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A traveling salesman problem with pickups and deliveries, time windows and draft limits: Case study from chemical shipping

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ABSTRACT

This paper introduces and studies a real in-port ship routing and scheduling problem faced by chemical shipping companies. We show that this problem can be modeled as a Traveling Salesman Problem with Pickups and Deliveries, Time Windows and Draft Limits (TSPPD-TWDL). We propose a mathematical formulation for the TSPPD-TWDL and suggest a solution method based on forward dynamic programming (DP) to solve the problem. A set of label extension rules are also proposed to accelerate and enhance the performance of the algorithm. Computational studies show that the label extension rules are essential to the DP-algorithm, and the proposed solution method is able to solve real-sized in-port routing and scheduling problems in chemical shipping efficiently.

1. Introduction

Maritime transport is the backbone of international trade and world economy, accounting for around 80% of global trade by volume and over 70% of global trade by value [33]. However, with the current reduced level of world economic growth coinciding with overcapacity in the global fleet [8], proper routing and scheduling is crucial for the shipping companies to remain competitive. To measure their commercial performances, most shipping companies use the *time charter equivalent* (TCE) rate as one of their key performance indicators (KPIs). It is used to get a nuanced perspective of the company's earnings and to compare the performance in terms of revenue between different geographical voyage routes, ship types and fiscal quarters, etc. For example, to measure the profitability of an individual voyage performed by a ship owned by the shipping company, the voyage earning in terms of TCE can be used as KPI and calculated using the following formula:

$$\text{Voyage Earning in TCE} = \frac{\text{Freight revenue} - \text{Voyage costs}}{\text{Voyage duration}}\left[\frac{\text{USD (\$)}}{\text{day}}\right]$$

It can be seen that one important factor influencing the voyage earning is voyage duration, which consists of the time spent at sea and time spent in ports. For some shipping companies, despite that their trade routes are all over the world, large profit improvements can be made by optimizing the port call operations and reducing time spent in ports, as more efficient port calls would directly translate into higher transport availability for more cargoes. Furthermore, in some tramp shipping segments, such as chemical shipping, a ship usually has to visit multiple terminals within the same port for loading and unloading, due to specific requirements by different customers and also the fact that some cargoes need to be handled at specialized cargo terminals equipped with appropriate facilities. In these cases where many terminals have to be visited within the same port, proper routing and scheduling *in port* becomes of great importance, affecting both the performance of each voyage and the total performance of the shipping company.

In this paper, we describe and solve a real life in-port ship routing and scheduling problem faced by Odfjell, a Norwegian public listed chemical shipping and tank terminal company based in Bergen, Norway. The problem considers a ship arriving in a particular port with numerous terminals and aims to find an optimized plan with shortest time spent in port that comprises sequencing decision for visiting terminals and the corresponding departure plan. Fig. 1 shows a small example port call at the Port of Houston. In this example, before the port call the ship moors at an anchorage point in the Galveston Bay outside the Houston Ship Channel. It then enters the Port of Houston and services three terminals along the channel before sailing off for a new voyage.

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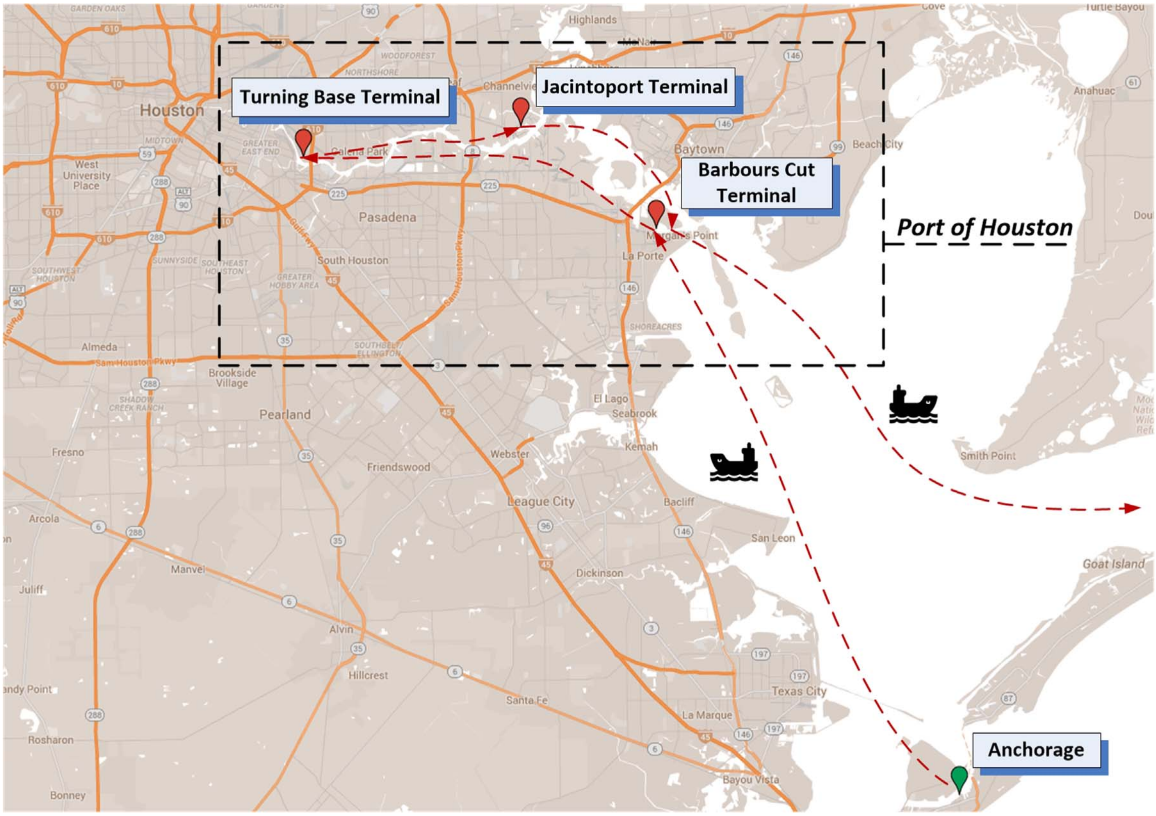

Fig. 1. Illustration of an example port call. The ship approaches the Port of Houston from an anchorage point in the Galveston Bay and services three terminals within the port.

The sequence of the terminal visits are illustrated with dashed arrows.

The problem of ship routing and scheduling in port can be very complex due to the combination of various requirements and especially when numerous different cargoes and port terminals are involved. When approaching a port the ship usually carries a number of contracted cargoes to be delivered to their corresponding destination terminals in the port. While during the same port call, the ship also needs to pick up a number of other contracted cargoes to be delivered to other ports along the ship's remaining trading route. Fig. 2 shows a small example of in-port routing and the associated pickup and delivery operations. The terminals in the port are represented by circled numbers. In this example, the ship sails from *Anchorage* to *Terminal-1*, carrying cargoes *A* and *C* which are to be delivered to *Terminal-1* and *Terminal-3*, respectively. The ship also needs to pick up cargo *B* from *Terminal-2*. The route in port and the related pickup/delivery operations in this example are: *Anchorage* →*Terminal-1*(*Unload A*)→*Terminal-2*(*Load B*)→*Terminal-3*(*Unload C*)→*Anchorage*.

While routing the ship inside the port as well as scheduling the pickup/delivery operations, there usually are various time windows within which the cargoes have to be serviced (for loading or unloading) at specified terminals. Apart from these cargo restrictions, the routing decisions also need to take into account the limitations of the port terminals. One such important limitation is the *draft limit* of every terminal, as before entering as well as leaving a terminal the ship must ensure that it is physically possible to do so. The *Draft* of a ship is the vertical distance from the bottom of the ship's hull to the waterline, which determines the minimum depth of water the ship can safely navigate. The *Draft limit* is the height from the seabed to the waterline, as seen in Fig. 3. The ship's draft (and expected draft after servicing the terminal), depending on the weight of the cargoes on board and the ship's physical measures and carrying capacity, must be taken into consideration before approaching every terminal such that the terminal draft limit is not exceeded.

The problem of routing and scheduling a ship in port is, in principal, similar to the *Traveling Salesman Problem with Pickups and Deliveries* (TSPPD) [3], which is also known as the *Single-Vehicle One-to-Many-to-One Pickup and Delivery Problem* (1-M-1-PDP) [14]. The TSPPD is a generalization of the *Traveling Salesman Problem* (TSP), and considers an additional constraint when designing a pickup-delivery tour: the full capacity of the vehicle cannot be exceeded throughout the tour. Exact and heuristic algorithms have been proposed for TSPPD, see for example, Mosheiov [20]; Gendreau et al. [13]; Renaud et al. [27,26]; Baldacci et al. [2].

The time window considerations have also been widely addressed in the literature on TSP and other routing and scheduling problems, where the times at which services begin are decision variables, and are constrained within time windows defined by the earliest and latest service start times. Reviews are for example presented by Solomon & Desrosiers [31] and Desrosiers et al. [6]. For the *Traveling Salesman Problem with Time Windows* (TSPTW), various approximate and exact algorithms have been presented by, e.g., Christofides et al. [5]; Baker [1]; Savelsbergh [28,29], Desrosiers et al. [7].

In this paper we present the in-port ship routing and scheduling problem as a *Traveling Salesman Problem with Pickups and Deliveries, Time Windows and Draft Limits* (TSPPD-TWDL). To our best knowledge, the TSPPD-TWDL has not been addressed yet in the literature. Rakke et al. [25] incorporate the draft limits in a traveling salesman problem in maritime transportation. Other examples are: Hennig [15] and Hennig et al. [16], that consider a crude oil tanker routing and scheduling problem; Christiansen et al. [4], that present a MIRP in the cement industry; and Song