Omega 57 (2015) 271–281

Contents lists available at ScienceDirect

Omega

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

Supply vessel planning under cost, environment and robustness considerations ☆

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ARTICLE INFO

Article history:
Received 3 February 2015
Accepted 18 May 2015
Available online 2 June 2015

Keywords:
Green maritime logistics
Supply vessel operations
Ship routing and scheduling
Emissions
Speed optimization
Weather uncertainty
Robustness

ABSTRACT

Offshore oil and gas installations need reliable cargo deliveries. The vessels supplying these installations on a periodic basis are expensive and constitute a source of emissions of greenhouse gases. Incorporating vessel speed optimization into the supply vessel planning process may significantly reduce fuel consumption and hence emissions. In addition, speed optimization may yield cost reductions if the number of vessels used does not increase. A main uncertainty factor, especially in the winter season, is the weather conditions which impact sailing and service times. Cost minimization and the application of speed optimization strategies may have implications on the robustness of weekly supply vessel schedules since idle times in the schedules are reduced. We develop a simulation-optimization based methodology that considers costs, emissions and robustness in the generation of weekly supply vessel schedules. Results of analyses conducted on real instances show that robustness requirements may yield both increased emissions and costs in the winter season. However, depending on instance characteristics, different degrees of robustness can be incorporated with both costs and emissions reductions through speed optimization.

1. Introduction

Offshore oil and gas installations need reliable cargo deliveries from supply vessels in order to produce oil and gas. Cargo delivery failures may in the worst case result in a temporarily shut-down of production, with millions of dollars in lost income. However, supply vessels are an expensive logistics resource and a source of greenhouse gases emissions in offshore upstream logistics. One vessel may have a yearly cost of more than ten million dollars and produce emissions of 9000 tons CO_2. Moreover, weather uncertainty is an important factor to consider when planning for the winter season since sailing and service times increase in rough weather.

The supply vessel planning problem is multi-objective. A planner would like to obtain a cost-efficient and energy-efficient schedule with sufficient robustness against weather uncertainty to avoid frequent use of extra vessels. Cost minimization leads to a reduction in the number of vessels and in idle schedule time. Speed optimization makes use of idle time to achieve fuel consumption reductions and hence emissions reductions. To generate a robust schedule, idle time is important in order to have sufficient flexibility to deal with bad weather conditions and unforeseen events.

The contribution of this paper is threefold: first in showing how to include robustness requirements in order to ensure a certain level of robustness into the generation of supply vessel schedules, second in developing a methodology for the construction of cost efficient, green and robust vessel schedules, and third in analyzing the trade-offs between costs, emissions and robustness in supply vessel planning.

The remainder of the paper is organized as follows. Section 2 gives an introduction to supply vessel planning, including cost considerations, emissions and robustness, concluded by the aim of the paper. Section 3 provides a literature review. Section 4 describes the simulation-optimization methodology developed for generation of cost efficient, green and robust supply vessel schedules. Analyses on real instances are carried out in Section 5, and conclusions are drawn in Section 6.

2. Supply vessel planning

In supply vessel planning on the Norwegian continental shelf (NCS), each supply base has its own set of installations to serve,

☆ This manuscript was processed by Associate Editor Lodi.

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http://dx.doi.org/10.1016/j.omega.2015.05.006
0305-0483/

and each installation requires one or more visits per week. Supply vessels are used to service the installations according to a weekly schedule. This schedule is fixed for some weeks or months ahead to achieve predictability in the supply operations. A new weekly schedule is generated when the installations change locations or when there are substantial changes in the activity level of some installations.

At a tactical level, the supply vessel planning problem (SVPP) consists of constructing a weekly sailing schedule. This schedule is defined by the specification of the vessels used and by individual vessel schedules which consist, for each vessel, of a set of voyages. Each voyage starts and ends at the supply base, and is defined by a sequence of installations to visit. All sailing distances, from supply base to the installations, between the installations, and the return sailing to the supply base, are called legs of the voyage. All voyages in a weekly schedule have the same fixed start time of the day and the same time of the day for voyage completion (end time). The voyage start and end times are connected to the opening hours at the base since the loading and unloading of vessels at the base is performed during the opening hours. Fig. 1 depicts a weekly schedule. Each day of the week consists of three eight-hour slots shown as vertical lines. The voyages are shown as bars of different shades. All voyages start and end at 08:00 since the base is open from 08:00 to 16:00, and the turnaround time for loading and unloading the vessel is eight hours. Due to the fixed start and end times of a voyage, its duration is measured in days. A voyage may have a duration of more than one day due to the distant location of installations from the shore. A maximum voyage duration is imposed to ensure that all installations in a voyage will receive their supplies within this number of days from the voyage start. In the example of the weekly schedule shown in Fig. 1, the maximum voyage duration is three days, yielding from one to three voyages of two or three days for a vessel per week. Due to a circular time horizon, some voyages may start at the end of a week and end at the beginning of the following week. Offshore installations without drilling operations have daily opening hours when vessels can perform their service (for example between 07:00 and 19:00). In what follows, we will call the opening hours at an installation as its daily time window. On a voyage of several days duration, an installation with daily opening hours is visited in one of its daily time windows. To ensure short lead times from the suppliers to the installations in the upstream supply chain, the departures of the vessels (or voyage start days) visiting a particular installation should be fairly evenly spread throughout the week.

A weekly vessel schedule may have different types of vessel waiting (idle) time. Within a voyage time window, defined as the time interval between the voyage start and end, there may be waiting times before the start of the opening time at the installations and some waiting time before the start of the opening hours at the base after vessel arrival. There may also be waiting time at the base between voyages in a schedule. All these waiting times create a schedule slack which can be used to reduce speed, or as a buffer against bad weather conditions.

In the supply vessel planning problem, as in most real-world problems, several objectives must be considered. In the construction of weekly schedules, trade-offs must be made between costs, emissions and robustness considerations. It may be impossible to find a single schedule that simultaneously optimizes costs and emissions along with the incorporation of robustness requirements. Improving one objective may result in worsening another one, for example increased robustness requirements may yield increased costs if an extra vessel is required.

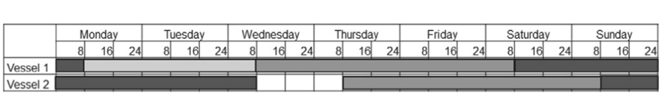

Fig. 1. Weekly schedule.

2.1. Costs

Supply vessels are an expensive resource within the offshore upstream logistics. Statoil, the largest oil and gas operator on the NCS, hires the vessels and plans the supply vessel operations including the generation of weekly schedules. The costs considered in the planning process are the sum of the charter cost and of the fuel cost for each vessel, the vessel charter cost being considerably higher than the fuel cost. An increase in the number of vessels therefore yields a substantial increase in the total cost, and the operator will try to minimize the number of vessels required for the supply vessel service. The schedule fuel consumption is the sum of the fuel consumed when sailing, waiting at the installations and servicing the installations.

Cost minimization coincides with the minimization of fuel consumption (and emissions) as far as there is no need for extra vessels. However, a cost minimization objective can result in little slack in the weekly vessel schedule, yielding frequent delays of consecutive voyages and offering few possibilities to reduce speed and hence emissions.

2.2. Emissions

Supply vessels are one of the largest sources of emissions in offshore upstream logistics. A vessel using marine gas oil as fuel generates emissions of carbon dioxides (CO_2), nitrogen oxides (NOx), sulphur oxides (SOx) and particles (PM). Emissions of CO_2 and SOx are linearly dependent on the carbon and sulphur content of the fuel, while emissions of NOx and PM are dependent on both the amount of fuel consumed and the engine conditions. In sea transport, fuel consumption is dependent on speed, payload, hull conditions and weather conditions [40]. Speed is a key determinant of fuel consumption, and fuel consumption can be approximated as a cubic function of speed per time unit [39]. A 20% reduction in speed may yield a nearly 50% reduction in fuel consumption, and a more than 30% reduction in fuel consumption per distance sailed. Moreover, a vessel will consume more fuel when sailing in rough weather than in calm sea due to the added resistance from waves and wind, see for example Lindstad et al. [31] for a thorough description.

Emission reductions through speed optimization may lead to the use of extra vessels and thereby to increased costs. Moreover, speed reductions without fleet size increase may yield little slack in the schedule and thus a reduced time buffer necessary to withstand bad weather.

2.3. Robustness

Weather factors such as waves, wind and currents significantly impact vessel operations [31,40]. For supply vessel operations, weather influences both sailing and service at offshore installations. The planners of offshore supply consider wave height as the most important weather factor since it affects sailing time, service duration, and may cause waiting at installations for the start of service due to safety regulations for loading and unloading operations. In what follows, we consider weather as an univariate variable of significant wave height defined as the average of the one-third highest waves during a period of 20 min [35]. The Norwegian Meteorological Institute has compiled historical data for significant wave heights every three hours since September 1957 for a set of locations in the North Sea. For a single point the wave heights in a given three-hour time period are highly dependent on those observed in the previous time period. Since