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MIRPLib – A library of maritime inventory routing problem instances: Survey, core model, and benchmark results

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ABSTRACT

This paper presents a detailed description of a particular class of deterministic single product Maritime Inventory Routing Problems (MIRPs), which we call deep-sea MIRPs with inventory tracking at every port. This class involves vessel travel times between ports that are significantly longer than the time spent in port and require inventory levels at all ports to be monitored throughout the planning horizon. After providing a comprehensive literature survey of this class, we introduce a core model for it cast as a mixed-integer linear program. This formulation is quite general and incorporates assumptions and families of constraints that are most prevalent in practice. We also discuss other modeling features commonly found in the literature and how they can be incorporated into the core model. We then offer a unified discussion of some of the most common advanced techniques used for improving the bounds of these problems. Finally, we present a library, called MIRPLib, of publicly available test problem instances for MIRPs with inventory tracking at every port. Despite a growing interest in combined routing and inventory management problems in a maritime setting, no data sets are publicly available, which represents a significant "barrier to entry" for those interested in related research. Our main goal for MIRPLib is to help maritime inventory routing gain maturity as an important and interesting class of planning problems. As a means to this end, we (1) make available benchmark instances for this particular class of MIRPs; (2) provide the mixed-integer linear programming community with a set of optimization problem instances from the maritime transportation domain in LP and MPS format; and (3) provide a template for other researchers when specifying characteristics of MIRPs arising in other settings. Best known computational results are reported for each instance.

1. Introduction

In 2011, the international shipping industry handled over 80% of the volume of world trade, of which bulk goods were a primary component. Indeed, of the nearly 9 billion tons of goods in international seaborne commerce traded in 2011, bulk goods such as coal, crude oil, iron ore, and liquefied natural gas accounted for well over 50% of this quantity and easily represented several hundreds of billions of US dollars in value (UNCTAD, 2012). With such colossal figures expected to grow over future decades, effective maritime transportation is of utmost importance. In this paper, we study a particular maritime transportation planning problem known as the Maritime Inventory Routing Problem (MIRP), which plays an integral role in global bulk shipping.

Inventory routing problems (IRPs) involve the integration and coordination of two components of the logistics value chain: inventory management and vehicle routing. Maritime inventory routing problems are a special class of IRPs that arise in a maritime setting. IRPs have come to prominence because they are an integral component in vendor managed inventory (VMI), a policy in which a central decision maker coordinates both the inventory and its distribution within a supply chain (Campbell, Clarke, Kleywegt, & Savelsbergh, 1998). The survey paper on combined inventory management and vehicle routing problems by Andersson, Hoff, Christiansen, Hasle, and Løkketangen (2010) provides a summary of research on IRPs in road and maritime settings. Coelho, Cordeau, and Laporte (in press) also review IRPs with more focus given to methodological aspects. The book chapter by Christiansen, Fagerholt, Nygreen, and Ronen (2007) provides an overview of maritime transportation along with many references.

Despite the importance of maritime transportation, the application of operations research (OR) techniques within this area has not yet gained widespread acceptance. There are three primary indicators of this underdevelopment. First, in industry, there are

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only a handful of publicly reported OR-based decision support systems being used for maritime applications compared with dozens used in road-based ones. Second, compared to other modes of transportation, there are very few special-interest groups in major OR societies devoted to the maritime industry. Third, in academia, there are no publicly available benchmark instances on which researchers can test their algorithms (Christiansen, Fagerholt, Nygreen, & Ronen, 2013). One possible explanation for the latter issue as it pertains to maritime inventory routing is that there is no single well-defined problem definition for a MIRP. Instead, there are many variants that address particular aspects of a specific industrial application (Andersson, Hoff, et al., 2010). Christiansen et al. (2013) define a MIRP as "a planning problem where an actor has the responsibility for both the inventory management at one or both ends of the maritime transportation legs, and for the ships' routing and scheduling." While this definition is both reasonable and concise, it leaves ample room for interpretation and variation.

In recent years, there have been several appeals to create a set of benchmark instances for maritime transportation problems for the research community. Andersson, Hoff, et al. (2010) urge authors, in collaboration with industrial partners, to make their data available along with a full and rich description of the model so that other can reproduce it. Similarly, Christiansen and Fagerholt Christiansen and Fagerholt (2011) write "... there are still not any published sets of benchmark problems for maritime transportation problems, while there are numerous in land-based transport." A primary goal of this paper is to help fill this void by introducing a set (or "library") of benchmark instances for a particular class of single product MIRPs. By doing so, we hope to help maritime inventory routing gain maturity as an important and interesting class of planning problems and to spur the development of better mathematical models and more advanced algorithms. We call this library MIRPLib in the spirit of other libraries in the OR community such as TSPLib (Reinelt, 1991), MIPLib (Koch et al., 2011), ORLib (Beasley, 1990), MineLib (Espinoza, Goycoolea, Moreno, & Newman, 2013), and LINER-LIB (Brouer, Alvarez, Plum, Pisinger, & Sigurd, in press), which have been used for the traveling salesman problem, mixed-integer linear programming (MILP), OR, open-pit mining, and liner shipping network design, respectively.

In order to create the first publicly available library of MIRP instances, we scoped the problem to be interesting and accessible. We study a core model that involves the distribution of a single product and requires that inventory levels at all loading and discharging ports must stay within prespecified bounds during every time period throughout the entire planning horizon. It is assumed that vessel travel times between ports are significantly longer than the time spent in port so that port operations need not be explicitly modeled. We refer to this class of problems as *deep-sea MIRPs with inventory tracking at every port*. We believe that this class of problems is a suitable starting point for a library since it most closely resembles the traditional concept of VMI in which a central entity is tasked with maintaining inventory levels at all suppliers and customers, while simultaneously managing the distribution of the inventory.

Our emphasis on a core model is in line with what Christiansen and Fagerholt (2011) describe as "a need to direct the research on maritime transportation towards more basic research." By focusing on a core model that lies at the intersection of many of the models seen in the literature, we believe that researchers can compare their algorithms in a meaningful way without having to understand a detailed variant of this base model. Meanwhile, this does not discount the importance of rich models. We hope researchers can use this library as a template before making their data available to the community.

The single product MIRP that we study as our core model is best described in terms of its main components: ports and vessels. Each port is classified as a loading port, where product is produced and loaded onto vessels, or as a discharging port, where product is consumed, typically after being discharged from vessels or from an alternative source (e.g., a pipeline). Product can be stored in inventory at both types of ports. Each port has: exactly one classification type, "loading" or "discharging"; a variable inventory capacity; a fixed number of berths limiting the number of vessels that can simultaneously load or discharge in a given time period; lower and upper bounds on the amount of product that can be loaded or discharged in a period; and deterministic, but possibly non-constant, per-period bounds on the rate of production or consumption. If the bounds in a single period coincide, then the rate is fixed. Each discharging port has a deterministic, but possibly non-constant, per-period unit price for the quantity discharged. Port operations, such as time to berth and time to set up equipment for loading or discharging, are not explicitly modeled.

To transport the product, the planners control or charter a fleet of heterogeneous vessels. Each vessel belongs to a particular vessel class and has a fixed capacity, a cruising speed, and a travel cost. Vessels make voyages between ports by picking up inventory at one or more ports and delivering inventory to one or more ports. Vessels may partially load and discharge so that two or more ports of the same type (loading or discharging) may be visited in succession. In general, a vessel will fully discharge before loading at another port, but this is not required in the model. A berth is only occupied by a vessel when loading or discharging. Thus, there can be more vessels at a port than there are berths. Using the nomenclature of Andersson, Hoff, et al. (2010), this core MIRP model can be classified as a deterministic, finite-horizon, split-pickup and split-delivery problem. The solution of this planning problem specifies routes, i.e., the sequence and times of ports visited, for each vessel as well as the quantity of product loaded or discharged in each time period by each vessel.

Having discussed the basic characteristics of a MIRP, we now attempt to distinguish this problem from the class of road-based IRPs, which have received far more attention in the literature. MIRPs possess several noteworthy idiosyncrasies that differentiate them from an IRP typically encountered in road-based applications (see, e.g., Andersson, Hoff, et al., 2010). First, the classical IRP assumes that a fleet of vehicles are located at a central depot (a single supplier) and are dispatched to customers to satisfy demand before returning to the depot in the same period. In a maritime setting, the notion of a single central depot is conspicuously absent. Likewise, vessels are typically traveling long distances and around the clock making the time dimension of the problem very important. Second, the planning horizon is typically longer in a maritime setting due to time-consuming port operations and long travel times. On the other hand, with shorter planning horizons, models for road-based applications typically require finer granularity. Third, in a maritime setting, vessels typically visit relatively few (3 or fewer) ports in succession when loading or discharging, whereas traditional IRPs may involve tens of customers to visit with a small quantity (relative to vehicle capacity) being loaded at each visit. A notable exception to this difference is in the fuel distribution problem where it is a common assumption that trucks should not visit more than 2 or 3 gas stations (see, e.g., Cornillier, Boctor, Laporte, & Renaud, 2008).

It is also important to distinguish maritime inventory routing problems from a closely related class of problems known as *cargo routing problems*. As discussed in Al-Khayyal and Hwang (2007), cargo routing problems are mainly constrained by the cargo, which is usually defined by the loading and discharging ports, and by *time windows* for loading and discharging. Inventory routing problems are constrained by inventory requirements such that the inventory level of products at ports should be maintained. In general, cargo routing is performed under more restrictive constraints since the