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Discrete Optimization

# Alternative approaches to the crude oil tanker routing and scheduling problem with split pickup and split delivery

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ABSTRACT

The crude oil tanker routing and scheduling problem with split pickup and split delivery is a maritime transportation task where an industrial operator needs to ship different types of crude oil from production sites to oil refineries. The different crude oils are supplied and demanded in many ports in certain time windows. Pickup and delivery quantities are known in advance but no pairing of pickup and delivery needs to be predefined and can be decided together with shipment quantities during optimization. Pickup and delivery quantities may be split arbitrarily among the ships in the fleet. We compare two alternative path flow model approaches to investigate their degree of applicability in a column generation setup. For this purpose we apply route pregeneration prior to optimization. The first approach uses continuous decision variables for pickup and delivery to decide on shipment quantities. In the considerably shorter second formulation cargo quantities are discretized and included into the paths. The second approach is capable to solve larger instances and is more efficient in terms of computational performance, however solution quality may decrease due to the discretization.



## 1. Introduction

Routing and scheduling problems result from the need of transportation between different locations. In this paper we study a routing and scheduling problem that arises in maritime transportation. Out of the different types of shipping and related optimization problems described by Christiansen, Fagerholt, Nygreen, and Ronen (2007, chap. 4) the considered problem belongs to the domain of industrial shipping. In industrial shipping companies own vessels to execute their own transportation needs. Typically these are producing companies that need to ship raw materials as well as half finished or finished products.

The maritime transportation problem considered is the *crude oil tanker routing and scheduling problem* as introduced by Hennig et al. (2012). In the considered segment of maritime crude oil transportation ships transport different products from the Middle East to North America, Europe and the Asia-Pacific region. It may take more than five weeks before a laden ship arrives at its destination. Companies involved in this kind of activity may have refineries in many locations that require large deliveries of crude oil. Refineries demand crude oil to produce a range of petroleum products. For that they need oil of different quality, which for the purpose of transportation planning can be treated as different products.

The core problem considered in this paper can briefly be described as follows: Ships operate on a network that consists of nodes and arcs. Each node is a port associated with a time window for pickup or delivery. A single port may have several time windows and thus several nodes may belong to the same port. In addition to time window bounds and name of port, nodes are characterized by the quantity of a particular product to be picked up or delivered. No predefined pairings between pickup and delivery nodes are specified, and these pairings remain to be decided. Nodes are clustered in fairly remote regions for either only pickup or only delivery. Transportation is carried out by a fleet of heterogeneous ships. Each ship is capable to carry several different products simultaneously in separate cargo tanks. While a single ship will only visit a certain node once, no limit on the number of node visits of different ships is enforced. Node specific product quantities may be split arbitrarily among different ships. Limits on the maximum number of visits at a node and the freedom of splitting can be inferred from minimum required pickup or delivery quantities. For the problem at hand it is important to note that ships serving the same pickup node may deliver the product to different (multiple) delivery nodes.

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Most maritime industrial routing and scheduling problems considered in the literature deal with predefined cargoes. These cargoes are of a certain size and have to be shipped from a definite origin to a definite destination. Examples of such problems are mentioned by Christiansen, Fagerholt, and Ronen (2004) and in the specific case of crude oil shipping by Hennig et al. (2012). A recent review on ship routing and scheduling problems (Christiansen, Fagerholt, Nygreen, & Ronen, 2013) details further progress in the field. If the problems are well constrained route pregeneration together with an optimization model is used. More complicated problem formulations have been treated with column generation. The reader is referred to Barnhart, Johnson, Nemhauser, Savelsbergh, and Vance (1998) for a very clear review of column generation. Maritime industrial routing and scheduling problems typically assume that a cargo has to be transported on a single ship. Acknowledging the improvements to be gained by the allowance of splitting cargo quantities in vehicle routing, Nowak, Ergun, and White (2008), Andersson, Christiansen, and Fagerholt (2011) and Korsvik, Fagerholt, and Laporte (2011) study the pickup and delivery problem with split loads. In this problem a cargo can be served by several vehicles. The next logical extension, allowing non-paired pickups and deliveries, has received almost no attention in the literature, however it is mentioned by Savelsbergh and Sol (1995) and a real application is discussed by McKay and Hartley (1974). The inventory routing problem, which also includes the aspect of splitting cargo quantities, is another related problem class. A relevant maritime inventory routing example is described by Christiansen (1999), which deals with a single product that has several supply and several demand points. In this example, several ships can visit the same port, however instead of having time windows and fixed pickup/delivery quantities, inventories at supply and demand points change over time and are required to be kept within their capacity limits. In a sense quantity splitting takes place since several ships can pickup from and deliver to the same inventories. A further problem addressing inventories for maritime oil transportation is treated by Aizemberg, Kramer, Pessoa, and Uchoa (2014). The authors deal with oil transportation between platforms and terminals, where inventory limits on both sides must be satisfied at each day. Shipments take only a day and tankers use their entire capacity. Further detailing of the maritime transportation itself is not within the scope of the paper. Andersson, Hoff, Christiansen, Hasle, and Løkketangen (2010) review further problems of this kind in a maritime and non-maritime context. For further in-depth study of these problems we point the reader to a good problem classification scheme described by Berbeglia, Cordeau, Gribkovskaia, and Laporte (2007) and more insights into the related split delivery vehicle routing problem treated by Archetti and Speranza (2008).

The purpose of this paper is to examine and demonstrate the performance of two mathematical problem formulations which both could be used in a column generation algorithm. For routing problems with a potentially very large route set column generation is a proven solution approach. It relies on problem decomposition which itself heavily relies on the mathematical problem formulation. In this paper we focus on the performance of the path flow formulation assuming that the needed paths could be generated on demand in a column generation scheme. Therefore the two path flow formulations examined in this paper contain sets of *a priori* generated paths. These sets, reduced to a manageable size, can give good indication of the problem formulation's behavior. Keeping the focus we omit an in-depths study of particular path and path generation properties. The key differentiator between both formulations is the quantity split: The first model can split node quantities arbitrarily and decide ship load levels in a continuous manner. In contrast, the second model is based on quantity discretization. The node quantity split and ship load levels are determined in certain discrete steps. This mixed integer formulation is an improved version of the model introduced by Hennig et al. (2012). The improvement is a simplification of the objective function and time constraints and is discussed in this paper.

The paper is structured as follows: The problem is introduced and described in more detail in Section 2, where its relationship to the general pickup and delivery problem defined in Savelsbergh and Sol (1995) is discussed. Both solution approaches based on different path flow optimization models are presented in Section 3. In the same section we briefly describe the schemes used to *a priori* generate routes considered in the path-flow models. Section 4 summarizes the computational study and includes the description of test instances, the benefits of the improved mixed integer formulation and the computational results for the two approaches. Finally computational results for the models are compared and conclusions are drawn in Sections 5 and 6.

## 2. Problem description

The problem studied can be considered an extension of the general pickup and delivery problem (GPDP) as described by Savelsbergh and Sol (1995). In Savelsbergh and Sol (1995) a set of *shipments* (originally referred to as requests) must be serviced by a fleet of vehicles. Each vehicle can have unique positions at the start and end of operation. Each shipment is a total cargo quantity to be picked up at one or several origins and to be delivered to one or several destinations. A shipment cannot be shared between several vehicles, and vehicles are only eligible for a shipment if they have a sufficiently large cargo capacity. A vehicle must first visit all pickup nodes (origins) and then consequently all delivery nodes (destinations), however each origin and destination may be visited exactly once.

In the studied problem the set of shipments is serviced by a fleet of ships. Similar to the GPDP a shipment refers to a unique product. Each shipment consists of a number of pickup and delivery nodes with respective cargo quantities, which we call *requirements*. The sum of all pickup and the sum of all delivery requirements for a shipment are both equal to the shipment quantity. In contrast to the GPDP the condition that a shipment cannot be shared among several vehicles is relaxed. In addition the split of requirements among several ships is permitted. Stricter than in the GPDP each requirement has to be serviced within a specified time window. Service in this context means the start of pickup or delivery operation. The entire pickup/delivery operation may take up to several days due to the large quantities involved. Hence, time and costs for pickup and delivery have to be taken into account. Pickup and delivery are allowed to end outside time window bounds. In an operational environment time window bounds may be somewhat soft (Fagerholt, 2001), however for the purposes of this study we only consider hard time windows.

The fleet of ships in the problem is heterogeneous. A number of differently sized cargo tanks onboard each ship allow simultaneous transportation of different products. Typically at maximum four different products are carried and each product can use one or more cargo tanks. Instead of a single, total vehicle capacity each ship has both a total weight and a total volume capacity. Both capacities not only depend on the ship itself but on physical restrictions of the water way and visited ports. As a consequence capacities are network-arc specific. Each arc in the network may have a maximum weight and volume capacity. Apart from ship individual capacities each ship has specific speeds, a cost structure and an initial position at a given time. In the considered problem ship capacities are relatively similar due to the inclusion of only a single ship size class.

The structure of shipments and ship routes deviates from the GPDP definition. The GPDP requires all pickup nodes to be serviced before their delivery nodes. That may not be feasible in the considered problem. Due to the geography of the problem, a ship route can be divided into so called *voyages*. A voyage is a journey that connects nodes in distant pickup and delivery regions. Distances between regions are large enough such that in a voyage all pickups occur prior to all deliveries. In our problem time windows can be specified such that for a shipment not all pickups can be served before all deliveries. That