is needed. A regulatory agency, such as the United States Coast

Guard may use **IOTS** to conduct various hypothetical analyses to further study the merit of alternative marine shipping policies.

5. Summary

We have presented the development of a medium-range strategic maritime oil transportation problem that addresses some of the issues and concerns raised by OPA'90. The maritime oil transportation problem is formulated as a multiobjective, multicommodity, multiple origin-destination, and a multimodal problem. The two objectives being considered here are the minimization of transportation and risk costs. An interactive solution methodology was presented along with a web-based decision support module: **IOTS. IOTS** could be linked in the future with a dynamic web-based database platform that synthesizes and updates risk and transportation marine data from various sources and users of the maritime system network.

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