Fleet sizing for offshore supply vessels

Yauhen Maisiuk¹, Irina Gribkovskaia²

Faculty of Economics, Informatics and Social Sciences
Molde University College - Specialized University in Logistics
Molde, Norway

Abstract
Supply vessels provide offshore installations with necessary supplies on periodic basis from an onshore base according to weekly sailing plans. Each plan is built for a certain time horizon to guarantee required level of service to offshore installations at least cost. In a sailing plan several voyages are assigned to each vessel. The execution of sailing plans is affected by stochastic weather conditions. A vessel may not perform all visits within the planned voyage duration because of bad weather influencing vessel’s sailing and service time. In such cases, additional vessels may be needed. Deciding on the number of supply vessels to hire on the long-term basis is an important part of the strategic fleet size planning. We present a discrete-event simulation model that evaluates alternative fleet size configurations of vessel fleet size for an annual time horizon.

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1 Introduction
Supply vessels provide offshore installations with necessary supplies from an onshore supply base. Installations require periodic visits that are performed

¹ E-mail: yauhen.maisiuk@himolde.no
² E-mail: irina.gribkovskaia@himolde.no
according to weekly sailing plans. A weekly sailing plan consists of a set of voyages with defined start days. A vessel may sail several voyages per week. Each voyage represents a route with duration of several days, starting and ending at onshore supply base and visiting a set of installations. The problem of optimal fleet composition and periodic routing of offshore vessels was studied in [2], [4].

Each sailing plan remains unchanged for a finite number of weeks before it is renewed because of changes in installations’ demands and relocation of mobile offshore units. The sailing plan does not account for stochastic factors and therefore is used mainly for determining of fleet size. The major stochastic factor in supply vessel planning is uncertainty in weather conditions, which affects number of vessels needed to maintain the planned service. Because of delays associated with rough weather conditions some installations may not be serviced within the planned voyage duration, and not received supplies have to be delivered later with other vessels, which can significantly increase total cost of the fleet. Several approaches for creating robust weekly sailing plans are studied in [1].

The problem of determining the fleet size of vessels to hire on long-term basis to ensure supply service is an important part of the strategic fleet size planning. Similar problem for offshore anchor handling vessels was studied in [5]. We introduce a discrete-event simulation model for evaluation of alternative supply vessel fleet size configurations for an annual horizon consisting of several periods with different weekly sailing plans.

In the next section, we give an overview of the approach for construction of weekly sailing plans. Afterwards, the developed discrete-event simulation model is presented.

2 Algorithm for construction of weekly sailing plans

The two-stage method for generation of weekly sailing plans was introduced in [2]. We describe the method to introduce characteristics of the problem. At the first stage, a cheapest feasible voyage is generated for each vessel for every possible set of installations this vessel can serve within a possible voyage duration measured in days. The upper bound on a possible voyage duration is required to limit the lead time for delivery to installations included in voyage. Adding slack at the end of voyages is used to improve their robustness against weather uncertainty. Installations’ locations, visit frequencies and amount of cargo per visit define the requirements, while vessel capacity, departure time from the base and installations’ opening hours specify the constraints.
At the second stage, the selected voyages are input to a set covering model assigning voyages to start days. The model’s notation is as follows. Set $N_i$ contains all offshore installations, set $V$ contains all available supply vessels, set $T$ contains days of the planning horizon and set $L$ is the set of all possible voyage durations measured in days. Let $R_j$ be the set of pregenerated shortest feasible voyages a vessel $j \in V$ may sail, and where subset $R_{jl}$ contains voyages with a duration of $l$ days ($l \in L$). $x_{jkt}$ is a binary variable equal to 1 if vessel $j$ starts to sail voyage $k$ ($l \in L$) on day $t$, and 0 otherwise. $y_j$ is a binary variable equal to 1 if vessel $j$ ($j \in V$) is used in the solution, and 0 otherwise. Parameter $s_i$ is the required number of visits for installation $i$, and $b_t$ is the maximum number of vessels that can be loaded at the supply base on day $t$. $f_j$ defines the maximum number of days vessel $j$ may be in service during the planning horizon. $c_j$ is the daily time-charter cost of vessel $j$. The following three parameters are calculated in the voyage generator for each shortest feasible voyage. $c_{jk}$ is the fuel cost of voyage $k$ sailed by vessel $j$, $d_{jk}$ is the duration of voyage $k$ sailed by vessel $j$ in days, and $a_{ijk}$ is equal to 1 when vessel $j$ services installation $i$ on voyage $k$, and 0 otherwise. The model is formulated as follows:

$$\min \sum_{j \in V} c_j y_j + \sum_{j \in V} \sum_{k \in R_j} \sum_{t \in T} c_{jk} x_{jkt}$$

subject to

$$\sum_{j \in V} \sum_{k \in R_j} \sum_{t \in T} a_{ijk} x_{jkt} \geq s_i, \quad i \in N$$

$$\sum_{k \in R_j} \sum_{t \in T} d_{jk} x_{jkt} - f_j y_j \leq 0, \quad j \in V$$

$$\sum_{j \in V} \sum_{k \in R_j} x_{jkt} \leq b_t, \quad t \in T$$

$$\sum_{k \in R_{jl}} x_{jkt} + \sum_{k \in R_j} \sum_{q=1}^{l-1} x_{jk,(t+q) \mod |T|} \leq y_j, \quad j \in V, t \in T, l \in L$$

The objective (1) of the model minimizes the sum of the total vessel time-charter costs and the fuel costs for all voyages. The frequency constraints (2) ensure that each offshore installation gets a required number of visits during the planning horizon. The linking constraints (3) guarantee that the total duration of all voyages sailed by a vessel does not exceed the total number of
days the vessel may be in service during the planning horizon $T$, while daily berth capacity constraints (4) are used to avoid that there are more vessels loaded at the supply base on a specific day than the onshore base can serve. The constraints (5) ensure that a vessel returns to the supply base before it starts a new voyage. To ensure a steady supply from the base, the departures of cargo from the supply base to each installation should be spread. The following constraint

$$ p_r \leq \sum_{j \in V} \sum_{k \in R} \sum_{h=0}^{h_r} a_{ijk} x_{jk,(t+h) \mod |T|} \leq \bar{p}_r, \quad i \in N_r, \quad t \in T, \quad r \in F $$

(6) guarantees that the departures to an installation are evenly spread throughout the planning horizon. Here $F$ is the set containing all visit frequencies required by the installations, and $N_r$ is the set of all installations with visit frequency $r$. To control the spread of departures throughout the planning horizon, the length of an auxiliary sub-horizon for the installations with visit frequency $r$ is denoted by $0 \leq h_r \leq |T|$, where $p_r$ and $\bar{p}_r$ are defined as the lower and the upper bound on the number of visits during this sub-horizon. This solution approach can generate optimal sailing plans for instances no more than 12 installations. For larger instances, a large neighborhood search heuristic of [4] can be applied.

3 Discrete-event simulation model

The planning of supply vessel operations is critical as operations at offshore installations depend on timely supplies from the shore. The planning period consists of periods with different sailing plans that define a simulation horizon. Voyages in a sailing plan are scheduled chronologically and repeated on weekly basis for the period of the sailing plan. To perform all voyages in the sailing plan several vessels are needed. Uncertainty in weather conditions affect execution of voyages resulting in a shortage of available vessels and a need for additional vessels. The option of allowing downtime at installations is not considered as waiting costs of drilling rigs and production installations are much higher than vessel costs. The company does not own offshore supply vessels. Instead, vessels are hired on time-charter and spot hire from shipping companies. Deciding on the number of supply vessels to hire on the long-term basis is an important part of the strategic fleet size planning. This decision has a strong economic effect on the total chartering cost as daily hire rates on the spot market can fluctuate between 20,000 and 45,000 euros.

The dependence of vessel supply operations on weather conditions makes
the problem highly stochastic. In compliance with safety regulations adopted by oil and gas producers working on Norwegian continental shelf, vessel is allowed to perform service at installations (loading and unloading) when the wave height does not exceed a certain threshold. The state of the weather at the time of planned visit to an installation may affect execution of vessel sailing plan, making some visits impossible during the planned voyage duration. Installations not visited on a voyage as planned must be served individually as soon as the weather allows. If there are no available vessels, a vessel from the spot market is hired for a single-visit voyage at a higher short-term rate. Spot rates represent another source of uncertainty as they are often significantly higher and volatile as opposed to time-charter rates. Time-charter vessels are cheaper than vessels from spot market, but require much longer commitment period. Probability distributions best fitting stochastic elements inherent to the problem are difficult to handle through analytical approaches. For these reasons, discrete-event simulation is chosen as a methodology.

The objective of the work was to develop a discrete-event simulation model for evaluation of alternative configurations of the fleet size. By experimenting with various values for the design factor (number of time-charter vessels) and examining corresponding efficiency measures (total vessel hire cost and number of vessel hire days), the number of vessels on time-charter hire minimizing the total cost is determined. The logic flowchart of our simulation model is depicted in the Figure 1 and key blocks are explained below.

Discrete-event simulation model imitates a sequence of voyages as it evolves over time. The state variables of the model describe model’s state at only a countable number of points in time. The major state variable in the model is number of vessels in use. Another state variable is a number of non-performed planned visits to installations that arise because of the influence of the bad weather. The discrete points in time are the ones at which an event occurs, where an event is defined as an instantaneous occurrence that may change the state of the model [3].

The model accordingly simulates sequences of installations visit events that are triggered by corresponding voyage events. A voyage event is defined as a compound abstract object consisting of a number of visits to installations. A voyage occurs at a known start time and lasts for a planned period of time. Visit to an installation is defined as another event. These two types of events can be easily considered as processes as they are spread over time after the moment of its occurrence. The stochastic factor (weather conditions) influences on possibility and time of occurrence of installations’ visit events.

The weather generation procedure is built upon the concept of alterna-
tion of durations of two distinct states of the weather window at each of the offshore installations for the duration of the simulation horizon. The simple distinction between only two weather states (operative and inoperative) is considered for the purpose of verification of visit occurrence at installation. The weather generator relies on the sampling of durations of operative and inoperative weather from a set of estimated probability distributions with respect to offshore location and month of the year. The applied weather modeling approach is similar to the one described in [5].

![Flow diagram of discrete-event simulation model](image)

The model has been implemented in two variants. In basic version, sequence of visits on a voyage is simulated as it is stated in sailing plan. However, in real life by the time when voyage should start, the weather forecast is known, and visits to installations may be re-scheduled. To account for that, we have included in the second variant of the model a re-route procedure. It imitates re-planning actions against weather uncertainty that are taken in real-life by marine coordinators in order to provide ordered supply service to offshore installations. The re-route procedure is used to find a feasible sequence of voyage visits where maximum number of installations affected by weather will
be visited within planned voyage duration. Comparison of two model variants shows that less non-performed visits to installations on planned voyages occur if the re-route procedure is included in the model. Finally, the model allows not only to define cost-efficient fleet size, but also evaluate robustness of sailing plans.

References


