Transportation Research Part C 19 (2011) 1225–1242

Contents lists available at ScienceDirect

Transportation Research Part C

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

Routing and scheduling of RoRo ships with stowage constraints

Bernt Olav Øvstebø [a], Lars Magnus Hvattum [a,*], Kjetil Fagerholt [a,b]

[a] Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Norway
[b] Norwegian Marine Technology Research Institute (MARINTEK), Norway

ARTICLE INFO

Article history:
Received 27 January 2010
Received in revised form 11 January 2011
Accepted 4 February 2011

Keywords:
Maritime transportation
Tabu search
Squeaky wheel optimization

ABSTRACT

Roll-on/Roll-off ships are used for international transport of vehicles and other rolling equipment. We consider the problem where a ship sails between two geographical regions, picking up cargo in the first and making deliveries to the second. Several variations are considered with optional cargoes, flexible cargo quantities, and ship stability restrictions. Decisions must be made regarding the route and schedule of the ship as well as the stowage of cargo onboard. The problem is modeled as a mixed integer program, which has been solved using Xpress. In addition, a tailor made heuristic procedure is built using components from tabu search and squeaky wheel optimization. Extensive computational results are presented, showing that the heuristic is able to handle realistically sized problem instances.

1. Introduction

Roll-on/Roll-off (RoRo) ships transport cargo on wheels such as cars, trucks, farming equipment, and military equipment. Intercontinental trade involved more than 17 million vehicles in 2004, growing 5% annually, and regional trade involved more than 26 million vehicles, growing 3–4% per year (MDS Transmodal, 2006). Almost all of this trade is conducted using RoRo ships. The deep sea fleet for vehicle transport, consisting of ships with a capacity in excess of 3000 CEUs (Car Equivalent Units), had 355 ships in 2006, and the regional fleet of ships with a capacity of up to 3000 CEUs consisted of 152 ships.

In international vehicle trade, RoRo ships sail between different regions of the world according to predefined plans. Planning of operations in the maritime transport industry can mainly be divided into three categories: strategic, tactical, and operational planning. Strategic planning is concerned with a time horizon of several years, and typically involves investment and network design decisions. On a tactical level, the decision maker must determine which ships should operate which routes and when they are required to arrive to each region. These decisions lay the premises for planning on the operational level. On the operational level, one must decide which cargoes to carry and which routes to follow in order to pick up and deliver these cargoes. For RoRo ships, operational decisions must also be made regarding stowage: for a given route with pick-ups and deliveries, it must be determined how the cargoes should be stored on the ship during the voyage.

When creating these plans, the planner must at all times balance the scope of the plan and the tractability of the problem. Increased scope, that is, planning for longer time periods and more ships simultaneously, gives more flexibility. This enables the planner to find solutions that exploits synergy better than if the problem was partitioned into smaller problems and solved sequentially. However, solving a planning problem of large scope is more difficult than solving the subproblems of which it is composed. In addition, problems of larger scope typically require more information, which may not be readily available. We focus on the operational level of planning, trying to incorporate as many decisions as possible while studying whether the resulting problem can be solved efficiently by exact or heuristic solution algorithms. By simultaneously

* Corresponding author.
E-mail address: lars.m.hvattum@iot.ntnu.no (L.M. Hvattum).

0968-090X/$ - see front matter
doi:10.1016/j.trc.2011.02.001

considering routing and scheduling decisions as well as stowage planning, we are extending the effort by Øvstebø et al. (2011)) who studied the stowage of RoRo ships on a predefined ship route.

In this paper we will look at the problem of deciding a route and a schedule for a RoRo ship while simultaneously providing a stowage plan. Relevant existing research is reviewed in Section 2. Section 3 then gives a thorough description of the problem considered, including a MIP formulation. A heuristic solution method is presented in Section 4. Extensive computational results are illustrated in Section 5, followed by concluding remarks in Section 6.

2. Related literature

Research on maritime transportation has increased much during the last years (Christiansen et al., 2004). Much of this research is concerned with routing of ships. Christiansen et al. (2007) give an insight into maritime transportation on several levels, including ship routing and scheduling. A generic decision support system for ship routing used by the shipping industry is presented in (Fagerholt, 2004; Fagerholt and Lindstad, 2007).

Maritime stowage problems can be subdivided according to the type of ship considered, and the main part of research has focused on container ships. Container ships carry stacks of containers, and the stowage problems are often formulated as the minimization of container and crane movements along the route of the ship. Surveys of container ship stowage are made by Steenken et al. (2004) and Stahlbock and Voß (2008). Many of the considerations to be taken when stowing container ships are described in an early contribution by Martin et al. (1988). Later work focuses on providing mathematical models and heuristic algorithms (Avriel et al., 1998; Kang and Kim, 2002; Wilson and Roach, 1999), as well as using exact methods (Li et al., 2008). Recently, research on stowage of bulk ships has been conducted. Bulk ships carry their cargo in tanks or compartments, and the problem is to allocate the cargo to these tanks, subject to capacity, stability, and hazardous material constraints. Hvattum et al. (2009) consider several variations of the *tank allocation problem*, and show that it is $\mathcal{NP}$-hard even in its simplest form. They also perform analysis to determine which attributes of realistically sized problem instances create difficulties for a standard mixed integer program (MIP) solver. Finally, Øvstebø et al. (2011) consider RoRo ships and provides a mathematical formulation for finding stowage plans given a fixed route. Both standard MIP solvers and tailor made heuristics are used to solve the *RoRo ship stowage problem* (RSSP).

Some research has been done on combining stowage and routing and scheduling. In a maritime setting, Fagerholt and Christiansen (2000a) consider the integrated problem of routing and stowage in the bulk shipping industry. The problem is referred to as the *ship scheduling and allocation problem*, and is solved through a set partitioning approach in two phases. The first phase generates a set of feasible routes with optimal allocation of cargoes to the ship compartments, and phase two solves the set partitioning problem. The method for finding routes with optimal allocation is described in Fagerholt et al. (2000b). Dynamic programming is used to solve a *traveling salesman problem* with allocation, time windows, and precedence constraints.

For general or land-based applications, much effort has been expended in recent years looking at problems combining routing and scheduling with various loading and stowage restrictions. Erdoğan et al. (2009) consider the *pick up and delivery traveling salesman problem with first-in first-out loading*, and test two different constructive heuristics and two improvement heuristics, probabilistic tabu search and iterated local search. Probabilistic tabu search gives the best results out of the two improvement heuristics, but there is not much difference between the two constructive heuristics.

Moura and Oliveira (2009) present a mathematical formulation to the integrated problem of vehicle routing and container loading. Their objective is to minimize travel cost and capital cost of vehicles. They test two solution approaches to the problem: sequential and hierarchical. In the sequential approach, both routing and stowage is considered at the same level, while for the hierarchical approach, routing is the main problem and stowage is the subproblem. They conclude that the hierarchical approach is best when the number of boxes per customer is low, while the sequential is best when the number of boxes per customer is high.

Iori et al. (2007) introduce the *two-dimensional loading capacitated vehicle routing problem* (2L-CVRP), and employ a Branch-and-Cut procedure to solve it to optimality for instances with up to 35 customers and over 100 items. The 2L-CVRP has been solved using tabu search by Gendreau et al. (2008) and Zachariadis et al. (2009). Fuellerer et al. (2009) use ant colony optimization (ACO) to solve the 2L-CVRP, and they also consider different loading constraints with respect to orientation of items. Doerner et al. (2007) solve a similar problem, which they call the *multiple stacks vehicle routing problem*, based on the wood-product industry. Here, items can be arranged on pallets, which are then loaded into the truck. They use both tabu search and ACO, and the latter shows to be the better approach. Gendreau et al. (2006) introduce the *three-dimensional loading capacitated vehicle routing problem*. They use tabu search to solve instances with up to 100 customers, 200 items, and 25 vehicles. They test the impact of imposing different loading constraints, such as a last-in-first-out (LIFO) policy. Finally, they test their heuristic on a set of real world instances from the Italian furniture industry.

The *double traveling salesman problem with multiple stacks* is introduced by Petersen and Madsen (2009). The problem consists of finding routes in two separate networks to minimize the total cost, where cargo is picked up in the first network and delivered in the second. When picking up cargo it must be placed in one of multiple stacks that operate according to the LIFO principle, and no repacking is allowed when going between the networks. Good heuristic solutions are obtained using a large neighborhood search. Felipe et al. (2009) present several new neighborhoods for the problem and a variable neighborhood search that outperforms previous heuristics.