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A simulation study of the fleet sizing problem arising in offshore anchor handling operations

Aliaksandr Shyshou [a,*], Irina Gribkovskaia [a], Jaume Barceló [b]

[a] Molde University College, Postbox 2110, N-6402 Molde, Norway

[b] Department of Statistics and Operations Research, CENIT, Universitat Politècnica de Catalunya, Campus Nord, Edifici C5, Office 215, Jordi Girona Salgado 1-3, 08034 Barcelona, Spain

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ABSTRACT

A fleet sizing problem arising in anchor handling operations related to movement of offshore mobile units is presented in this paper. Typically, the intensity of these operations is unevenly spread throughout the year. The operations are performed by dedicated vessels, which can be hired either on the long-term basis or on the spot market. Spot rates are frequently a magnitude higher than long-term rates, and vessels are hired on the spot market if there is a shortage of long-term vessels to cover the ongoing anchor handling operations. Deciding the cost-optimal fleet of vessels on the long-term hire to cover future operations is a problem facing offshore oil and gas operators. This decision has a heavy economic impact as anchor handling vessels are among the most expensive ones. The problem is highly stochastic because durations of anchor handling operations vary and depend on uncertain weather conditions. Moreover, future spot rates for anchor handling vessels are extremely volatile. The objective of this paper is to describe a simulation model for the fleet sizing problem. The study was initiated by the largest Norwegian offshore oil and gas operator and has received considerable acceptance among the planners.

1. Introduction

This study was initiated by the Norwegian offshore oil and gas operator StatoilHydro. Drilling operations, performed by drilling rigs, are an essential part of oil and gas exploration and production process. Most drilling rigs in the portfolio of StatoilHydro are mobile units moored to the seabed by anchors. Upon completion of the drilling operations at a given location, a rig is typically moved to a different location. Rig movements usually follow an annual plan. To perform a rig move, a number of anchor handling tug supply (AHTS) vessels are needed. The company does not own AHTS vessels: these are hired from the shipping companies. There are basically two types of hire contracts: long-term and spot (short-term). Spot rates are frequently significantly higher than the long-term ones, sometimes by an order of magnitude, and spot vessels are usually hired when there is a shortage of vessels on long-term contracts. The option of a rig waiting for long-term AHTS vessels to become available is not considered as rig waiting costs are much higher than vessel costs. Deciding on the number of AHTS vessels to hire on the long-term basis is an important part of the strategic fleet size planning. This decision has a heavy economic impact as AHTS vessels are among the most expensive ones (daily hire rates on the spot market may be as high as 900,000 Norwegian Kroner (NOK), corresponding to approximately 100,000 euros).

The dependence of anchor handling operations on weather conditions adds considerably to the problem complexity. Normally these operations cannot be performed when the wave height exceeds a certain threshold. Another challenge lies in the fact that each drilling rig is a separate organizational unit whose drilling schedule is planned independently. As a result, rig moves quite often overlap and the company should have enough AHTS vessels to cover several rig moves being performed simultaneously. The unpredictability of weather conditions and vessel rates makes the problem highly stochastic. Moreover, as later analysis will show, probability distributions best describing stochastic phenomena inherent to the problem are non-trivial and quite complex to handle through analytical approaches. For these reasons discrete-event simulation has been chosen as a methodology.

The objective of the work described in this paper was to design and develop a discrete-event simulation model for evaluation of alternative AHTS fleet size configurations. According to Law and Kelton (2000) discrete-event simulation concerns the modeling of a system as it evolves over time by a representation in which the state variables change instantaneously at separate points in time. These points in time are the ones at which an *event* occurs,

* Corresponding author.
E-mail addresses: Aliaksandr.Shyshou@himolde.no (A. Shyshou), Irina.Gribkovskaia@himolde.no (I. Gribkovskaia), jaume.barcelo@upc.edu (J. Barceló).

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where an event is defined as an instantaneous occurrence that may change the state of the system. Experimenting with a simulation model frequently amounts to varying a number of inputs (usually referred to as *experimental design factors*) and examining respective changes in certain outputs (also called *efficiency measures*). In this paper, we describe a model used to simulate a sequence of rig move events. Each event starts at a discrete point in time and triggers a type-specific set of anchor handling operations changing the number of moves being performed and the number of vessels being used, which are major state variables. Stochastic factors include weather conditions and durations of anchor handling operations. The annual vessel hiring cost, consisting of long-term hire cost and spot hire cost, is used as an efficiency measure. Future spot rates for AHTS vessels and number of vessels on long-term hire are regarded as experimental design factors. The output analysis aims at identifying the number of AHTS vessels on long-term hire minimizing the total vessel hiring cost depending on future spot rates.

The remaining of the paper is organized as follows. The next section contains a relevant literature review. In Section 3 a more thorough problem description is given together with the conceptual design of the simulation model. Input modeling is the subject of Section 4. The implementation of the proposed simulation model is presented in Section 5. Output analyses are carried out in Section 6. Finally, some conclusions are drawn in Section 7.

2. Literature review

The real-life fleet-sizing problem presented in this paper is highly stochastic, which justifies the use of a simulation approach. The literature review therefore focuses on the application of discrete-event simulation to problems involving fleet sizing decisions. We make a distinction between maritime and other applications. For each publication we identify major uncertainty factors inherent to the problem studied and efficiency measures used to evaluate the performance of the system, and we relate them to our problem whenever this is relevant.

Within maritime sector applications there are two relevant recent surveys of the ship routing and scheduling literature Christiansen et al. (2004) and Christiansen et al. (2007). In the vast majority of papers reviewed, analytical methods, as opposed to simulation, are used to solve fleet sizing problems, which is perfectly justified in deterministic contexts. However, there are a few publications using discrete-event simulation to capture the stochastic nature of the problems studied.

Darzentas and Spyrou (1996) have developed a simulation-based decision aiding tool for transport system design in the Aegean Islands. The sources of uncertainty include demand variance and weather conditions. Using the simulation model, the authors have compared several combinations of different vessel types, harbour layouts, routes, passenger and vehicle demands, and even the establishment of new ports. The main measures of efficiency include the fraction of covered demand, the maximum number of ships queueing in ports, as well as vehicle and passenger delays. It is noteworthy that, during the simulation, a ship departure may be delayed by the weather, while in our application a starting time of an anchor handling operation may be delayed by the weather when the vessel is already offshore.

Richetta and Larson (1997) have described an application of discrete event simulation to model the increased complexity of New York City's refuse marine transport system. Waste trucks unload their cargo at land-based transfer stations where refuse is placed in barges and then towed to the Fresh Kills Landfill in Staten Island. An advanced dispatching module was incorporated into the simulation model. Major randomness factors consisted of site-dependent refuse rates. The authors demonstrated that the model reasonably well tracked the behavior of the real system. A cost evaluation model was also developed to assess different system designs. Efficiency measures of interest included deferred refuse tonnage and tug utilization rates. This work is an extension of an earlier study by Larson (1988).

An application of simulation techniques to determine the most convenient composition of owned and leased refrigerated containers for the transpacific cargo trade was presented by Imai and Rivera (2001). The authors developed a cost evaluation of five different owned container fleets for five random demand patterns. If a given fleet size is insufficient to cover the cargo demand, additional containers are leased from the spot market – a provision shared with our model. A general setup is also quite similar to our model – quantifying the impact of owned fleet size on the total cost.

Fagerholt and Rygh (2002) have performed yet another simulation study on the design of a sea-borne system for fresh water transport from Turkey to Jordan. In this paper, the authors have described a problem faced by a major international shipping company. Fresh water is to be transported at sea with high regularity from Turkey to discharging buoys by the coast of Israel, then in pipelines from the buoys to a tank terminal ashore, and finally through pipeline from Israel to Jordan. Breakdowns of ship, buoy and pipeline facilities were identified as stochastic elements. The analysis aimed at answering questions regarding the required number, capacity and speed of vessels, the capacity and number of discharging buoys, the design and capacity of pipelines and the capacity of the tank terminal. The main efficiency measures consisted of ship waiting times, the number of pipeline stops and the maximum level of storage in the tank.

Simulation modeling of crude oil lightering in Delaware Bay was proposed by Andrews et al. (1996). Crude oil destined for Philadelphia area refineries is transferred to lighters from the tankers in Delaware Bay because the channel in the Delaware River is too shallow for fully loaded tankers. Lightering is the process of transferring crude oil from tankers to lighters (smaller ships). Simulation was seen as the appropriate methodology as the tanker arrivals were random and service time was largely uncertain due to the weather and the amount of crude to lighter. Weather uncertainty is accounted for by assigning each barge a weather sensitivity parameter, which measures to what extent weather conditions influence lightering operations. The authors have developed a simulation model to study the effects of various policies on service levels. The results were used by a provider of lightering services and its largest customer to examine ways in which they could improve their working relationship. The customer considered alternative lightering solutions, including doing its own lightering. The results of the simulation study showed that acquiring a separate fleet can be costly and allowed both parties to evaluate other alternatives for reducing costs and improving response times.

Vis et al. (2005) have described a fleet sizing problem for the vehicles transporting containers between unloading buffer areas and storage areas at a maritime container terminal. Each container in the buffer area has a time window in which the operation can start. The objective is to minimize the vehicle fleet size such that the transportation of each container starts within its time window. The authors have developed an integer linear programming model to solve the problem of determining vehicle requirements under time-window constraints. Discrete-event simulation was used to validate the estimates of the vehicle fleet size by the analytical model. Parameters described stochastically in the simulation model included crane cycle times, release times of containers and vehicle travel times. The objective of the simulation is to examine how many vehicles are required to transport all the containers in such a way that the unloading time of the ship is minimized. A close agreement between the results of the analytical and simulation models was observed.

We now proceed to some applications outside the maritime domain. Quadrifoglio et al. (2008) have studied the impact of specific operating practices used by demand responsive transit providers on productivity. The authors have applied simulation to investigate the effect of using a zoning versus a no-zoning strategy and time window settings on performance measures such as total trip miles, deadhead miles and fleet size. Contrary to our problem, the fleet size in this application is an efficiency measure rather than an experimental design factor. Empirical distributions for types of request, call-in times, pick-up times as well as spatial distributions for pick-up and drop-off locations are an integral part of the input.

An application of simulation to tactical locomotive fleet sizing for freight train operations is presented by Godwin et al. (2008). A railroad system in which an *a priori* freight train schedule does not exist is considered. Random order arrival rates at each station considerably complicate locomotive fleet size planning. Simulation is therefore chosen as a solution approach and the study shows that the throughput increases with the number of locomotives up to a certain level. After that, the congestion caused by the movements of large number of locomotives in the capacity constrained rail network offsets the potential benefit of a large fleet.

To the best of our knowledge, the application we consider is original and the problem has not been previously studied. Moreover, our weather modeling, specifically designed for weather dependent operations, is quite novel.

3. Problem description and modeling considerations

Drilling operations of StatoilHydro in the Norwegian Sea and the Barents Sea are mostly performed in four offshore operation regions: the North Sea region, the Western region, the Northern region, and the Barents Sea region. AHTS vessels are loaded with necessary anchor handling equipment at four main onshore bases: Bergen, Mongstad, Kristiansund and Hammerfest. Spot vessels in most cases arrive from the British Sector, namely from Aberdeen. The Norwegian continental shelf onshore bases and offshore operation clusters are depicted in Fig. 1.

The Marine Operations department in StatoilHydro is responsible for the planning and follow-up of rig moves for contracted drilling rigs. For each such move, three or four anchor handling vessels

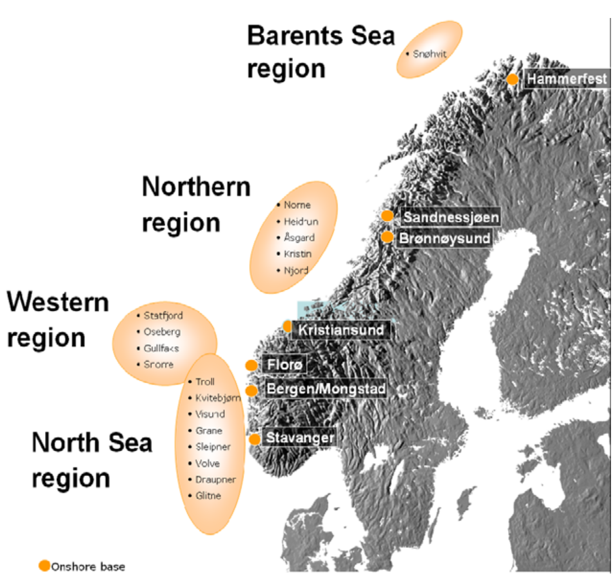

Fig. 1. StatoilHydro onshore bases and operation regions.

are normally required for a number of days. Based on individual drilling rig schedules, the Marine Operations department compiles a preliminary annual rig moving plan. For a given rig move, it contains the information regarding the new rig location, the starting date of the move, the AHTS vessels and mooring equipment to be used, as well as other relevant information. The rig moving plan is approximate and is subject to periodic revisions. A conventional rig move involves the following operations:

1. vessel mobilization (preparing for the move and loading necessary equipment at the mobilization base);
2. sailing to rig location;
3. anchor recovery from the seabed;
4. towing the rig to new location;
5. anchor deployment (running anchors into the seabed) with tension test (to ensure anchors are properly set);
6. sailing to base;
7. vessel demobilization (reporting and unloading the equipment).

We will refer to anchor recovery and anchor deployment with tension test (operations 3 and 5) as anchor handling operations. Sometimes anchors have to be pre-laid at the future rig location, which means that only operations 1,2 and 5–7 are performed by AHTS vessels. When the rig is later towed to its new location, it has to be connected to a pre-laid system which saves some time during operation 5. Occasionally, rigs have to be brought to onshore repair shop, requiring steps 1–4 or 2–4. After being repaired rigs are typically brought back offshore. Conventional rig moves, pre-lay operations and connecting to a pre-laid system will be referred to as *major rig move operations*. *Minor replacement and repair operations* (e.g. chain replacement in an anchor line) also require AHTS vessels and are reflected in the rig moving plan.

Anchor recovery and anchor deployment with tension test are weather-dependent operations. Significant wave height (SWH) is a measure used to quantify weather conditions for anchor handling operations. It is defined as the average height (trough to crest) of the one-third largest waves. Current safety norms disallow anchor handling operations when SWH exceeds 3.5 meters. A *weather window* for an anchor handling operation is the time period during which SWH is less than 3.5 meters for at least 1.5 times longer than the expected time of the operation. The time period during which an AHTS vessel is waiting for a weather window to perform an anchor handling operation is referred to as wait-on-weather (WOW).

Each drilling rig operates independently of the others, which means that sometimes rig moves come sequentially, and sometimes partly or fully in parallel. Moreover, rig moves are often delayed by long WOW periods. In addition, during the operations, AHTS vessels experience a great variety of delays mostly related to equipment breakdowns (most frequently winches on AHTS vessels). These delays are grouped into a compound Wait-on-Platfrom (WOP) term. WOP delays mostly occur prior to anchor recovery. As a result there are frequently more overlapping rig moves than initially planned. This implies that the number of vessels in use at any given moment may be quite high depending on the total number of rig moves being performed. As a result during the peak operation periods there may not be enough long-term AHTS vessels to cover all the rig moves being performed simultaneously, and additional vessels may have to be hired on the spot market. Spot rates are extremely volatile and can be several times higher than the long-term ones. Challenged with the uncertainties in weather conditions and future spot rates for AHTS vessels, the company wanted to have a tool that would enable it to evaluate the impact of different future spot rates on the cost-optimal number of AHTS vessels on long-term hire.

We propose a simulation-based prototype for such a tool. The engine of the tool is a model in which a succession of rig move events are simulated. Each rig move event, depending on its type, triggers a sequence of operations whose durations are sampled from respective probability distributions. The model logic ensures that the weather-dependent anchor handling operations are affected by the weather. Weather conditions are represented by high-sea periods (SWH above 3.5 meters) and low-sea periods (SWH at most 3.5 meters) whose durations are generated for each cluster of drilling locations according to month-specific distributions. High-sea and low-sea periods alternate and an anchor handling operation is only allowed to start when its weather window fits the remaining duration of the low-sea period. Additionally WOP delays are generated according to a probability distribution expression best describing historical data. Upon completion of a rig move, the starting time for the next move of a given rig is updated accounting for the delays experienced during the currently completed move. Occasionally, a rig move event may start with less than the required number of long-term AHTS vessels available. In this case additional vessels have to be hired from the spot market. Frequently, these additional vessels arrive from Aberdeen. Spot rates are generated according to quarter-specific probability distributions. The total vessel hiring cost for the simulation period of specified length, consisting of long-term and spot components, was used as an efficiency measure. The simulation objective is to evaluate the impact of two experimental design factors (future spot rates and number of vessels on long-term hire) on the chosen efficiency measure.

4. Input specification and modeling

This section contains basic model assumptions and general data considerations. We also describe the modeling of major inputs: rig move durations, high-sea and low-sea period durations, and specification of daily hire rates for AHTS vessels. Many of these phenomena will be described by random probability distributions. Relevant distributions are displayed in Table 1 (refer to Law and Kelton (2000), whose notation we follow, for a more detailed description of these distributions).

4.1. General assumptions and data considerations

The rig moving plan for the year 2008, with 68 operations related to anchor handling involving 17 mobile drilling rigs, was used as the primary source of information. For each operation the plan specifies its type (conventional rig move, pre-lay operation, connecting to a pre-laid system or minor repair–replacement operation), the drilling rig involved in the operation, the tentative starting date, the new drilling destination (irrelevant for minor repair–replacement operations), and the mobilization base.

Sometimes the number of vessels required for a given operation is specified in the rig moving plan. When this is not the case, according to historical data, about 45% of major rig move operations require three vessels and the remaining 55% require four vessels. Minor repair and replacement operations normally require one AHTS vessel. According to a subject matter expert (SME) opinion, when an AHTS vessel is hired on the spot market, there is a 20% chance that it is on the Norwegian continental shelf and 80% chance that it is in Aberdeen. The duration of a long-term vessel hire contract is at least one year.

For simulation purposes, the four offshore operation regions were disaggregated into 11 clusters. Each of the 11 clusters is defined by its *center* whose latitude and longitude coordinates are averages of the locations defining the cluster. Moreover, each cluster has an associated *diameter* measure related to its spatial characteristics (the larger the cluster the larger the diameter). Pairwise distances between cluster centers and mobilization bases were then calculated by means of the great circle distance formula (using the equatorial radius). For between-cluster rig moves, distances between cluster centers were used. For intra-cluster rig moves, the distance was sampled from a continuous uniform distribution between 0 and the cluster diameter.

4.2. Operation durations

In this subsection we describe a way to model the durations of the operations associated with a rig move.

4.2.1. Mobilization, demobilization and sailing durations

Sailing and towing times are based on respective distances and vessel speeds (12 nautical miles per hour for sailing, four nautical miles per hour for towing). Based on discussions with SMEs, it has been determined that a probability distribution best describing time to mobilize a vessel is *triang* (6,24,24), that is, the maximal and the most likely value is 24 hours, but occasionally it can be done faster. Similarly, a probability distribution best describing time to demobilize a vessel is *triang* (4,8,12).

Table 1
Notation for random probability distributions.

Notation	Description	Probability density function
expo (β)	Exponential distribution with mean parameter β	$f(x) = \begin{cases} \frac{1}{\beta}e^{-\frac{x}{\beta}} & \text{for } x > 0 \\ 0 & \text{otherwise} \end{cases}$
gamma (β, α)	Gamma distribution with shape parameter α and scale parameter β	$f(x) = \begin{cases} \frac{\beta^{-\alpha}x^{\alpha-1}e^{-\frac{x}{\beta}}}{\Gamma(\alpha)} & \text{for } x > 0 \\ 0 & \text{otherwise} \end{cases}$
beta (β, α)	Beta distribution with shape parameters β and α	$f(x) = \begin{cases} \frac{x^{\beta-1}(1-x)^{\alpha-1}}{B(\beta,\alpha)} & \text{for } 0 < x < 1 \\ 0 & \text{otherwise} \end{cases}$
triang (a, m, b)	Triangular distribution with minimum (a), mode (m), and maximum (b) values specified as real numbers $a < m < b$	$f(x) = \begin{cases} \frac{2(x-a)}{(m-a)(b-a)} & \text{for } a \leqslant x \leqslant m \\ \frac{2(b-x)}{(b-m)(b-a)} & \text{for } m \leqslant x \leqslant b \\ 0 & \text{otherwise} \end{cases}$
Weibull (β, α)	Weibull distribution with shape parameter α and scale parameter β	$f(x) = \begin{cases} \alpha\beta^{-\alpha}x^{\alpha-1}e^{-(x/\beta)^{\alpha}} & \text{for } x > 0 \\ 0 & \text{otherwise} \end{cases}$
LN (μ_l, σ_l)	Lognormal distribution with scale parameter $\mu = \ln(\mu_l^2/\sqrt{\sigma_l^2 + \mu_l^2})$ and shape parameter $\sigma = \sqrt{\ln[(\sigma_l^2 + \mu_l^2)/\mu_l^2]}$	$f(x) = \begin{cases} \frac{1}{x\sqrt{2\pi\sigma^2}}e^{-\frac{(\ln(x)-\mu)^2}{2\sigma^2}} & \text{for } x > 0 \\ 0 & \text{otherwise} \end{cases}$

4.2.2. Anchor handling and WOP durations

In reality, the duration of an anchor handling operation depends on a number of factors, including the sea depth, the complexity of the infrastructure on the seabed, the type of mooring equipment used, etc. The functional relationship between these factors and the duration of the rig move is difficult to establish. However, as indicated by the SMEs, historical data give a fair idea of the variation in anchor handling operation durations.

More than 80 detailed rig move reports (for the years 2005–2008) were studied to collect the data related to anchor handling operation durations. Some of the reports contained incomplete information and the number of usable reports was reduced to 71. Extensive historical data (years 2002–2007) are also available for WOP durations. The data related to WOP and anchor handling durations are summarized in Table 2. The "Maximum" column contains a maximum duration of the respective operation over the number of observations given in the second column. The "Mean" and "Standard deviation" columns are self-explanatory. All durations are measured in hours.

To generate the durations of anchor handling operations and WOP during simulation, we fit theoretical probability distributions to the historical data. Typical statistical procedures to assess the quality of fit are Kolmogorov–Smirnov (K–S) and Chi-square tests. The results are displayed in Table 3.

A small p-value for a test (say less than 0.05) is an indication of a poor fit. It can be seen that the quality of the fit for the WOP duration is low for both tests. However, none of the theoretical distributions provided a statistically valid fit. As a general rule in such situations, the distribution expression minimizing the square error of the fit was chosen. To illustrate, the fitting of a theoretical probability distribution for the duration of anchor recovery operation is depicted in Fig. 2.

The duration of anchor handling operations (recovery and deployment) in Tables 2 and 3 are reported as performed by one AHTS vessel, e.g. if an anchor handling operation actually takes 24 hours and is performed by three vessels, its duration is 24×3=72 hours. During the simulation, the sampled anchor handling (recovery and deployment) durations for one vessel are divided by the number of vessels assigned to the rig move to obtain the actual duration of an anchor handling operation.

4.3. Weather modeling

The Norwegian Meteorological Institute maintains a grid of sensors in the Norwegian sea, which, among other information, register SWH. These data are occasionally of unacceptable quality (e.g. due to sensor breakdowns) and were therefore not used. However, the data "hind forecasted" with the help of a meteorological model are available for each grid point from January, 1955 to December, 2006. The SWH data are discretized and reported on a 6-hour basis.

We have identified the nearest grid point for each of 11 offshore operation clusters and transformed the data into month-specific durations of high-sea and low-sea periods using linear interpolation between neighboring 6-hour measurements. These durations were then used to fit theoretical distributions for high-sea and low-sea period durations for each month and each grid point, yielding a total of 2 (high and low) $\times$11 (number of clusters) $\times$12 (number of months) = 264 distributions. The probability fitting procedure is identical to the one of Section 4.2.2. Table 4, whose entries are calculated based on the 52-year period (1955–2006) of "hind forecasted" data for the grid point nearest to the Ormen Lange cluster (63.67 northern latitude, 6.09 eastern longitude), is helpful in understanding SWH modeling.

The "Mean" and the "Standard deviation" columns contain average duration (in hours) of the high-sea period starting in a given month and its standard deviation respectively. The "Maximum" column reveals the longest continuous high-sea period starting in a given month during the 52-year period. The number of high-sea periods starting in a given month during the 52 years is found in the "Number of observations" column. This is the number of observations we have used to fit a probability distribution expression given in the "Distribution expression" column. Not surprisingly high-sea period durations tend to be longer in winter and shorter in summer. There is a pair of such tables for each cluster. High-sea and low-sea periods for each cluster are sampled one after the other (high-sea period, then low-sea, then high-sea again, etc.) from identified month- and location-specific distributions.

4.4. Vessel rates

The daily long-term hire rate was set to the average of long-term rates for vessels already on hire. AHTS vessel spot rates forecasts for the period from the second quarter of 2008 to the fourth quarter of 2009 were produced based on historical quarterly data (from the first quarter of 1997 to the first quarter of 2008). The SPSS 15.0 for Windows software was used as a time series analysis tool. A simple seasonal model was chosen by the expert option of the Time Series Modeler. Upper and lower 95% confidence levels were also reported (UCL and LCL, respectively). The historical data and the predicted data with their confidence levels are depicted in Fig. 3.

It has been decided to distinguish between three scenarios for the future spot rate: average, above average, and below average. This corresponds to considering three future scenarios from the perspective of the company: average, pessimistic and optimistic. During the simulation experiments, spot rates were generated according to quarter-specific distributions shown in Table 5.

The value of δ was set to 0.3, resulting in 30% higher than average spot rates under the above average scenario and in 30% lower than average spot rates in the below average case. The triangular distribution was mainly chosen for its simplicity since the main goal is to perform a comparison study.

Table 2
Operation durations: data summary.

Operation	Number of observations	Mean	Standard deviation	Maximum
WOP	1045	20.9	28.7	238
Anchor recovery	71	86.2	29.9	172
Anchor deployment with tension test	71	94.5	46.3	286

Table 3
Distributions best describing operation durations.

Operation	Distribution expression	K–S test p-value	Chi-square test p-value
WOP	*Weibull* (18.8, 0.727)	<0.01	0.0366
Anchor recovery	31+ *Weibull* (61.6, 1.84)	>0.15	0.271
Anchor deployment with tension test	20+ *gamma* (31.1, 2.39)	>0.15	0.00516

5. Model implementation, verification and validation

In this section, we discuss the implementation, verification and validation of the simulation model in Arena 9.0 (a simulation software package developed by Rockwell Software whose detailed description can be found in Kelton et al. (2003)). Arena was chosen for three reasons:

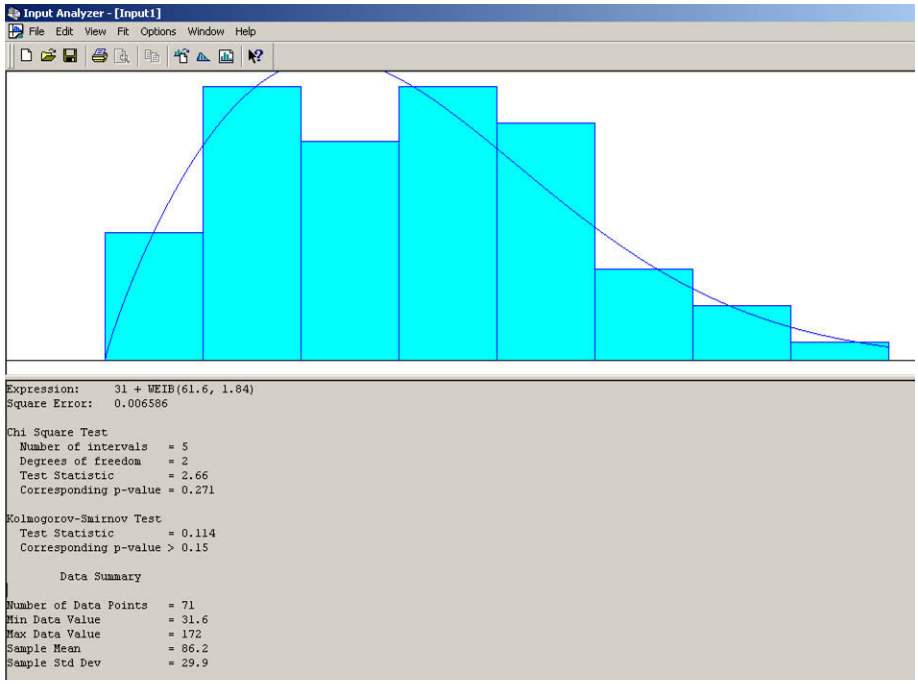

Fig. 2. Fitting a theoretical probability distribution for the duration of anchor recovery operation.

Table 4
High-sea period durations for Ormen Lange cluster ((63.67*N*, 6.09*E*).

Month	Number of observations	Mean	Standard deviation	Maximum	Distribution expression
1	271	65.8	82.4	554	2+ *LN* (72.6,153)
2	219	62.7	69.3	377	2+ *Weibull* (56.9,0.883)
3	247	48.6	55.3	316	1+ *LN* (50.1,77.8)
4	192	33.4	27.7	143	1+ *Weibull* (34.6,1.21)
5	102	29.5	26.4	154	1+ *expo* (28.5)
6	78	23.5	17.3	73.1	2+ *expo* (21.5)
7	54	19.6	14.7	59.5	2+ *Weibull* (19,1.27)
8	58	24.6	16.5	70.7	3+ *Weibull* (22.9,1.22)
9	171	37.3	30.9	213	2+ *Weibull* (36.8,1.12)
10	253	46.3	45.7	252	2+ *expo* (44.3)
11	279	48.5	45.4	275	2+ *Weibull* (47.3,1.04)
12	287	68.8	76.8	482	2+ *Weibull* (64.5,0.93)

- It combines the ease of use of high-level simulators with the flexibility of general-purpose programming languages. This enables convenient modeling and a more efficient implementation using Arena's Object Model and its integration with Microsoft Excel for reading the inputs and writing out the outputs for later analysis.
- It includes dynamic animation in the same work environment, which was very helpful in model development and extremely useful in explaining the model logic to the company.
- It provides integrated support for statistical design and analysis. Most of the input probability distributions were identified with the help of Arena Input Analyzer.

5.1. Implementation

A top-level flowchart for the simulation model is depicted in Fig. 4. Before the simulation, the inputs are read from a Microsoft Excel input file. The "Build input-dependent model structure" arrow means that after reading the inputs, the logic for generic "*Perform anchor handling operations* submodel" is replicated and made location-specific for each cluster. Cluster- and month-specific weather (high-sea and low-sea durations) probability distributions are also initialized. Such an input-dependent model initialization eases model reusability with different input specifications. When the inputs are read and input-dependent model structure is built, simulation begins. The simulation model itself consists of a number of submodels. In the remaining part of this section we briefly describe these submodels and how they interact with each other.

"Trigger rig move events and allocate vessels" submodel. At the initialization stage, the rig moving plan is read from the input file and an entity is created for each anchor handling operation in the rig moving plan. Each such entity is released a certain time (normally 72 hours; 96 hours for remote clusters) prior to the move start. If the number of AHTS vessels is not specified in the rig moving plan it is generated according to the distribution specified in Section 4.1. Then, the required number of nearest long-term AHTS vessels is located. This is justified as vessels mobilize and demobilize at the same base, which means that they return to the same base after completing the rig move. This tends to make any extra movements of the vessels between the bases suboptimal. AHTS vessels stay at an onshore base when they are not used, because of crew and safety considerations.

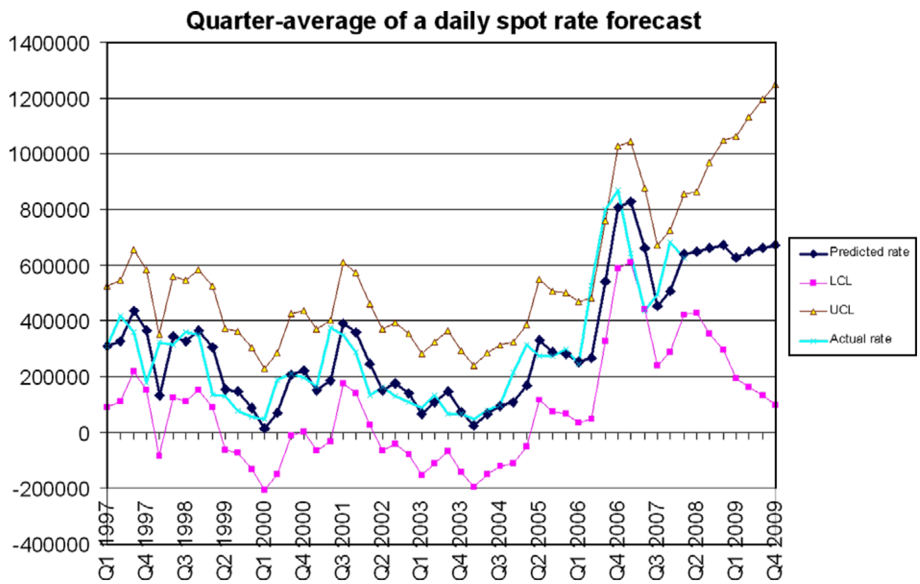

Fig. 3. Quarter-average spot rate forecasting in NOK.

Table 5
Modeling future spot rates.

Future spot rate scenario	Distribution expression
Average	$triang\ [LCL, Forecast, UCL]$
Above average	$triang\ [(1+\delta)LCL, (1+\delta)Forecast, (1+\delta)UCL]$
Below average	$triang\ [(1-\delta)LCL, (1-\delta)Forecast, (1-\delta)UCL]$

AHTS vessels, which are hired on long-term basis, are paid for irrespective of whether they are used or not. A practical implication of this is that long-term vessels are utilized, whenever they are available. If there is a shortage of long-term vessels, the number lacking is hired on the spot market. Spot rates are generated according to quarter-specific probability distributions of Section 4.4. The vessels assigned to the anchor handling operation are then brought to a specified mobilization base.

"Perform anchor handling operations" submodel. Depending on the type of the rig move (as described in Section 3), necessary operations are performed whose durations are sampled from probability distributions of Section 4.2. Anchor recovery and deployment operations are only allowed to start when the remaining duration of low-sea period is 1.5 times longer than the operation duration (as mentioned in Section 3), thereby ensuring compliance with safety regulations. Upon completion of a rig move, the starting time for the next rig move of a given drilling rig is updated accounting for delays (WOW and WOP) that took place during the currently completed rig move.

"Weather generation" submodel. For each operation cluster high-sea and low-sea periods are generated alternately from cluster- and month-specific distributions described in Section 4.3.

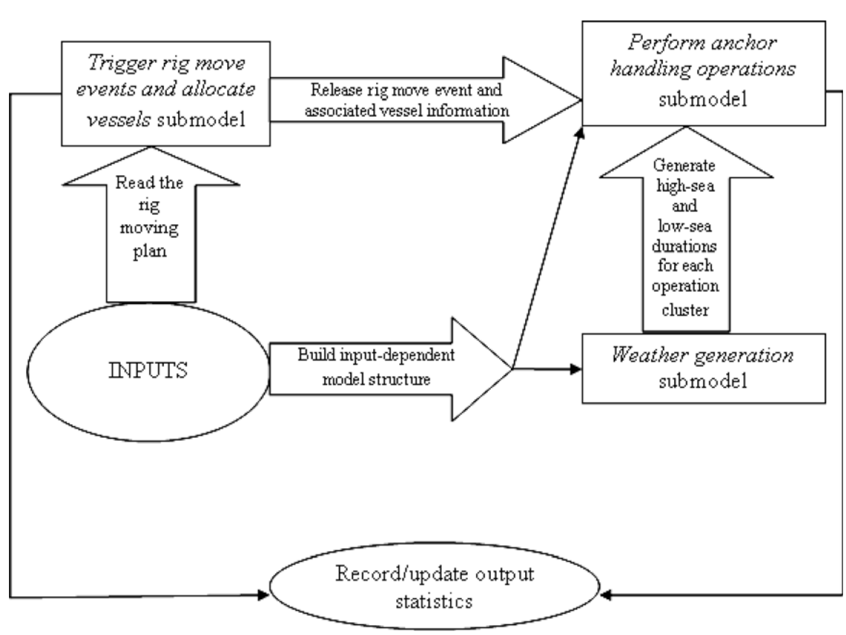

Fig. 4. Arena implementation flowchart.

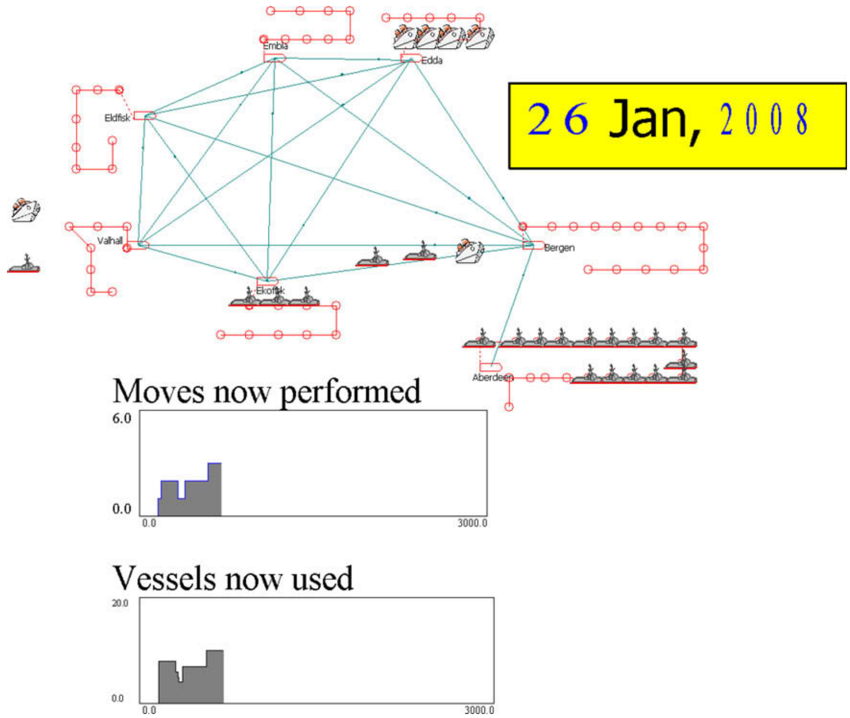

Fig. 5. Simulation model animation.

5.2. Verification

Animation is an important aid in verifying the model. Fig. 5 is an animation snapshot of a small artificial example with five operation clusters, and two mobilization bases: Bergen and Aberdeen. All long-term AHTS vessels stay in Bergen when idle, whereas the spot vessels return to Aberdeen after demobilization in Bergen in 80% of the cases (cf. Section 4.1). The left of the network shows two ship icons: the top one represents an AHTS vessel on long-term contract, the bottom one represents a spot vessel.

The current date is displayed in the upper right corner. Two figures at the bottom show the current number of moves performed and vessels used, respectively. Four long-term and three spot AHTS vessels are currently involved in anchor handling operations. It can also be observed that one long-term and two spot vessels are returning to the mobilization base in Bergen, giving a total of 10 vessels being used. The current configuration has five AHTS vessels on long-term hire and three moves are currently being performed. The animation has been of great value in debugging the model and in communicating the project results to the company.

5.3. Validation

To validate the model, the number of spot hire days measure was used, which is a compound metric for the number of spot AHTS vessels and their hire durations. For example, using four spot vessels for six days gives $4 \times 6 = 24$ spot hire days. Table 6 contains the information regarding simulated and actual spot hire days accumulated up to the date given in the first column. The entries of columns 4 and 5 are minima and maxima over 100 simulation replications. A 95% confidence interval for the simulated spot hire days is of the form Average $\pm$ Half width.

It can be observed that simulated averages are significantly smaller than actual spot hire days. There are several reasons for this. An important assumption of the simulation model is that spot vessels go off hire as soon as the rig move underlying their hire is completed. However, AHTS vessels are quite often used in operations other than anchor handling, e.g. in periodic supply trips to offshore installations or in stand-by (when required by safety regulations) operations. This in turn implies that spot AHTS vessels are occasionally kept when they are not needed for anchor handling. For example, in January 2008 there were only three rig moves relatively uniformly spread throughout the month, which makes 46 spot hire days an unlikely value (if AHTS vessels were only used for anchor handling). The current simulation modeling should rather be regarded as a decision aiding tool for "isolated" anchor handling operations. However, it is regarded as an important step towards integrated fleet planning for different kinds of offshore operations.

Another reason for deviation is that there is one more delay type generally referred to as "well problems", which comprises a wide range of drilling delays. Once hired to move a rig, which suddenly experiences, for example, a well completion delay, spot vessels are kept until the problems are resolved and the rig can eventually be moved. These waiting periods can be quite substantial and, according to discussions with SMEs, are unpredictable and not easily quantifiable. Finding a way to estimate and quantify them can be a direction for future work.

There may be time periods when there are no vessels on the spot market. If a rig move is scheduled to start within such a time period with a shortage of long-term vessels to perform it, an additional waiting time for the needed number of AHTS vessels to become available has to be incurred. It is an implicit assumption of

Table 6
Simulated and actual spot hire days.

Simulated spot hire days					Actual spot hire days
Date	Average	Half width	Min	Max	
01.02.2008	8.02	2.51	0	39	46
01.03.2008	39.2	8.04	0	188	176
01.04.2008	167.42	14.71	54	396	347
01.05.2008	238.32	15.87	112	449	420

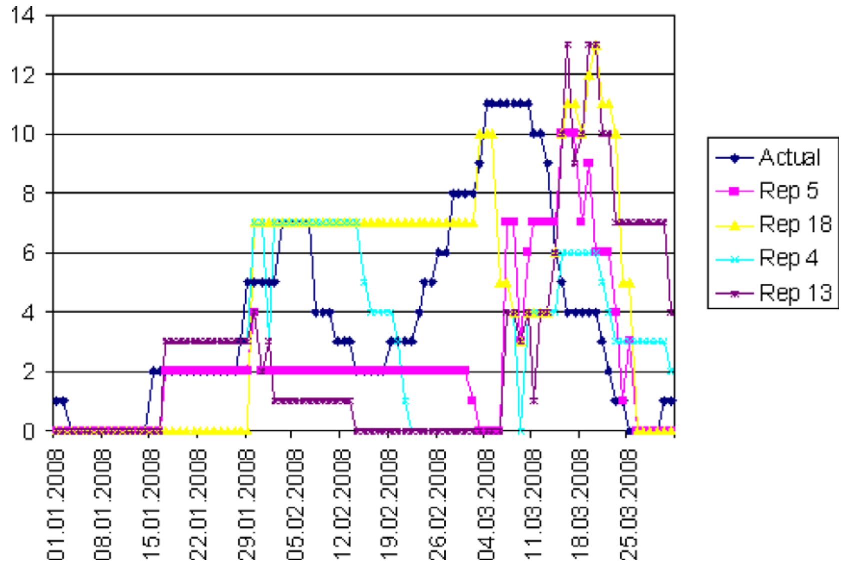

Fig. 6. Simulated and actual number of AHTS vessels on spot hire.

the model that the desired number of AHTS vessels is always available from the spot market. Relaxing this assumption is yet another way to bring the model closer to reality.

Fig. 6 depicts the actual number of AHTS vessels on spot hire in the first quarter of 2008, and the output of the best three (replications 5, 18 and 4) and the worst (replication 13) out of 20 replications with respect to *sum of squared daily deviations* of simulated number of spot vessels on spot hire from the actual ones.

It can be observed that simulated peak periods lag behind the actual peaks. The reason is that the model was designed to simulate future anchor handling operations on the basis of the rig moving plan which is approximate and almost never followed literally. Rig move starting dates normally tend to be postponed due to delays during previous rig moves (WOW and WOP) and well problems (recall that the former two were modelled, while the latter was not). However, the validation period (first quarter of 2008) referred to the past, and operation starting dates were actual and already included all the delays. So when the simulation period is in the past, WOW and WOP delays are incurred twice. The model logic could have been changed to account for this resulting in a more accurate validation picture. However, SMEs indicated that taking a rig move plan and modeling various kinds of delays would result in a more realistic representation of future anchor handling operations, which was the primary goal of our study.

It has to be said that simulated spot hire costs (using average spot rate scenario) were extremely close to the actual ones for the first four months of 2008. Remembering that the simulated number of anchor handling days was significantly lower than the actual value, this implies that the average level of future spot rates described in Section 4.4 produces higher rates than the ones actually paid by the company. Indeed, during the period considered the average spot rate the company rented AHTS vessels at was below the market average. But recall that the primary motivation for the model development was to evaluate the impact of different future spot rates on a cost-optimal number of AHTS vessels on long-term hire. A more careful future spot rate modeling is also a potential direction for future research efforts.

6. Output analysis

We used SPSS 15.0 for Windows as a tool to analyze the simulation output. The simulation run length was set to one year. Although the last (68th) operation of the rig moving plan has been scheduled to start on November 15th, 2008, on average only 66 operations were completed by December 31st, 2008, because of WOW and WOP delays.

In an experimental design two factors are distinguished, namely future spot vessel rates and number of vessels on long-term hire. As mentioned in Section 4.4, three levels of spot rates are considered: average, above average, and below average. The behavior of the total vessel hiring cost, which is the main efficiency measure, is then examined by varying the number of vessels on long-term hire.

Each configuration of the simulation model was run for 100 replications, which took about 282 seconds in each case. Extreme cost values were then removed from consideration to reduce variance estimates and have tighter confidence intervals. These extreme cost figures were often caused by one or several spot AHTS vessels being severely delayed by the weather during a rig move. This situation is unlikely in practice because a spot vessel undergoing long delay would normally be replaced by a long-term one. In each configuration, there was at most one such extreme value. Sections 6.1, 6.2 and 6.3 contain the output analyses based on 99 replications. ANOVA is used as a method to identify best homogeneous subset in each configuration. This is justified as 99-element output arrays are independent samples of a random variable representing total vessel hiring cost. ANOVA is also quite robust to deviations from normality and constant variance assumptions of the underlying samples, as mentioned by Johnson and Bhattacharyya (1996).

6.1. The average case

The case of average spot rates is displayed in Fig. 7.

There is no statistically significant difference between 6-, 7-, 8-, and 9-vessel configurations according to ANOVA post hoc tests. Although finding an outright winning configuration is not the subject of the paper, the number of replications could be increased to obtain tighter confidence intervals and ideas of Boesel et al. (2003a), Boesel et al. (2003b) and Hong and Nelson (2006) could be adapted.

6.2. The above average case

Recall that in the case of above average spot rates all the parameters of respective distribution were increased by 30%. The output 95% confidence intervals for total vessel hiring cost are depicted in

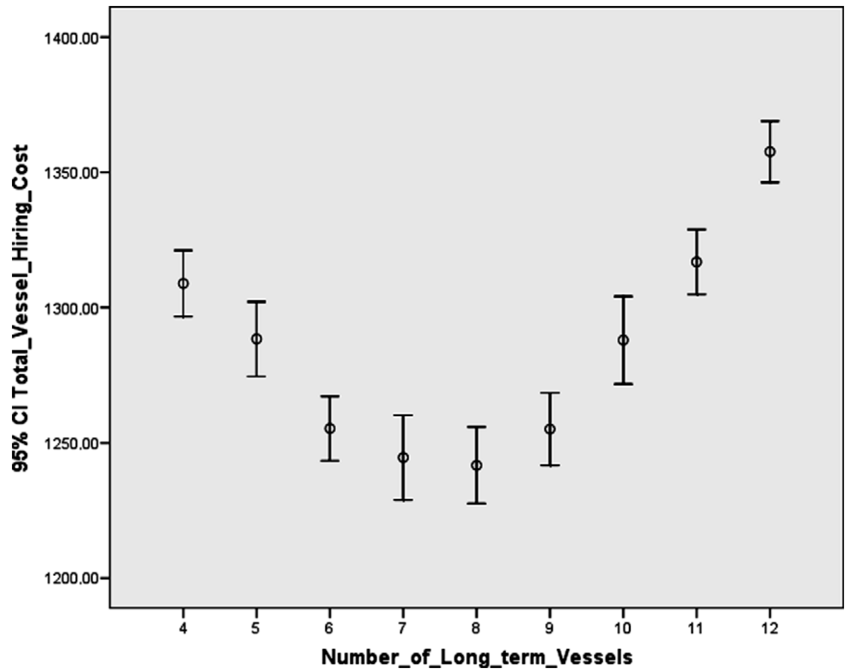

Fig. 7. Ninety-five percentage confidence intervals for total vessel hiring cost: average future spot rates (millions of NOK).

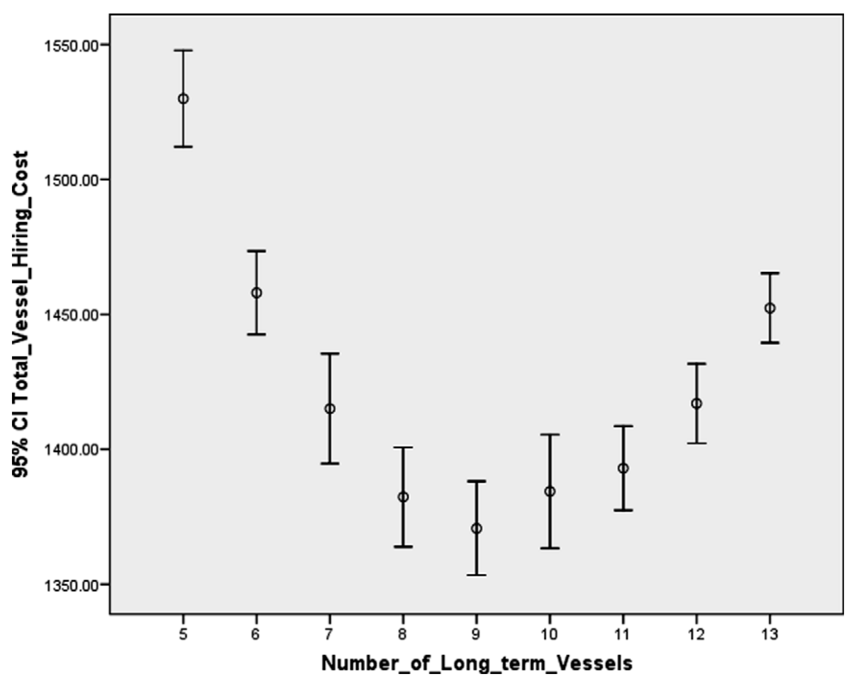

Fig. 8. Ninety-five percentage confidence intervals for total vessel hiring cost: future spot rates above average (millions of NOK).

Fig. 8. ANOVA post hoc tests revealed that the best homogeneous subset includes 8-, 9-, 10-, and 11-vessel configurations. As one might expect a reaction to above average future spot rate is the decision to have more vessels on long-term hire.

6.3. The below average case

The simulation output with the spot rate factor at the below average level is presented in Fig. 9. The best homogeneous subset now includes 2-, 3- and 4-vessel configurations. The explanation of a more drastic reduction in the cost-optimal number of vessels on long-term hire from the case of average future spot rate (compared to reduction from the above average to the average case) is twofold. First, the intensity of anchor handling operations is unevenly spread throughout the year. There are time periods with no anchor handling operations performed and, therefore, no anchor handling vessels used. Second, vessels on long-term hire have to be paid for, irrespective of whether they are used or not. These two facts make the cost-optimal number of vessels on long-term hire more sensitive to decreases in the spot rates than to increases of the same magnitude. In other words, a certain decrease of the future spot rate would have a larger impact on long-term fleet size

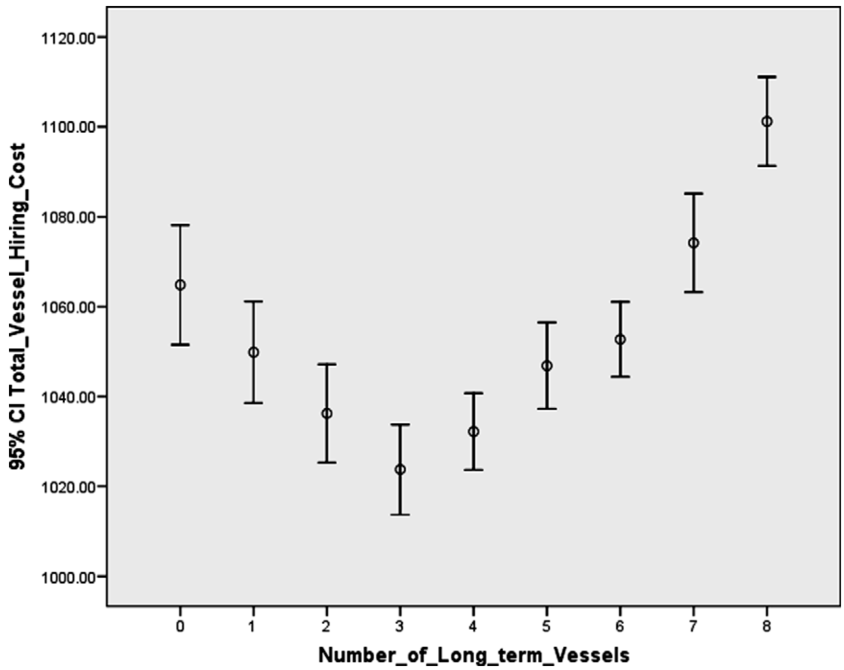

Fig. 9. Ninety-five percentage confidence intervals for total vessel hiring cost: future spot rates below average (millions of NOK).

than an equivalent spot rate increase. For example, when the spread of operations is sufficiently uneven and the spot rates are sufficiently close to long-term rates a 0-vessel configuration might be the best one.

7. Conclusions

Anchor handling tug supply vessels are among the most expensive vessel types used by offshore oil and gas operators. Determining their fleet size calls for careful planning. Dependence of anchor handling operations on uncertain weather conditions and high volatility of the spot rates for AHTS vessels considerably complicates the planning. We have presented a prototype for a simulation-based decision support tool enabling the evaluation of the cost-optimal number of AHTS vessels on long-term hire for different future spot rate scenarios. Significant effort was spent on weather modeling. Output analysis shows that the cost-optimal number of long-term AHTS vessels is quite insensitive to an increase of future spot rates from the average to the above average level. A much greater sensitivity is observed in case of a decrease to the below average future spot rate level.

This study has received considerable attention and acceptance among the planners in StatoilHydro, the largest Norwegian offshore oil and gas operator. It could also be perceived as an important step towards integrated fleet planning, i.e. fleet planning for all vessel types that can be interchangeably used in different offshore operations.

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