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Innovative Applications of O.R.

Maritime crude oil transportation – A split pickup and split delivery problem

F. Hennig [a,*], B. Nygreen [a], M. Christiansen [a], K. Fagerholt [a], K.C. Furman [b], J. Song [b], G.R. Kocis [c], P.H. Warrick [c]

[a] *Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Alfred Getz veg 3, N-7491 Trondheim, Norway*
[b] *Corporate Strategic Research, ExxonMobil Research and Engineering Company, 1545 Route 22 East, Annandale, NJ 08801, USA*
[c] *ExxonMobil Research and Engineering Company, 3225 Gallows Rd., Fairfax, VA 22037, USA*

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ABSTRACT

The maritime oil tanker routing and scheduling problem is known to the literature since before 1950. In the presented problem, oil tankers transport crude oil from supply points to demand locations around the globe. The objective is to find ship routes, load sizes, as well as port arrival and departure times, in a way that minimizes transportation costs. We introduce a path flow model where paths are ship routes. Continuous variables distribute the cargo between the different routes. Multiple products are transported by a heterogeneous fleet of tankers. Pickup and delivery requirements are not paired to cargos beforehand and arbitrary split of amounts is allowed. Small realistic test instances can be solved with route pre-generation for this model. The results indicate possible simplifications and stimulate further research.

1. Introduction

Maritime crude oil transportation began in the end of the nineteenth century. Since then the volume of crude oil transported on seaways has steadily increased. The only significant exceptions have been oil crises in 1973 and 1979 with a subsequent decrease in crude oil consumption and production. Today tanker ships transport more than 1.86 billion tons of crude oil across the seas each year (see Rodrigue et al., 2006). The primal driving force for crude oil transportation is refinery requirements. Refineries use crude oil to derive various petroleum products. What type and how much of a petroleum product can be produced depends on refinery capabilities and the types of crude oil, so called grades, available. Refinery operations usually require several different crude oil grades to produce their desired product range. Today's dynamic global market for crude oil and refined products demands versatile refinery operations. Refineries have to adapt to changing crude grade availabilities and varying demand of refined products. This changing environment also affects transportation. If refinery requirements or supply options change, transportation has to be adapted.

The crude oil tanker routing and scheduling problem we study, which is similar to the problem of McKay and Hartley (1974), is potentially applicable to worldwide crude oil transportation. In the problem, a heterogeneous oil tanker fleet transports a number of crude oil grades from several loading ports to several discharging ports. Many loading ports supply a single, location specific crude grade. Some ports however supply several crude grades that also can be found in other loading locations. Refineries usually request several crude grades and hence have to be supplied from several loading ports. Pickups and deliveries are requested in specified time windows. While discharging time windows can be based on refinery production and storage plans, loading time windows usually are the result of negotiations with suppliers. Required pickup and delivery amounts can be split in arbitrary portions and be serviced by several tankers. It can be observed that loading as well as discharging ports often conglomerate in certain geographical regions.

Previous research on maritime crude oil tanker routing and scheduling has treated several aspects of the real world problem. Aspects that have been studied include heterogeneous tanker fleets, multiple products, port restrictions that limit access and cargo onboard, physical ship restrictions and time windows. Typically a cargo is perceived as a quantity of freight to be transported between a loading and a discharging port by a single ship on a single trip. Little attention has been paid to cases where the transportation of single cargoes can be shared between ships. Such a problem is usually referred to as *split problem*. In addition, almost no attention has been paid to cases where the typical cargo definition does not apply. If quantities in pickup locations are not dedicated to

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* Corresponding author. Tel.: +49 1724067010; fax: +49 3034338562.
E-mail addresses: Frank.Hennig@iot.ntnu.no (F. Hennig), Bjorn.Nygreen@iot.ntnu.no (B. Nygreen), Marielle.Christiansen@iot.ntnu.no (M. Christiansen), Kjetil.Fagerholt@iot.ntnu.no (K. Fagerholt), Kevin.c.furman@exxonmobil.com (K.C. Furman), Jinhwa.song@exxonmobil.com (J. Song), Gary.r.kocis@exxonmobil.com (G.R. Kocis), Philip.h.warrick@exxonmobil.com (P.H. Warrick).

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certain delivery locations, a pairing of pickup and delivery does not exist and thus is part of a solution. We found this *non-paired pickup and delivery* in only one crude oil related publication. Often tanker voyages have a rather simple structure or are based on a seemingly rigorous subset of possible ship routes. Where time windows are considered, these seem to be tight. The research in the field of oil tanker routing and scheduling applications has undergone a fairly natural development. We refer to the problem as *the oil tanker routing and scheduling problem* like for example in Sherali et al. (1999).

The purpose of this paper is to present a model for an oil tanker routing and scheduling problem similar to McKay and Hartley (1974) but more realistic with respect to modern crude oil shipping. The model replicates degrees of freedom present in real operations that are scarcely studied and challenging from an algorithmic point of view. Unlike many others, except McKay and Hartley (1974), we model non-paired supply and demand time windows and arbitrary split of supply and demand amounts. In contrast to McKay and Hartley (1974), we fulfill both pickup and delivery requirements. We also provide details on our solution procedure. Computational results are meant to stimulate further research on the topic that may result in the solving of large scale instances.

The paper is organized as follows: in Section 2 we show previous research on the oil tanker routing and scheduling problem. We also mention research conducted on different kinds of split problems. Section 3 gives a description of the problem and in Section 4 we explain the basics of the path flow model presented in Section 5. In Section 6 we explain how paths can be obtained in a pre-generation phase. Different transportation instances are solved by commercial software and presented in Section 7. In Section 8 discussions and conclusions are made.

2. Previous research

Oil tanker routing and scheduling is a well known task and, as far as the operations research literature is concerned, goes back to before 1950. It almost seems that the problem has undergone a natural evolution in parallel with increasing computational power and algorithmic advancements. For the purpose of describing oil tanker routing and scheduling problems and their solution approaches it seems justifiable to start in 1954 with the US Navy fuel oil tanker routing problem. In the first part of this section we review publications, which treat the oil tanker routing and scheduling problem, in order of their date of publication. Solution approaches and achievements are discussed. The main characteristics that appear in these papers are listed in Table 1 for the purpose of overview. For a comprehensive review on other maritime routing and scheduling problems see (Christiansen et al., 2004). The second part refers to the scarcity of research on pickup and delivery problems with split. We mention some examples and findings in connection with split problems.

2.1. The oil tanker routing and scheduling problem

The first problem we present, the US Navy fuel oil tanker routing problem, has received the attention of several researchers. In this problem a homogeneous fleet of tankers is engaged in worldwide fuel oil transportation. Dantzig and Fulkerson (1954) and Flood (1954) treat the problem in a similar manner. They assume a sufficiently large tanker fleet to satisfy the transport demand. The transport demand is given as the number of full shiploads needed between pairs of loading and discharging ports. No scheduling of pickup and delivery dates is necessary. While Dantzig and Fulkerson (1954) are interested in the minimum number of tankers, Flood (1954) minimizes ballast sailing costs. Both problems can be solved by linear programming and as stressed in Dantzig and Fulkerson (1954) as a transportation problem. Later Briskin (1966) points out that the transportation of full shiploads between port pairs is a coarse assumption. He instead proposes discharging port clusters, where the total cargo amount in a cluster is a full shipload. Dynamic programming is used to find routes and indirectly schedules within a discharge cluster. The proposed approach can be combined with the method of Dantzig and Fulkerson (1954) and then allows for a more detailed tanker routing. Finally, an under-sized fleet of tankers is allowed in Bellmore (1968). Not all cargoes can be serviced and therefore profit for the transport that can be carried out is maximized. The problem can be formulated as transshipment problem and remains solvable by linear programming.

Table 1
Main characteristics treated in the reviewed literature.

Problem aspects	Characteristics treated in the literature
Fleet types	Homogeneous/heterogeneous Sufficiently/insufficiently large
Cargo types	Full/partial shiploads Contracted/optional cargoes Single/multiple origin(s) and destination(s) Splitable cargoes
Cargo carrying	Single/multiple cargo(es) onboard
Ship routing	Single loading to single discharging port Single loading port cluster to single discharging port cluster Via multiple loading and discharging ports
Restrictions	Bunker fuel consumption Port draft restrictions Optimal speed selection Port inventory management

A shipping problem that is not explicitly linked to oil transportation but in its characteristics probably directly applicable to it is described by Appelgren (1969, 1971). Appelgren (1969) considers a heterogeneous fleet of tankers, where ships have different sizes, speeds and costs. Cargoes are specified by amount, cargo type, loading time window and discharging time window. Each ship carries only one cargo at a time. Whereas different cargo types could in principle be handled in Dantzig and Fulkerson (1954) and Flood (1954), specific cargo amounts and loading time windows are new. In addition the fleet is allowed to service additional spot cargoes. For solving the problem three solution approaches are discussed: a multi-commodity flow formulation, a path flow formulation with pre-generated routes and a column generation approach. The column generation approach is favored but only the linear relaxation of the master problem is solved to optimality. Feasible solutions were often found. The largest instance that was solved consists of 40 ships, 50 cargoes and a planning horizon of two to three months. In Appelgren (1971) the problem of fractional solutions is studied. The paper considers cutting planes and a branch-and-bound method to find feasible, non-fractional solutions. The branch-and-bound method with column generation in the root node proved to be very successful.

Another formulation of the problem is given by Bellmore et al. (1971). The problem is quite similar to the one described by Appelgren (1969) but does not consider spot cargoes. Tankers can be partially loaded and share cargoes. A tanker will only carry one, or part of one, cargo at a time. The authors suggest a column generation approach like Appelgren (1971), but only describe and discuss the branch-and-bound procedure.

The first paper that challenges the assumption of predefined cargoes (or port pairs) is McKay and Hartley (1974). The paper assumes independent, non-paired pickup and delivery requirements.