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The periodic supply vessel planning problem with flexible departure times and coupled vessels

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ABSTRACT

In upstream offshore petroleum logistics, periodic supply vessel planning plays an important role since it ensures the replenishment of offshore installations on a regular basis with all the necessary equipment and materials from an onshore base. The problem involves the determination of the fleet composition and of the vessel schedules over a given time horizon. We present an extended version of this problem involving flexible departures from the base and the possibility of coupling vessels by swapping their schedules. We propose a voyage-based model that can be solved exactly for small- and medium-size instances. For the solution of larger instances, we have developed an adaptive large neighborhood heuristic, which yields optimal or near-optimal solutions relatively fast on small- and medium- size instances. Its performance on larger instances is significantly better than that of alternative algorithms previously developed for the same problem.

1. Introduction

The purpose of this paper is to introduce, model and solve a new generalized periodic supply vessel planning problem (PSVPP) called the Periodic Supply Vessel Planning Problem with Flexible Departures and Coupled Vessels (PSVPP-FC). In the PSVPP and the PSVPP-FC, a fleet of heterogeneous vessels operating from a single onshore supply base supplies a set of offshore installations on a regular basis. The PSVPP-FC extends the PSVPP presented by Halvorsen-Weare et al. (2012) in two main ways. First, we introduce the concept of flexible departure times in vessel planning, and second, we consider coupled vessels. These two features are explained below. This is a real-life problem faced, for example, by the largest Norwegian oil and gas operator Statoil, but also encoutered in other companies. Supply vessels are a rather costly resource. For example, in Norway the daily charter cost of a vessel is currently around 200,000 NOK. Therefore, good planning of supply vessels is required to achieve cost-efficient supply. As we show, the two new features we consider can yield substantial cost reductions. We present a mathematical programming model for the PSVPP-FC and an adaptive large neighborhood search (ALNS) metaheuristic to solve it.

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1.1. Problem description

The PSVPP involves the simultaneous determination of the fleet composition and of the vessels schedules. A single-vessel schedule consists of a set of voyages assigned to given departure times of the planning horizon. A voyage is defined as a set of installations visited in a given sequence at specific times, starting and ending at the base.

The demand of an installation consists of tools and equipment needed to carry out exploration and production operations, as well as supplies of food and medicines. There exist some practical restrictions such as opening hours at the installations and at the base, supply vessel capacities and base capacities (expressed in number of departures per day), maximum voyage duration, and maximum number of visits on a voyage. The departures from the base to each installation are spread as evenly as possible over the planning horizon for the installations. The emphasis on the spread of departures rather than on visits results from the need to avoid delays in meeting the delivery requests from the installations. The spread of departures for an installation is achieved by imposing restrictions on the minimum and maximum numbers of departures to it within a certain time interval (sub-horizon) specified by the installation, depending on the required number of departures per week. For example, if an installation requires three departures evenly spread throughout the week, then during any sub-horizon of three days there should be at least one and at most two departures to this installation. In addition, there exists an obvious

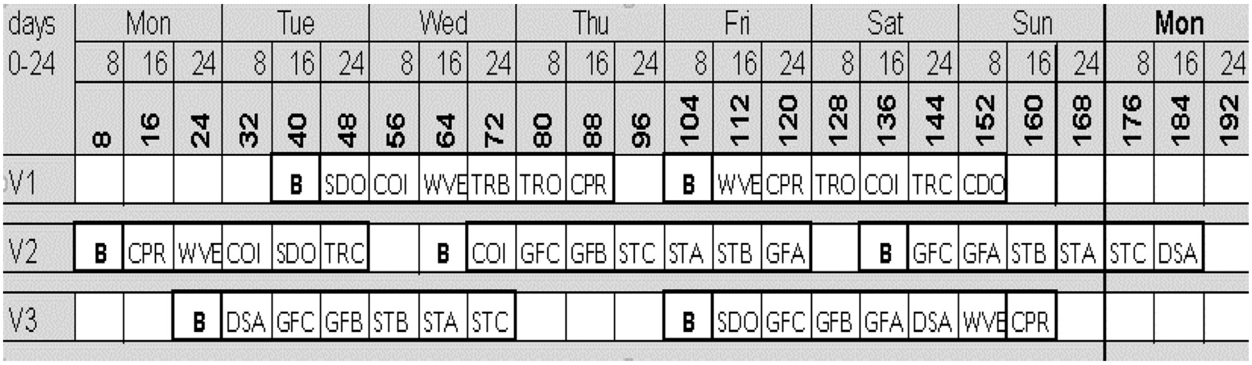

Fig. 1. Example of vessels sailing plan with flexible departures and coupled vessels.

natural constraint stating that voyages of the same vessel should not overlap in time. A vessel can only start loading and unloading operations for a voyage after it has returned to the base from its previous voyage. There may be also days (like Sundays) with no departures to any installation. In addition, each installation and the base are characterized by an average service time required for the loading and unloading operations.

The planning horizon for the vessels may be different from that of the installations. Each vessel is of a certain type which depends on its capacity and ability to serve certain sets of installations. In addition, each vessel has an associated daily charter cost, sailing speed and fuel consumption rate. The consumption rate is different during sailing, waiting and servicing at the installations, and at the base. The fuel cost is vessel-specific since vessels have different consumption rates. The vessels have a given turnaround time at the base, which this is the time needed for loading and unloading.

Compared with the PSVPP of Halvorsen-Weare et al. (2012), where there is only one possible fixed departure time for each day of the planning horizon, in the PSVPP-FC we work with a discrete set of available departure time options for the starts of voyages. We refer to this problem feature as *flexible departures*. Therefore, for each voyage the departure day and time should be determined. The use of flexible departures by companies such as Statoil is relatively recent and can only offer operational benefits since it yields a less constrained problem (this is confirmed in the computational experiments). However, it adds some difficulties from a modelling and algorithmic point of view. As far as we know, we are the first researchers to consider flexible departures.

If the planning horizon of the vessels is twice that of the installations, which is the case of Statoil, vessels of the same type may be *coupled* if certain conditions are fulfilled and if this leads to a cost reduction. Coupled vessels are vessels that swap their schedules in the second half of the vessels' planning horizon. To illustrate, we provide in Fig. 1 an example of a vessels sailing plan with flexible departures and coupled vessels (where installations have a one-week planning horizon and the vessels have a two-week planning horizon). There are three vessels (V1, V2 and V3) supplying 12 offshore installations. Vessels V1 and V2 are of the same type. Each day is subdivided into three eight-hour slots. The time is indicated by eight-hour intervals daily (row 2) and in number of hours from the beginning of the week (row 3). The schedule was constructed assuming that there are three daily possible departure times: 8 h, 16 h and 24 h. Each voyage is defined as a set of installations in the visiting sequence (marked with a bold line) preceded by an eight-hour turnaround time at the base (marked with the letter B). The three-letter codes refer to the names of the installations visited by the vessel. For example, vessel V1 starts its first voyage at 16 h on Tuesday, with loading operations at the base (B) from 8 h to 16 h, and ends at 16 h on Thursday. Looking at vessel V2, we see that its last voyage finishes on Monday of the second week. This is called an "end-of-week effect" . What is interesting here is that the first and last voyages of vessel V2 overlap (its last voyage ends on Monday at 16*h* while its loading and unloading operations start at 00*h* on Monday as well). Such a situation can be made feasible if vessels V2 and V3 swap their schedules in the second half of the vessels' planning horizon. Two conditions must be fulfilled for swapping. The first is that the two vessels involved must be of the same type (the same capacity and the same set of installations they may serve). The second condition is that the last voyage of the first vessel V2 must end earlier (before 16 h in the example) than the start of loading and unloading operations of the first voyage of the second vessel V3 (the start time is 16*h*).

In general, the coupling of vessels results in a relaxation of the voyage no-overlap constraint for vessel V2, which means that a less expensive solution may be found. Flexible departures may result in both charter and fuel cost reductions since they allow more options for the reassignment of voyages to vessels (better packing) and enabling a reduction of the waiting time at the installations (by alternating the departure time within the day).

The aim is to construct a vessel schedule in such a way that the total vessel charter costs and the voyage service and sailing costs (or fuel costs) is minimized. The following constraints must be satisfied: number and spread of departures, time windows at installations, voyage duration and number of visits per voyage, voyage overlap, vessels' capacity and base capacity.

1.2. Problem classification and literature review

The problem under study is one of several problems associated with the supply and maintenance of offshore oil and gas production facilities, which require a complex support industry (Kaiser, 2010, 2015). Our study is related to supply management, but maintenance has also given rise to a rich research area (see Bassi et al., 2012; Ribeiro et al., 2014; da Silva et al., 2014 and Ribeiro et al., 2011).

The PSVPP and PSVPP-FC belong to the family of periodic vehicle routing problems (PVRPs). See Baldacci et al. (2011) and Vidal et al. (2012) for some of the best available exact and heuristic algorithms for this problem. In the PVRP, customers specify sets of feasible visit days over a time horizon (e.g., a week) and are served by vehicles that make single-day visits. However, the PSVPP is significantly more complicated than the classical PVRP since the supply vessels make multiple-day voyages and because of the presence of other features such as time windows and constraints on the even spread of departure times. The PSVPP with fixed departures involves fleet composition decisions, which means that all voyages should be assigned to a minimum possible number of vessels. Moreover, the fleet of vessels is heterogeneous, which further