Transportation Research Part D 37 (2015) 65–78

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

A bi-objective approach to routing and scheduling maritime transportation of crude oil

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ARTICLE INFO

Article history:
Available online 16 May 2015

Keywords:
Marine transportation
Crude oil
Routing
Scheduling
Hazardous materials

ABSTRACT

Maritime transportation, the primary mode for intercontinental movement of crude oil, accounts for 1.7 billion tons annually – bulk of which are carried via a fleet of large crude oil tankers. Although spectacular episodes such as Exxon Valdez underline the significant risk and tremendous cost associated with marine shipments of hazardous materials, maritime literature has focused only on the cost-effective scheduling of these tankers. It is important that oil transport companies consider risk, since the insurance premiums is contingent on the expected claim. Hence through this work, we present a mixed-integer optimization program – with operating cost and transport risk objectives, which could be used to prepare routes and schedules for a heterogeneous fleet of crude oil tankers. The bi-objective model was tested on a number of problem instances of realistic size, which were further analyzed to conclude that the cheapest route may not necessarily yield the lowest insurance premiums, and that larger vessels should be used if risk is more important as it enables better exploitation of the risk structure.

1. Introduction

Crude oil is procured from sources that are limited and dispersed around the world, and hence transportation over long distances is necessary. Maritime transportation, the primary conduit for intercontinental crude oil movement, accounted for 62% of world production for a quantity of 2.4 billion tons in 2005 (Rodrigue et al., 2009). The volume of crude oil shipments on marine networks, mostly carried on very large and ultra large crude carriers (i.e., VLCC and ULCC), is expected to increase – due in part to population growth, rapid industrialization, and elimination of trade barriers. These carriers belong to the largest classes of oil tankers with daily operating costs in the tens of thousands of dollars (Cheng and Duran, 2004), and the resulting planning problems are generally referred to as oil tanker routing and scheduling problems in maritime literature (Hennig et al., 2012). Although such problems have been studied over the past few decades, and we review the relevant works in Section 2, the resulting investigations focused only on cost.

A cost-only approach may not be appropriate for a hazardous material such as crude oil, since some of these shipments could lead to oil spills and occasional accidents resulting in significant environmental, social, and economic consequences. Two of the most prominent transportation-related oil-spill episodes are Exxon Valdez (United States) and Prestige (Spain), where the former necessitated a cleanup cost of over 2 billion dollars and the latter of around 100 million euros (ITOPF, 2009). Fortunately, such episodes are infrequent, although there are numerous occurrences of smaller spills – which could entail substantial

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http://dx.doi.org/10.1016/j.trd.2015.04.010
1361-9209/

cleanup costs (ITOPF, 2009). In response to the different oil-spill episodes, the International Maritime Organization (IMO) introduced the MARPOL regulations covering pollution of the maritime environment from operational or accidental causes (IMO, 2011), the European Union the Erika legislative package for maritime safety (EU Legislations, 2011), and the United States the 1990 Oil Pollution Act (Douligeris et al., 1997). While these regulations have necessitated the upgrading of fleet to prescribed standards (e.g. single to double hulled tankers) and the consideration of specified norms in tactical and operational decision making, interestingly, risk associated with oil-spill has not been explicitly incorporated in the intercontinental transportation domain. Note that such consideration is important because routing and scheduling decisions, while entailing huge operational costs, also result in significant oil-spill-related costs composed of cleanup, environmental damages, indemnification of other damages such as fisheries and tourism, and operational losses (Siddiqui and Verma, 2013). Hence, the risk stemming from oil-tanker movement on a given route deserves due attention, which is all the more important for international tankers – since 95% of the world's ocean tonnage is insured through membership in one of the 17 not-for-profit prevention and indemnity (P&I) clubs. Note that each member's (insurance) premium is established in accordance with the claims the member is likely to bring to the club (Jin and Kite-Powell, 1999). Furthermore, these insurances provide only limited liability coverage (IMO, 2013), i.e., not covering rare catastrophic events that lead mostly to bankruptcies. It is thus imperative for an oil transporter to be cognizant of the potential oil spill risks resulting from routing and scheduling decisions.

In this paper, we present a risk-cost based routing and scheduling framework for the case of a single oil supplier with multiple customers. The existence of alternative marine routes implies considering necessary cost and risk when making routing and scheduling decisions. For example, the crude oil suppliers in the Middle East having the option of using either the Suez Canal or going around the Cape of Good Hope to meet demand in North America and in Europe. Similar options are available for routing shipments from the South American ports in the Atlantic Ocean to ports in the Pacific Ocean either through the Panama Canal or around the South American coastline; and, the North East passage for moving goods between Europe and the Far Eastern countries. The proposed framework makes use of both the transportation risk and cost in routing and scheduling of crude oil shipments. It was observed that shorter (and less costly) routes may not necessarily be better from the perspective of risk, since the cost savings do not compensate for the increase in expected risk. It is important to highlight here that the transportation risks in the literature are defined in several different ways, e.g., it may be defined as simply the probability of accident or as some consequences (e.g. fatalities or damage related costs) (Erkut et al., 2007). We consider the most popular measure of risk, i.e., expected consequence defined as the product of probability and consequence, which also takes the form compliant with the IMO's Formal Safety Assessment guidelines (Siddiqui and Verma, 2013). It is important that consequence within the marine domain is usually measured and expressed as a composite of different types of costs (*viz.*, cleanup, environmental damages, and indemnification charges). We elaborate on the risk model and its measurement in Section 4.2.4.

The remainder of this paper is organized as follows. Section 2 provides an overview of the two most relevant streams of literature and highlights the absence of hazmat risk in the marine routing and scheduling works, and in turn sets the stage for the introduction of the problem of interest in Section 3. Section 4 presents the bi-objective model that aims to minimize both the operating cost and the transport risk (i.e., cost of oil-spill) across a given marine transportation network, and then outlines the parameter estimation techniques. Section 5 makes use of the existing marine network of one of the largest oil transportation companies for generating problem instances of the size encountered in real life, which are then solved using the proposed mathematical model. This section also reports the solution and provides a number of managerial insights on the marine routing and scheduling problem. We conclude the paper with some final remarks in Section 6.

2. Literature review

In this section, we review the most relevant streams of research. These bodies of literature include papers that focus on: routing and scheduling of oil tankers; and, maritime transportation of hazardous materials (hazmat).

The early research on routing and scheduling of oil tankers focused on the fuel oil transportation problem for the U.S. Navy. For this problem, Dantzig and Fulkerson (1954) presented an integer programming model that minimized the total number of tankers under a fixed oil supply schedule. The above problem was subsequently extended by Briskin (1966) who investigated full shipload demand for a cluster of ports, and then by Bellmore (1968) who studied the under capacity fleet situation. More recently, Brown et al. (1987) proposed an optimization model to solve a routing and scheduling problem faced by Chevron Shipping Company (CSC), a major oil firm with heterogeneous fleet. This study focused on crude oil shipment from the Middle East to Europe and to North America, and endeavored to determine the schedule for a given set of cargo. The CSC problem was also studied in Perakis and Bremer (1992) who proposed an integer programming formulation to schedule crude oil tankers, while the algorithmic details and test results from a realistic scheduling problem instance of CSC were presented in Bremer and Perakis (1992). Bausch et al. (1998) developed a decision support system that could be used to schedule the daily dispatch of liquid bulk products by ships and barges. Sherali et al. (1999) investigated the scheduling of a heterogeneous fleet of compartmentalized ships to transport a set of non-mixing cargo, and proposed a rolling horizon heuristic to solve the mixed-integer program. In a recent work, Kobayashi and Kubo (2010) studied the oil transportation problem in a tramp setting, i.e., a shipping company contracted to deliver a set of cargoes. The mathematical program, that involved local transportation of numerous petroleum products, was decomposed into two set partitioning problems of cargo pairing and tanker routing – and a column generation technique was proposed to solve it. In another standalone work, Kobayashi (2010) addressed a similar problem in a more strategic setting, i.e., long term planning and multiple planning stages, and proposed an approximate dynamic programming approach to solve the problem. Finally, there are three works that considered splitting a given demand into multiple shipments. McKay and Hartley (1974) proposed an integer programming formulation for oil tanker scheduling that permitted arbitrary splitting of ordered quantities. Their model, developed for the U.S. Defense, aimed at minimizing the cost of operations and fuel purchase at loading ports. Hennig et al. (2012) proposed a framework to solve maritime transportation of multiple grades of crude oil in the presence of both pickup and delivery time windows, and unpaired supply and demand quantities. Most recently, Siddiqui et al. (2013) proposed a mixed-integer program to solve the scheduling problem faced by an oil supplier of a single grade of crude with global customers, and supply-quota and port-capacity constraints.

It is interesting to note that although hazmat transportation has been a very busy research area over the past two decades, the focus has been mostly on highway and railroad transportation (Erkut et al., 2007). This is all the more surprising given the widespread use of maritime links to transport a whole variety of hazmat, including chemicals, crude oil, and petroleum products. The relevant works can be grouped under three threads: *risk* assessment; *spill-cost estimation*; and, *risk-based routing*.

One of the important pieces of work under the risk assessment domain was the development and the use of U.S. Natural Resource Damage Assessment Model for Coastal and Marine Environment proposed in Grigalunas et al. (1988), which in turn spurred a number of relevant works focused mostly in the Gulf of Mexico (Li et al., 1996; Iakovou et al., 1999; Yudhbir and Iakovou, 2001). Prince William Sound in Alaska, the site of Exxon Valdez episode, was the other location that received plenty of attention. To that end, Harrald et al. (1998) presented a risk assessment study that looked at human error in triggering tanker accidents, while Merrick et al. (2000) suggested measures to reduce the risk of spill from tanker accidents. In one of the few developmental efforts outside North America, Ulusçu et al. (2009) presented a model to calculate the total risk based on various geographical, meteorological, and traffic conditions, and proposed risk mitigation measures. Most recently, Siddiqui and Verma (2013) have proposed an expected consequence approach for assessing oil-spill risk from intercontinental transportation of crude oil. Finally, Martinez and Lambert (2010) presented a method to identify, screen and prioritize risks in marine transportation of liquefied natural gas (LNG), and Vanem et al. (2008a) outlined a generic and high-level risk assessment of LNG carriers.

Although oil-spill cost estimation has been an active research area within the maritime domain, we review just the notable works – and invite the reader to refer to Siddiqui and Verma (2013) for others. Etkin (1999) analyzed the oil-spill intelligence report international database to develop the basic estimates of area-wise cleanup cost, which were then revised to account for cleanup strategy, size of spill, oil type, and shoreline oiling (Etkin, 2000). Vanem et al. (2008b) revised the numbers presented in Etkin (1999) and identified three main types of damage costs, i.e., cleanup, environmental, and socioeconomic. Yamada (2009) made use of the international oil pollution compensation funds (ITOPF) database to propose a nonlinear regression model between total costs and weight of oil spill. This effort was followed by Kontovas et al. (2010) who considered current prices and removed outliers thereby improving the correlation coefficient between the dependent and independent variables, and then by Psarros et al. (2011) who tested the model on data collected from two separate databases.

Finally, a number of studies with risk consideration in routing marine traffic through the Gulf of Mexico were funded by the United States Coast Guard in response to the 1990 Oil Pollution Act in the United States. To that end, Douligeris et al. (1997) developed a national marine oil transportation system model that could be used to quantify oil movement within the geographic boundaries of the United States. Li et al. (1996) developed a comprehensive model for the marine oil transportation in the Gulf of Mexico, which could solve the oil flow distribution in a multimodal and multiproduct network, and also be used by regulatory agencies to evaluate alternate routing strategies. In a subsequent work, the above idea was expanded to include multiple O-D hazmat routing planning for the Gulf of Mexico (Iakovou et al., 1999). Finally, Iakovou (2001) presented a strategic interactive multi-objective network flow model that allowed for risk analysis and routing, which again was intentioned to help regulators assess risk and derive desirable routing schemes.

3. Problem description

In this section, we briefly discuss the managerial problem of interest and then outline the basic modeling assumptions.

At a higher level, the managerial problem involves determining efficient routes and schedules, for a set of heterogeneous crude oil tankers, to meet customer demands over a pre-defined planning horizon. Hence, this would translate into a tactical planning problem of an industrial shipping firm (Christiansen et al., 2007). Furthermore, each customer demand for a specific period is represented by a quantity and a delivery time-window. Finally, a number of delivery periods constitute the planning horizon of interest, which would start with the receipt of orders and end when all demand time-windows are covered. Although most crude oil companies face such problems when preparing routes and schedules for a heterogeneous fleet of tankers (i.e., industrial shipping firm that owns the cargo, and either owns or has a long-term contract on the vessels) to connect various supply and demand locations, their objective is to minimize cost. But as alluded earlier, it is important that these medium-term routing and scheduling decisions also take into consideration hazmat-risk, which could be captured through a composite estimate, e.g., cost of oil-spill. Note that these risk estimates, expressed as dollars, could be used as a surrogate of risk for negotiating insurance premiums between an oil transporter and the not-for-profit P&I clubs – which would stem directly from the type of tanker and the route. Hence, the managerial problem is to determine the best routes and schedules for a fleet of heterogeneous crude oil tankers such that the transport cost and the transport risk are minimized for the given set of demand over the specified planning horizon.

To make this more explicit, assume a number of customer locations, indexed by d, with different demands in each period. For example, $Q^{d(i)}$ refers to the quantity of crude oil demanded at location d in period i, which has to be serviced using the available vessels (routes). Note that in Fig. 1 there are two customer locations, and that each has two requirement periods. Hence, the planning horizon for this problem is just two periods. Finally, the three vessels become available for service at different times due to their prior commitments.

Before outlining the mathematical program in the next section, we list the six assumptions pertinent to the managerial problem outlined above. *First*, demand for each period is known at the start of planning horizon. *Second*, all relevant cost and risk parameters are known (estimated). *Third*, each tanker picks up its cargo from a single supply source and delivers the entire shipment to a single demand location. *Fourth*, no return cargoes are allowed. *Fifth*, a heterogeneous fleet of owned tankers of various classes is available, which could only operate on compatible routes and serve capable ports. For example, a fully-laden very large crude carrier (VLCC) cannot go through the Suez Canal. *Sixth*, tankers are not forced to return to the supply point within the planning horizon, and that they become available for service at different times due to prior commitments. *Seventh*, only one supply source is available. This is to tide over the operational issues, such as congestion and berthing sequence, associated with a cluster of ports in close proximity. Note that it is not uncommon to find a number of oil-supply ports in close proximity to each other, especially in the Middle East – which we further elaborate on in Section 5.

4. Model development

In this section, we first outline the bi-objective optimization model, and then discuss the parameter estimation technique.

4.1. Bi-objective model

Before outlining the model, we define four terms that are integral to the formulation. First, a *route* refers to a complete path followed by a tanker, i.e., travel from the supply to the demand point, and the return to the supply point. Second, a *voyage* refers to all elements of a journey. For example, waiting for and loading at the supply source, travel to and unloading at the demand location, and travel back to the supply point. Third, *loaded-leg* means the partial voyage until a tanker unloads cargo at a demand location. Fourth, *ballast* refers to the movement of empty tanker from the demand location to the supply point.

Sets and indices

D Set of customer locations, indexed by d
V^d Set of vessels compatible with customer location d, indexed by v
W_v^d Set of routes available for vessel v to serve customer location d, indexed by w
I Number of demand periods at a customer location, indexed by i
j An index to keep track of the trip number for a vessel

Decision variables

$$X_{v(j),w}^{d(i)} \quad \begin{cases} 1 & \text{if vessel } v \text{ on } j\text{th trip uses route } w \text{ to deliver oil to customer location } d \text{ in period } i \\ 0 & \text{otherwise} \end{cases}$$

$B_{v(j)}$ Waiting time for vessel v before starting the jth trip
$\underline{T}_{v(j)}$ Time when vessel v completes loaded-leg on the jth trip
$\overline{T}_{v(j)}$ Time when vessel v completes the voyage on the jth trip

Parameters

$C_{v,w}^d$ Cost to deliver to customer location d using vessel v on route w
$R_{v,w}^d$ Risk to deliver to customer location d using vessel v on route w
$Q^{d(i)}$ Quantity of crude demanded at customer location d in period i
$K_{v,w}^d$ Cargo carrying capacity of vessel v on route w when serving customer location d[1]
A^d Percentage of flexibility on periodic requirement at customer location d
M_v Waiting (idling) cost per unit time for vessel v
$L_{v,w}^d$ Time needed by vessel v to reach customer location d using route w
$E_{v,w}^d$ Time needed by vessel v to return from customer location d (i.e., empty) using route w
N_v Time until vessel v is available for service for the first time at the supply port
L_v Time needed to load vessel v
U_v^d Time needed to unload vessel v at customer location d
$\underline{S}^{d(i)}$ Start of delivery time-window at customer location d in period i
$\overline{S}^{d(i)}$ End of delivery time-window at customer location d in period i
τ Maximum number of allowable trips in a planning horizon

[1] Note that cargo carrying capacity of a crude oil tanker is a function of the route length, since as the loading requirement for bunker fuel and other operational supplies increase – the cargo carrying capacity decreases.

(**P**)
Minimize

$$\begin{aligned} &Cost: \sum_{v\in V^d}\sum_{1\leqslant j\leqslant\tau}\sum_{d\in D}\sum_{i\in I}\sum_{w\in W_v^d} C_{v,w}^d X_{v(j),w}^{d(i)} + \sum_{v\in V^d} M_v\left(\sum_j B_{v(j)}\right) \\ &Risk: \sum_{v\in V^d}\sum_{1\leqslant j\leqslant\tau}\sum_{d\in D}\sum_{i\in I}\sum_{w\in W_v^d} R_{v,w}^d X_{v(j),w}^{d(i)} \end{aligned} \tag{1}$$

Subject to:

$$\sum_{v\in V^d}\sum_{w\in W_v^d}\sum_{1\leqslant j\leqslant\tau} K_{v,w}^d X_{v(j),w}^{d(i)} \geqslant Q^{d(i)}(1-A^d) \quad \forall d\in D, \forall i\in I \tag{2}$$

$$\sum_{w\in W_v^d} S^{d(i)} X_{v(j),w}^{d(i)} - M\left(1-\sum_{w\in W_v^d} X_{v(j),w}^{d(i)}\right) \leqslant T_{v(j)} \forall v\in V^d, 1\leqslant j\leqslant\tau, \forall d\in D, \forall i\in I \tag{3a}$$

$$T_{v(j)} \leqslant \sum_{w\in W_v^d} \overline{S}^{d(i)} X_{v(j),w}^{d(i)} - M\left(1-\sum_{w\in W_v^d} X_{v(j),w}^{d(i)}\right) \forall v\in V^d, 1\leqslant j\leqslant\tau, \forall d\in D, \forall i\in I \tag{3b}$$

$$T_{v(1)} = N_v + B_{v(1)} + \sum_{d\in D}\sum_{i\in I}\sum_{w\in W_v^d}\left(L_v + L_{v,w}^d + U_v^d\right) X_{v(1),w}^{d(i)} \quad \forall v\in V^d \tag{4}$$

$$T_{v(j)} = \overline{T}_{v(j-1)} + B_{v(j)} + \sum_{d\in D}\sum_{i\in I}\sum_{w\in W_v^d}\left(L_v + L_{v,w}^d + U_v^d\right) X_{v(j),w}^{d(i)} \quad \forall v\in V^d, 2\leqslant j\leqslant\tau \tag{5}$$

$$\overline{T}_{v(1)} = T_{v(1)} + \sum_{d\in D}\sum_{i\in I}\sum_{w\in W_v^d} E_{v,w}^d X_{v(1),w}^{d(i)} \quad \forall v\in V^d \tag{6}$$

$$\overline{T}_{v(j)} = T_{v(j)} + \sum_{d\in D}\sum_{i\in I}\sum_{w\in W_v^d} E_{v,w}^d X_{v(j),w}^{d(i)} \quad \forall v\in V^d, 2\leqslant j\leqslant\tau \tag{7}$$

$$\sum_{d\in D}\sum_{i\in I}\sum_{w\in W_v^d} X_{v(j),w}^{d(i)} \leqslant 1 \quad \forall v\in V^d, 1\leqslant j\leqslant\tau \tag{8}$$

$$\sum_{d\in D}\sum_{i\in I}\sum_{w\in W_v^d} X_{v(j),w}^{d(i)} \leqslant \sum_{d\in D}\sum_{i\in I}\sum_{w\in W_v^d} X_{v(j-1),w}^{d(i)} \quad \forall v\in V^d, 2\leqslant j\leqslant\tau \tag{9}$$

$$X_{v(j),w}^{d(i)} \in \{0,1\} \quad \forall v\in V^d,\ \forall w\in W_v^d, 1\leqslant j\leqslant\tau,\ \forall d\in D,\ \forall i\in I \tag{10}$$

$$B_{v(j)} \geqslant 0 \quad \forall v\in V^d, 1\leqslant j\leqslant\tau \tag{11}$$

$$L_{v(j)} \geqslant 0 \quad \forall v\in V^d, 1\leqslant j\leqslant\tau \tag{12}$$

$$E_{v(j)} \geqslant 0 \quad \forall v\in V^d, 1\leqslant j\leqslant\tau \tag{13}$$

M is a large positive integer.

(**P**) is a mixed-integer bi-criteria optimization model with cost and risk objectives. The first set of terms in (1) represent the cost of routing shipments from the only supply source to the different customer locations and the waiting (idling) cost at the supply port, while the corresponding risk of oil-spill is captured in the second set of terms.

Constraints set (2) ensure that the total committed delivery capacity (not quantity) to customer location d in period i equals or exceeds the requirement. Note that tanker capacities are a function of both the customer location and the route, and that the choice of route depends on the compatibility of a vessel with the characteristics of a given route. For example, a fully laden VLCC cannot go through the Suez Canal. A common practice in crude oil supply contracts is to allow a range within which actual quantity can be delivered (Sherali et al., 1999). The specified percentage allowance, A^d, in fact facilitates better utilization of tanker capacities since the actual delivery amount need not be exactly equal to the demand in that period. It is important to note that the proposed model will deliver a set of vessels with sufficient total capacities, which the transport manager would use to meet demand during a given time period by distributing the ordered quantities amongst the recommended vessels.

Constraints sets (3)–(7) are concerned with delivery time windows, and the impacted variables. (3) ensure that vessel v on the jth trip makes a delivery at customer location d in period i – only if it can do so feasibly, i.e., $X_{v(j),w}^{d(i)} = 1$, only if the corresponding $T_{v(j)}$ is feasible within the relevant time window. The relationship between $X_{v(j),w}^{d(i)}$ and the corresponding $T_{v(j)}$ is established via the next four constraints. More explicitly, (4) estimates the time until vessel v finishes its first loaded-leg, while (5) represents vessel availability for all other used trips. (6) and (7) estimate the time when voyage ends

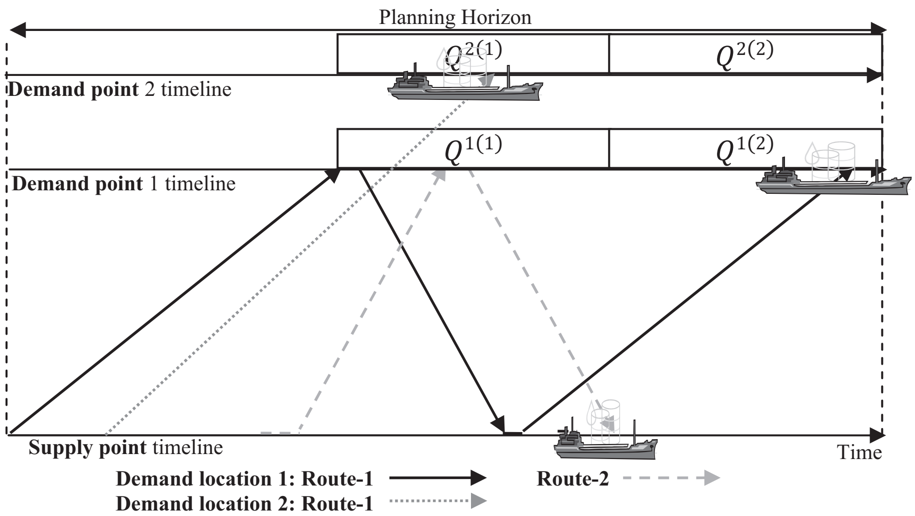

Fig. 1. Movement of vessels between supply and demand locations.

for a vessel, which is fed into (5) for determining availability. It should be clear that travel times are a function of the route a tanker would take. Finally, we have defined τ as the maximum number of allowable trips during a planning horizon, which will serve as an upper bound on the number of possible trips for a vessel.

Constraints sets (8) and (9) ensure the structural integrity of the problem. (8) ensures that vessel v on the jth trip makes a single delivery of the entire cargo, while (9) would make sure that a vessel embarks on trip j only if it has finished trip $j-1$. Finally, the sign restrictions are enforced through (10)–(13).

4.2. Parameter estimation

For each vessel, four sets of parameters have to be estimated, and they are: capacity; operating cost; travel time; and, risk for each route.

4.2.1. Capacity

As indicated earlier, the capacity of a vessel varies with both the customer location and the route to get there. For example, if H^d represents the maximum weight a vessel can carry to customer location d, and $\overline{K}_{v,w}$ the maximum carrying capacity of vessel v on route w, then $K^d_{v,w} = \min\{H^d, \overline{K}_{v,w}\}$.

4.2.2. Cost

Since daily operating costs of oil tankers are a function of bunker fuel prices that exhibits significant fluctuation (Devanney, 2013), we have used a rule-of-thumb. For loaded-leg, we assume that daily operating cost is 4% of capacity of a vessel on loaded-leg. For example, if the capacity is 317,129 tonnes, then the daily operating cost is around $12.7 K. On the other hand, ballast-leg will cost 80% and idling 10% of the daily amount for loaded-leg.

4.2.3. Time

We assume vessel speed between 14 and 16 knots for loaded-leg, and a knot higher on ballast-leg (MAN, 2011). It is important to note that the loading and unloading time could vary between 24 h and 72 h depending on the number of pumps and the vessel capacity (Baltic, 2013), and hence we assume one day for each type of operation.

4.2.4. Risk

Risk was estimated using the assessment methodology developed in Siddiqui and Verma (2013), which is compliant with the Formal Safety Assessment guidelines of IMO. As indicated earlier, expected consequence – defined as the *probability of accident* times the resulting *consequence* – has been used to measure transport risk incurred by oil tankers. This measure, also called the traditional risk, has been used to evaluate transport risk of highway and railroad shipments (Erkut and Verter, 1995; Verma, 2009).

In an effort to propose a methodology consistent with the safety assessment framework of the International Maritime Organization (IMO), Siddiqui and Verma (2013) have grouped oil spills into two categories: *minor* (i.e., $\leqslant$7 tonnes), and *major*. Now, consider a tanker route-link l (a homogeneous segment of the route) of known length (Fig. 2). If p^M_l and p^m_l are the probabilities of a tanker meeting with an accident, resulting in major $\left(S_l^M\right)$ or minor spills (S_l^m), respectively, on link l, then the transport risk posed by this tanker over link l can be represented by

$$R_l = p_l^M S_l^M AC_l^M + p_l^m S_l^m AC_l^m \tag{14}$$

where AC_l^* is the adjusted per unit oil-spill cost for link l. It should be clear that transport risk for a route composed of links l and $l+1$ is a probabilistic experiment, since the expected consequence for link $l+1$ depends on whether the tanker meets with an accident on link l. The expected consequence for link $l+1$ is $(1-p_l^M)\left(p_{l+1}^M S_{l+1}^M AC_{l+1}^M + p_{l+1}^m S_{l+1}^m AC_{l+1}^m\right)$. In general, the risk of a route will be the sum of expected consequence over all the links.

In (**P**), a route is defined as the journey from the supply point to the customer location and back, where the links used for loaded-leg could be different than those used for ballast-leg. Furthermore, while both crude oil and bunker fuel pose risk on the loaded-leg, ballast-leg carries just the bunker fuel. Hence, if the loaded-leg can be divided into y homogeneous links, and the index for ballast-legs runs from $y+1$ to z, the expected consequence for route w being used by vessel v to customer location d can be expressed as:

$$R_{v,w}^d = R_{v,w(1)}^d + \sum_{g=2}^{y}\left(R_{v,w(g)}^d \prod_{f=2}^{g}\left(1-p_{f-1}^M\right)\right) + \sum_{g=y+1}^{z}\left(R_{v,w(g)}^d \prod_{f=2}^{g}\left(1-p_{f-1}^M\right)\right) \tag{15}$$

where the first term represents the risk of oil-spill on the first link of the loaded-leg and the second that associated with the remaining links, while the third indicates the transport risk from bunker fuel (i.e., ballast-leg). Note that although Eq. (15) can be used in this manner to estimate risk of oil-spill for any route and vessel, it requires information on probability of accident, spill size, and adjusted cost-of-spill per tonne. It is pertinent to indicate that oil spill incidents can occur due to varying causes including vessel collision, grounding, non-accidental structural failures, or fire and explosion, and that the actual spill profiles or discharge rates may vary (Eliopoulou and Papanikolaou, 2007). However, it is important to note that the publicly available data is not very detailed (i.e., cause of spill and resulting volume) even on a global scale, and almost impossible for specific links. Thus, we consider accident probabilities and spill scenarios at an aggregate level but note that the proposed methodology will yield more accurate results if detailed data were available. Next, we briefly outline the estimation technique for the three parameters, and invite the reader to refer to Siddiqui and Verma (2013) for all relevant details.

4.2.4.1. Probability of accident: Oil-spill statistics from 1974 to 2010 was parsed, and the around 1200 relevant data points representing major spill were coded on a maritime map comprised of Marsden squares, which are physical spaces defined by 10° each of longitude and latitude. The number of accidents resulting in major spills was divided by the total number of tanker voyages through a given square to yield the respective probability. Probability of minor spill on the other hand was calculated by: first determining the probability of a major spill for a square (or a link) with identical flow density; and then prorating the average probability using the historical split of 0.81 and 0.19 for minor and major spills, respectively.

4.2.4.2. Size of oil-spill: We assume loss of entire cargo for major spills, and hence $p_l^M = K_{v,w}^d$ for the loaded-leg, and the amount of bunker fuel for the ballast-leg. It is important to note that the full loss scenario entails the most conservative approach for a decision maker and alternative approach, e.g., average spill size can be used (Siddiqui and Verma, 2013). Such conservative approach is reasonable not only because such rare events are not covered by insurance, but also due to the associated socio-economic, political and environmental significance. For minor spills, we assume the threshold value of 7 tonnes. Doing so enables us to also consider scenarios where the loss of the entire cargo is less likely, in part necessitated by the categorization of the spill profile data.

4.2.4.3. Cost of oil-spill: Although Siddiqui and Verma (2013) have presented results using four of the most popular spill-cost estimation models available in maritime literature, it was demonstrated that using the only linear model by Etkin (1999) together with the nonlinear model of Psarros et al. (2011) may be enough to get meaningful results. To elaborate, using Etkin (1999), the cost of oil-spill for a given link l on route w for vessel v to destination d is:

$$R_{v,w(l)}^d = p_l^M S_l^M AC_l^M + p_l^m S_l^m AC_l^m \tag{16}$$

where $AC_l^* = 2.5C_l^* \times (SLO \times OT \times CT \times SS_l)$; and C_l^* is the cleanup cost associated with the given type (i.e., major or minor) on link l. Furthermore, OT is the oil-type; SS the spill size; SLO the shoreline oiling; and, CT the cleanup strategy. This model has been critiqued for failing to capture the nonlinear relationship between spill size and per unit spill cost, and does not estimate the total cost. On the other hand Psarros et al. (2011) capture these elements but ignore to account for location, oil type, and cleanup strategy. The exact expression using Psarros et al. (2011) is:

$$R_{v,w(l)}^d = \left\{p_l^M \times \left(S_l^M\right)^{0.6472} + p_l^m \times \left(S_l^m\right)^{0.6472}\right\} \times 61,150 \tag{17}$$

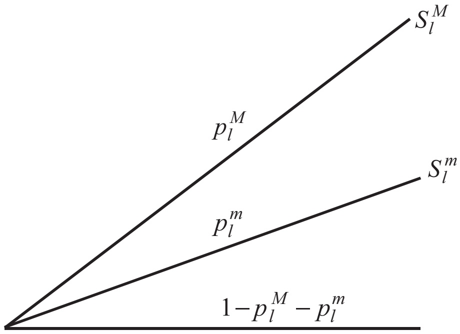

Fig. 2. Spill events on link l.

For expositional reasons, we invite the reader to refer to Siddiqui and Verma (2013) for all other relevant details. However, we use both Etkin (1999) and Psarros et al. (2011) for estimating the cost of oil-spill in (**P**).

5. Computational experiments

In this section, we use the proposed mixed-integer program to solve 64 problem instances (i.e., 32 using each of the two cost of oil-spill estimation techniques) to develop managerial insights that could help decision makers prepare routes and schedules for crude oil tankers. We ground the model parameters in a real-life problem setting involving Saudi Aramco – the largest producer and exporter of crude oil, which is described in §5.1. In §5.2, we provide the detailed solution of the proposed problems and in §5.3, we report on our analyses conducted on the instances generated on this problem setting. Finally in §5.4, we sketch the impact of the proposed approach on insurance premiums.

5.1. Problem setting

Fig. 3 represents the routes used by Vela International Marine Limited (www.vela.ae), the wholly owned subsidiary of Saudi Aramco, whose primary responsibility is to deliver crude oil to customers in North America and in Europe. There are two routes to both the demand locations, one through the Suez Canal and the longer one around Africa. While the shorter route is 6792 and 3803 nautical miles to North America and Europe, respectively, the longer one is 12,084 and 6393 to the two demand locations. Note that since Saudi Aramco runs most of its operations from a cluster of ports, which are in close proximity of each other in the Persian Gulf, we treat the cluster as a single supply source. Similarly, there may be a cluster of drop-off points both at the North American (Gulf of Mexico) and European locations. This clustering of points permits solving larger problems (larger fleet) while studying the underlying behavior of the basic problem. Vela maintains a heterogeneous fleet of tankers including VLCC, Suezmax and Aframax. We have assumed that Vela has a total of 30 tankers (10 of each type), whose capacities and average speeds are indicated in Table 1. Finally, demand data for oil imports from Saudi Arabia was approximated from the U.S. Energy Information Administration database (www.eia.gov), and one-quarter of that was assumed as the demand for Europe (Table 2).

5.2. Solution of the illustrative problem

Two of the most common techniques for solving multi-objective models, such as (**P**), are preemptive optimization and weighted sums (Rardin, 1998; Verma et al., 2011). The former calls for a sequential solution process, while the latter associates weights to different objective values. We pose the routing and scheduling problem from the perspective of the oil transport company, who is interested in minimizing not just the operating costs but also the expected costs of oil-spills. Although we associate equal weights to both the cost and the risk objectives to solve the realistic problem instance referred to as the base-case, we also report in §5.3.1 on a parametric analysis performed by attaching different weights to the two objectives. It is important to reiterate that the cost of oil-spill models proposed by both Etkin (1999) and Psarros et al. (2011) were used to solve each of the 11 problem instances, and hence a total of 22 problem instances were solved. CPLEX Optimizer 12.1 (IBM, 2010) was used to solve (**P**), while the input files were generated using MATLAB (Mathworks, 2004). The base-case of (**P**) contained 1782 variables, including 1600 binary variables, and 1180 constraints.

Table 3 provides a snapshot of the base-case solution. With Etkin's oil-spill model as the input, (**P**) could be solved in 1000 s within half a percentage of the optimum solution, with an operating cost of \$9.4 mn and a risk of \$693 mn. On the other hand with the oil-spill framework proposed in Psarros et al. (2011), (**P**) could be solved to optimality much faster for a comparable operating cost of \$9.6 mn but a significantly lower risk of \$119 mn. The large discrepancy in the risk numbers is because in Etkin's model the cost of oil-spill varies linearly with the spill volume, and hence the resulting values could be inflated (Siddiqui and Verma, 2013). Note that our assumption regarding loss of entire lading is resulting in risk values

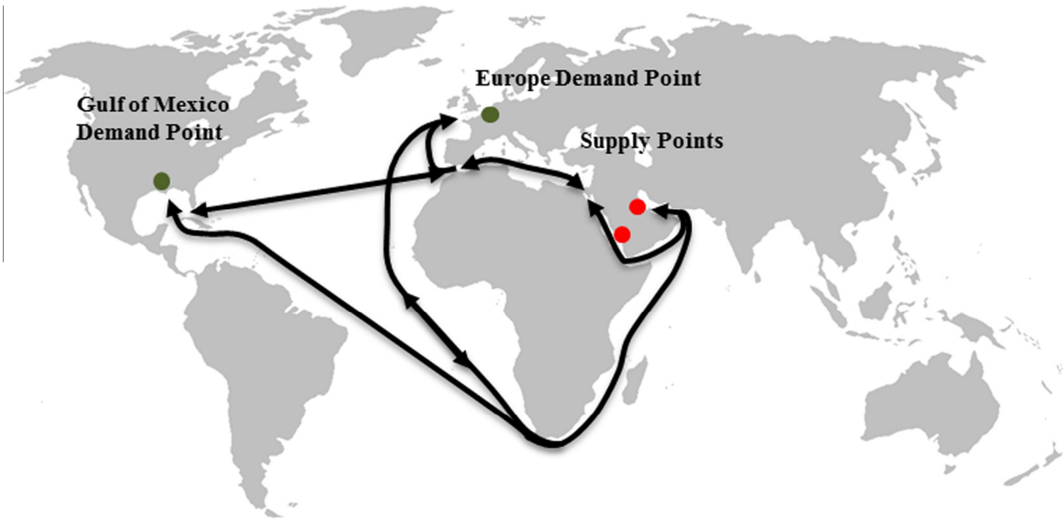

Fig. 3. Primary routes of Vela.

Table 1
Vela fleet.

VLCC		Suezmax		Aframax	
Capacity (DWT)	Speed (knots)	Capacity (DWT)	Speed (knots)	Capacity (DWT)	Speed (knots)
317.1	14.8	200	15.3	120	15.3
317.1	14.4	200	15.8	120	15.8
317.1	14.1	200	15.0	120	15.0
317.1	14.2	150	16.0	120	16.0
301.6	15.7	150	14.7	120	14.7
301.2	14.7	140	15.1	85	15.1
301.6	14.9	140	14.4	85	14.4
301.6	15.8	140	15.0	85	15.0
301.5	14.5	130	14.8	85	14.8
301.9	15.7	130	15.3	85	15.3

Table 2
Crude oil imports (in kilo-tonnes).

Demand location	Week 1	Week 2	Week 3	Week 4
United States	1174.6	466.0	1000.8	1140.2
Europe	293.70	100.8	216.40	246.60

much higher than the operating cost, which implies that risk is dominating the solution. To this point, note that all the tankers are using the longer route around Africa to serve the two demand locations – since this route has lower risk than the one through the Suez Canal. It is also clear that Etkin's model prefers smaller ships thereby requiring more trips, while Psarros et al. attempts to exploit the non-linearity of cost of oil-spill by using all the VLCC class tankers. For example, based on Etkin's model, eighteen of the twenty-four trips are made to North America – of which twelve are carried out by the Suezmax and the Aframax tankers. On the other hand, using Psarros et al. (2011), fifteen of the twenty-one trips being made to North America – of which only six are carried out using the two non-VLCC class tankers. Hence, under the latter setting, traffic from six non-VLCC tankers is shifted to three additional VLCC tankers. Finally, most of the VLCC tankers are being used to service demand in North America, because doing so facilitates exploitation of both the cost and the risk economies of scale. For instance, of the seven VLCC tankers being used under Etkin (1999) – six are operating on the North American route, and nine of the ten for Psarros et al. (2011).

5.3. Managerial insights

In this subsection, we will conduct a risk-cost analysis of the realistic problem instance; and, parametric analysis on the composition of fleet to gain managerial insights into the problem.

Table 3
Base-case solution.

Spill-model	$ million		Type of tanker		Number of trips	Africa route	CPU time	Gap %
	Cost	Risk	VLCC	Others			Seconds	
Etkin	9.4	693	7	17	24	24	1000	0.28
Psarros et al.	9.6	119	10	11	21	21	24.3	0.00

5.3.1. Risk-cost analysis

To explore trade-offs between cost and risk, 20 additional problem instances, corresponding to weight combinations between (1,0) and (0,1) by increments of 10%, but excluding the (0.5,0.5) base-case, were solved. For expositional reasons, we report and analyze the results based on Etkin (1999), and comment on any exceptions observed when using Psarros et al. (2011). In general, all the ten additional problem instances using Etkin's linear model were within a gap of 1.2% of the optimum solution in 1000 s of computing time, whereas all problem instances could be solved to optimality in less than 50 s for the non-linear model.

Each row in Table 4 (and each point in Fig. 4) represents a non-dominated solution, with *min cost* and *min risk* constituting the two extremes. While the *min cost* solution results in maximum risk (i.e., cost of oil-spill), the *min risk* solution entails one of the highest costs. It was interesting to note that there were only four distinct solutions across the 11 problem instances, and five when using Psarros et al. (2011). For expositional reasons we have grouped similar solutions, and used legends to refer to the group. For example, legend *III* refers to the group that contains two solutions: base-case; and, when cost has 60% of the weight. It is important to note that under the *min cost* all the non-VLCC tankers are using the Suez Canal, which results in shorter and hence cheaper routes. It should be clear that fully-laden VLCC tankers are too big to use the Suez Canal, and hence have to go around Africa. On the other hand, even a 10% weight on the risk objective forces most of the traffic from the Suez Canal to the longer route around Africa. For example, nineteen of the twenty-four trips under legend *II* and all the trips under legends *III* and *IV* use the longer but less risky route. This implies that using longer but less risky route for crude-oil tankers may be worthwhile, if doing so could translate into a reduction in the (expected) insurance premiums to be paid to the P&I clubs. For instance, the *min risk* solution is $1.4 mn more than the *min cost* solution, though the reduction in expected cost of oil-spill is around $280 mn.

Min cost solution, using the cost of oil-spill model of Psarros et al. (2011), was exactly the same as that for Etkin (1999), except the risk value which was substantially lower (i.e., $180.4 mn v/s $974.3 mn). In general, it was noticed that the number of VLCC used was much higher, since the nonlinearity of the cost of oil-spill favored using bigger vessel – thereby reducing the number of trips. For example, nine of the ten problem instances (i.e., excluding *min cost*) used twenty-one trips – of which ten were completed using VLCC tankers. This is different than the values in Table 4 (i.e., only seven of the twenty-four trips were completed by VLCC tankers), because there is incentive in sending higher volume of crude oil since the cost of oil-spill increases at a decreasing rate with volume. Hence, in general, other factors being constant Psarros et al. (2011) would favor using VLCC while Etkin (1999) would prefer smaller tankers.

5.3.2. Scaled parameters

It is clear from §5.2 and §5.3.1 that risk (i.e., cost of oil-spill) dominates operating cost in all instances, except when risk carries zero weight. In an effort to get an unbiased insight into the Vela problem, we used the ratio of average routing cost to average routing risk to scale the risk coefficients, and solved 10 resulting problem instances. Table 5 depicts the solution using Etkin's (1999) cost of oil-spill model, and we note that similar results were obtained using the model proposed in Psarros et al. (2011).

It is interesting to compare the base-case without and with scaled risk parameters, which are depicted in Tables 4 and 5, respectively. Without scaling, a total of twenty-four tankers including seven VLCC were being used, while the equivalent numbers are twenty-six and six with scaling. In addition, all the twenty-four tankers were using the longer but less risky route without scaling, whereas only the six VLCC tankers are using that route with scaling thereby necessitating using more non-VLCC class tankers. Note that both these results underline the dominance of risk and hence the need for scaling. Now with scaling, the routes for both the Suezmax and Aframax class tankers are truly being determined by the weighted combination of both the operating cost and the transport risk. Finally, note that all the tankers are using the Africa route only under the *min risk* setting (Table 5), although without scaling, this phenomenon was exhibited with as low as 10% weight on risk (i.e., Table 4).

5.3.3. Vessel mix

In an effort to get an understanding of the fleet-mix impact on routing, we solved 32 problem instances using the cost of oil-spill models of Etkin (1999) and Psarros et al. (2011). For consistency, we report the results for the 16 problem instances obtained using the former approach, and note that similar results were found for the latter.

Table 6 depicts the snapshot of the results obtained when the base-case problem instance was solved with different fleet-mix using Etkin (1999). For this part of the analysis we have assumed 300 K DWT to be the capacity of a VLCC, 150 K DWT for a Suezmax, and 120 K DWT for an Aframax tanker. For example, in the 3rd scenario, eight VLCC tankers would

Table 4
Risk-cost numbers using Etkin (1999).

Legends		$ million-s		Number of VLCC	Other tankers	Africa route
		Cost	Risk			
I	*Min cost*	8.03	974.33	6	20	6
II	*A* = [*cost* = 0.9, *risk* = 0.1] *B* = [*cost* = 0.8, *risk* = 0.2] *C* = [*cost* = 0.7, *risk* = 0.3]	9.14	693.39	7	17	19
III	*D* = [*cost* = 0.6, *risk* = 0.4] *Base case*	9.38	692.95	7	17	24
IV	*E* = [*cost* = 0.4, *risk* = 0.6] *F* = [*cost* = 0.3, *risk* = 0.7] *G* = [*cost* = 0.2, *risk* = 0.8] *H* = [*cost* = 0.1, *risk* = 0.9] *Min risk*	9.42	692.91	6	19	25

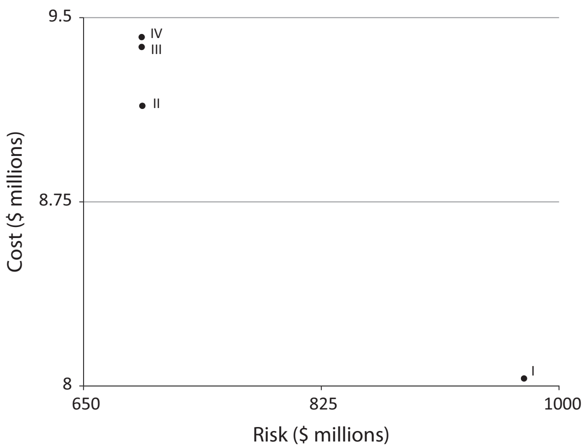

Fig. 4. Weight-based solutions using Etkin (1999).

Table 5
Solution with scaled risk and using Etkin (1999).

Legends	$ millions		Number of VLCC	Other tankers	Africa route
	Cost	Risk			
Min cost	8.03	974.33	6	20	6
A′ = [*cost* = 0.75, *risk* = 0.25]	8.38	732.20	6	20	6
Base case	8.71	699.49	6	20	6
B′ = [*cost* = 0.25, *risk* = 0.75]	8.72	698.72	7	18	7
Min risk	9.42	692.91	6	19	25

provide 2.4 mn DWT of capacity, whereas the eight Suezmax and twelve Aframax tankers would provide another 2.4 mn DWT. A total of twenty-five trips were made – including eight each by VLCC and Suezmax, and nine by Aframax, which translates into a fleet utilization of 53% for VLCC and 47% for non-VLCC class tankers. All trips are being made using the longer route around Africa, for a total operating cost of $9.71 mn and an expected risk of $711.04 mn. It is important that (**P**) makes every effort to utilize every available VLCC, roughly double in capacity to the other two tanker classes, since that would result in lower operating cost and expected risk. To this point, the resulting ratio between actual and available capacity is in favor of VLCC class tankers.

Finally, 24 additional problem instances were solved by varying both the fleet-mix and the emphasis being placed on the two objectives. For expositional reasons, we report the results obtained using Etkin (1999) for just the 3rd scenario for min cost; min risk; and, when risk carries 5% weight (Table 7). To recall, we are assuming eight VLCC; eight Suezmax; and, twelve Aframax tankers. As expected, the *min cost* solution is the least expensive since most of the tankers are using the shorter, but riskier, route through the Suez Canal to meet demand at both customer locations, which in turn is resulting in high expected risk. On the other hand the *min risk* solution, exactly the same as the base-case solution, utilizes the eight VLCC tankers

Table 6
Impact of vessel-mix for base-case and using Etkin (1999).

Fleet-mix scenarios	Vessel type: number	Capacity ratio available/used	Number of trips	Africa route US; Europe	$ millions	
					Cost	Risk
1st	VLCC: 0 Suezmax: 18 Aframax: 18	0–100/0–100	36	15; 3 13; 5	9.71	711.62
2nd	VLCC: 4 Suezmax: 10 Aframax: 21	25–75/27–73	32	4; 0 7; 3 13; 5	9.73	711.34
3rd	VLCC: 8 Suezmax: 8 Aframax: 12	50–50/53–47	25	8; 0 5; 3 4; 5	9.71	711.04
4th	VLCC: 12 Suezmax: 4 Aframax: 6	75–25/80–20	21	11; 1 1; 2 1; 5	9.67	710.96

Table 7
3rd scenario with varying weights and using Etkin (1999).

Setting	$ millions		Number of trips	Africa route		Suez Canal route	
	Cost	Risk		N. America	Europe	N. America	Europe
Min cost	8.34	993.50	27	7; 0; 0		5; 7	3; 5
L [*cost* = 0.95]	9.01	715.62	27	7; 0; 0		5; 7	3; 5
Base-case	9.71	711.07	25	8; 5; 4	0; 3; 5		
Min risk	10.05	711.03	25	8; 5; 4	0; 3; 5		

Table 8
Percentage decrease in pure premium with different weights on risk.

Legends	Etkin (1999)				Psarros et al. (2011)			
	TEL (mn$)	Vessels used	PP (mn$)	% Decrease	TEL (mn$)	Vessels used	PP (mn$)	% Decrease
Min cost	23.38	25	0.935	–	27.36	20	1.367	–
[*cost* = 0.9, *risk* = 0.1]	15.24	21	0.725	22.42	18.15	21	0.86	36.83
[*cost* = 0.8, *risk* = 0.2]	13.55	22	0.616	34.13	15.23	21	0.73	46.97
[*cost* = 0.7, *risk* = 0.3]	13.23	21	0.629	32.64	14.20	20	0.71	48.08
[*cost* = 0.6, *risk* = 0.4]	12.24	20	0.612	34.54				
[*cost* = 0.5, *risk* = 0.5]	11.98	20	0.60	35.94				
[*cost* = 0.4, *risk* = 0.6]					14.05	20	0.70	48.65
[*cost* = 0.3, *risk* = 0.7]								
[*cost* = 0.2, *risk* = 0.8]								
[*cost* = 0.1, *risk* = 0.9]					14.03	25	0.56	58.97
Min risk								

thereby requiring two fewer trips by Aframax class tankers. Note that all the eight Suezmax tankers are utilized in each setting. Finally, as expected, all the tankers are using the longer but less risky route around Africa. To sum, smaller vessels are used if the cost objective receives most of the weight, and larger vessels if risk receives at least 10% importance.

5.3.4. Impact on insurance premium

Finally, we comment on the effect of considering risk on the insurance premiums of the tanker operations. Insurance premium, in general, is defined as the sum of total *actual* (or *expected*) loss, insurance processing expenses and profit, divided by the number of exposure units (Werner and Modlin, 2010). Given the context (and the absence of pertinent data), we ignore the processing expenses and profit, thereby left with *pure premium*. Note that total expected loss is equivalent to total expected consequence of the tanker operation in the given planning horizon, and number of exposure units implies number of tankers used to meet demand. Recall that earlier analyses were based on the loss of entire lading, which is typically not covered by insurance. Hence, we re-consider the base-case problem but with an average spill size of 3181 tonnes (Siddiqui and Verma, 2013), and once again use Etkin (1999) and Psarros et al. (2011) for relevant estimations (Table 8). It is evident that when cost is the only consideration, the pure premium values are the highest under both models. For instance pure premium, i.e., PP (mn $), is 0.935 under Etkin and 1.367 under Psarros et al. On the other hand, risk consideration has a positive impact on pure premium with minimum values at 0.599 and 0.561 using the two approaches, respectively. It is clear that risk consideration will result in a pure premium decrease of at least 22%, and up to a maximum of 59%.

6. Conclusion

Crude oil tanker routing and scheduling has been a very popular area of research in maritime transportation, though all the engagements have been from perspective of cost. We argue that such an approach may not be appropriate for a hazardous material such as crude oil, since some of the shipments could lead to oil spills and accidents resulting in significant environmental, social, and economic consequences. Furthermore, consideration of risk in routing and scheduling is important since 95% of the world's ocean tonnage is insured through membership in one of the 17 not-for-profit prevention and indemnity (P&I) clubs, and where insurance premium is established in accordance with the claims a member is likely to bring to the club. Furthermore, rare catastrophic events are not covered due to limited liability on these insurances. In this paper, we incorporate the risk assessment methodology for marine transportation, developed in Siddiqui and Verma (2013), to solve the intercontinental routing and scheduling problems of crude oil tankers. To that end, this is the first work that makes use of expected consequence risk and operating cost to tackle the tactical planning problem of a crude oil company with a heterogeneous tanker-fleet.

The proposed mathematical model was tested on numerous problem instances developed using the publicly available information for one of the largest oil producer and supplier in the world. Through extensive computational experiments, we can conclude the following: *first*, the shortest and hence the cheapest route may not lead to the lowest insurance premiums – and consequently the risk of oil spills, since they often traverse through high traffic density and high risk areas. For example, using the Suez Canal does reduce cost but the heavy traffic increases the risk of spill. *Second*, larger vessels should be used if risk is more important, since doing so enables the transporter to exploit both the economies of cost and risk. Note that this is achieved as larger vessels operating on low risk routes result in fewer trips, which imply both lower overall cost and risk. *Third*, given fewer routing options in maritime network, the impact resulting from changing fleet-mix is subordinate to the weight being placed on the risk objective. For example, if risk is more important all the vessels, irrespective of the mix, would be forced to the less risky route.

This work can be extended in several directions. First, the proposed framework can be extended to allow both the Suezmax and Aframax class tankers to carry refined petroleum products in non-mixing compartments. Second, the model could be augmented to permit VLCC tankers to use the Suez Canal by off-loading crude oil on entry, to be moved to the other end via SUMED pipeline, and subsequent loading at the other end. We reckon that such a multimodal movement of crude oil may provide counter-intuitive results, and further interesting insights into the marine crude oil shipments. Furthermore, as risk is not only a function of route but it is also a function of weather patterns and traffic conditions etc. a more elaborate risk assessment technique would provide better solutions to the problem.

Acknowledgements

This research was in part supported by a grant from the National Science and Engineering Research Council of Canada (OGP 312936). The second author is a member of the Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT) and acknowledges the research infrastructure provided by the Centre. The authors would like to thank an anonymous referee whose feedback improved the paper significantly.

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