Journal of Petroleum Science and Engineering 180 (2019) 369–379

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

An optimization model for the planning of offshore plug and abandonment campaigns

Steffen Bakker[a,*], Torbjørn Vrålstad[b], Asgeir Tomasgard[a]

[a] Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Alfred Getz veg 3, NO-7491, Trondheim, Norway
[b] SINTEF Industry, Trondheim, Norway

ARTICLE INFO

Keywords:
Plug and abandonment
Campaign planning
Decommissioning
Optimization
Mathematical programming
Vehicle routing
Petroleum economics

ABSTRACT

Plug and abandonment (P&A) operations can be time-consuming and thus very costly, especially for subsea fields. P&A of subsea wells require dedicated vessels such as high cost semi-submersible drilling rigs or lower cost Riserless Light Well Intervention vessels. This paper describes an optimization model that can be used to plan multi-well P&A campaigns by finding cost-efficient vessel routes and allocation of P&A operations to different rigs and vessels. The model's functionality is demonstrated on ten different synthetic cases, generated from realistic data. Results show that significant cost savings can be made by adapting the optimal solutions from this model compared to planning strategies that are currently used by operators, as well as by cooperating across fields and licenses in a large campaign.

1. Introduction

Thousands of offshore wells are planned to be permanently plugged and abandoned in the upcoming decades, and the total costs will be substantial (Myrseth et al., 2017; Oil & Gas UK, 2016). A significant portion of these wells are subsea wells, where the wells are located at one or more subsea templates across the entire field. In a mature area such as the North Sea for example, the Oil & Gas UK (2016) has estimated that the average P&A cost per well during the next decade is around £5–15 million. The main cost driver for plug and abandonment (P&A) operations is time consumption, and depending on well conditions, P&A operations can be very time-consuming (Ferg et al., 2011; Scanlon et al., 2011). Platform wells can be plugged and abandoned with the existing drilling rig at the platform or by coiled tubing and snubbing equipment, whereas subsea wells require dedicated vessels, conventionally semi-sub drilling rigs, with high spread rates. However, total rig rental time can be reduced if simpler parts of the P&A operation are performed by a riserless well intervention (RLWI) vessel (Saasen et al., 2013; Sørheim et al., 2011; Valdal, 2013).

Several authors have focused on duration- and cost-estimation of P&A operations. Kaiser and Dodson (2007) and Kaiser and Liu (2014) estimated the costs of different stages of the decommissioning operations in the Gulf of Mexico based on regression models. Moeinikia et al. (2014a,b, 2015a,b,c) developed a probabilistic method to estimate cost- and duration for P&A of subsea wells using a Monte-Carlo simulation approach. They showed that the implementation of rigless P&A technologies by moving operations from a rig to lighter vessels leads to significant cost and duration savings in subsea multiwell campaigns. Øia and Spieler (2015) and Aarlott (2016) presented statistics on the number of wells to be plugged and abandoned in Norway, and estimated total costs for P&A on the Norwegian Continental Shelf. They also conclude that there is potential for cost-savings when performing operations with a vessel instead of a rig.

Furthermore, since the rigs and/or RLWI vessels must physically move between the different subsea template locations, total time consumption can be reduced further by optimizing the allocation of the different types of mobile offshore units (MOU) during subsea P&A operations. As semi-sub rigs and light vessels can be used in many different combinations during multiwell campaigns, it may thus be challenging to manually find the most efficient allocation, sequence and routing of the required rigs and vessels. An optimization model can analyze all the different possibilities and suggest optimal solutions for MOU utilization for the entire campaign. This results in optimal plans that specify when particular operations on wells should be performed by which vessels or rigs, while complying to restrictions and constraints. Moreover, the optimization approach allows for scenario analyses, such that P&A engineers can evaluate how different strategies for vessel allocation, changed rental rates and effects of improved technology, affect decisions and the impact on total cost.

In this paper we describe an optimization model that can be used for

* Corresponding author.
E-mail address: steffen.bakker@ntnu.no (S. Bakker).

https://doi.org/10.1016/j.petrol.2019.05.042
Received 5 February 2019; Received in revised form 30 April 2019; Accepted 16 May 2019
Available online 24 May 2019

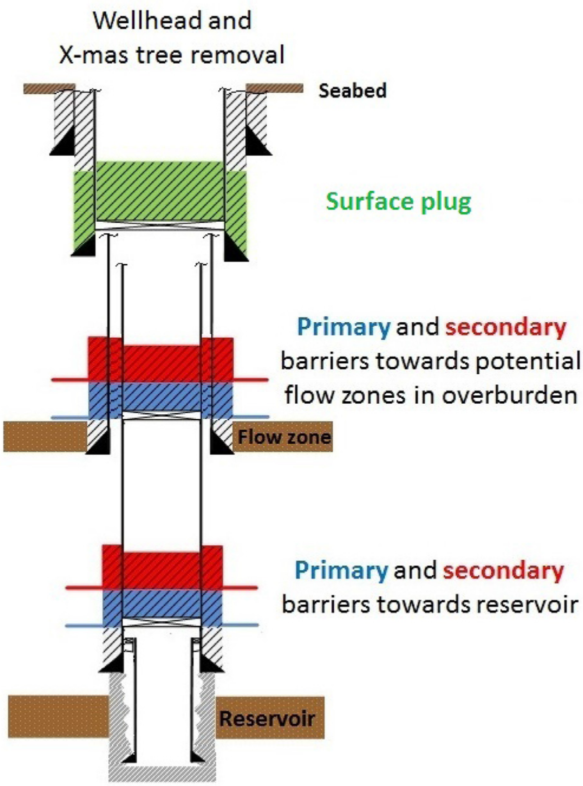


Fig. 1. Simplified illustration of a typical offshore production well after P&A. The color coding of primary barriers (blue), secondary barriers (red) and surface plug (green) are based on current Norwegian well barrier definitions (Standards Norway (2013)).

planning of P&A multiwell campaigns. Previously, Bakker et al. (2017) presented a simple version of the model used on relatively small cases, whereas in this paper we extend this model with more realistic features which enables us to solve realistically sized problems. We demonstrate the applicability of the model through different synthetic case studies based upon realistic data, and show that there is significant value in using an optimization model for planning P&A campaigns.

2. The plug and abandonment process

2.1. P&A operations

A review of P&A operations has been given by Vrålstad et al. (2019), but a brief summary is given below. Fig. 1 shows a schematic illustration of a plugged and abandoned well with the most important barriers and operations.

The purpose of P&A operations is to create several barriers in the well, where several plugs are placed inside the wellbore. Cement is normally used as plugging material, but other plugging materials can potentially be used as well (Saasen et al., 2011; Khalifeh et al., 2014; Vrålstad et al., 2019). P&A operations in a well-regulated area such as the Norwegian Continental Shelf require two independent barriers towards the reservoir (Standards Norway, 2013). Furthermore, any fluid-bearing formations in the overburden must also be isolated with two independent barriers. However, plug placement is only a small part of the full P&A operation. As the created barriers must cover the full cross-section of the well, poor annulus barriers must be removed. This can be achieved either by section milling (Scanlon et al., 2011) or the Perforate-Wash-Cement technique (Ferg et al., 2011; Delabroy et al., 2017). In addition, a surface plug is placed a few hundred meters below the seabed to prevent leakages of drilling mud from the well, and the wellhead and top of conductor are subsequently cut and removed. The total time spent on P&A operations can therefore be considerable.

To simplify P&A planning, the Oil & Gas UK (2015) has classified P&A operations into three distinct phases: Phase 1 “Reservoir abandonment” includes setting primary and secondary barriers towards the reservoir; Phase 2 “Intermediate abandonment” includes potential barriers in the overburden and the surface plug; and Phase 3 “Wellhead and conductor removal” includes shallow cuts of casings/conductor and wellhead retrieval. In addition to these three phases, Moeinikia et al. (2014a) suggested to include a Phase 0 “Preparatory work” as well, which includes pre-P&A work such as killing the well, logging the tubing quality and establishing temporary barriers. Table 1 lists these four phases and summarizes their contents, which are used in the remainder of this paper.

Subsea wells require mobile offshore units (MOU) to perform P&A operations. These MOUs comprise semi-submersible rigs (SSR), RLWI vessels and Light Construction Vessels (LCV). Each of these vessels might have different characteristics in terms of execution times, compatibility with operations, day rates, sailing times and (de-)mobilization times. We note that SSRs can be used all year round, whereas lighter vessels have a lower operability. On the Norwegian Continental Shelf, lighter vessels are not used in winter due to severe weather conditions (high waves). During these winter months they are either in the docks or operating in different countries/continents. To perform the plugging operations, the MOU must be able to maintain a position in line with the subsea wellhead. Depending on the water depth, an SSR has to be anchored, whereas an RLWI vessel always makes use of an integrated dynamic positioning system. Furthermore, rigs and vessels differ in the way they connect to a subsea well, what well control equipment they use and how fluid transport and intervention possibilities are organized. The main difference being that an SSR uses a workover or marine riser, whereas an RLWI vessel makes use of a riserless system. An illustration of these features is given in Fig. 2.

With current available technology, an SSR is required in the P&A process for various reasons. It provides amongst others fluid handling capacity, pulling capacity and rotation of drill string, and is needed to perform complex operations such as section milling. However, simpler elements of the P&A operation can be performed by lighter vessels to save rig time (Sørheim et al., 2011; Varne et al., 2017). An SSR can perform all P&A operations, whereas an RLWI vessel can perform Phase 0 and Phase 3 and an LCV can only perform Phase 3.

Table 1
Different phases of P&A operations for typical well with vertical Xmas tree (Vrålstad et al. (2019)).

Phase	Name	Contents
0	Preparatory work	Retrieve tubing hanger plugs, kill well, install deep set mechanical plug, punch/perforate tubing, circulate well clean
1	Reservoir abandonment	Rig up BOP, pull tubing hanger and tubing, install primary barrier with its base at top of influx zone (i.e. reservoir), install secondary barrier where the base of barrier can withstand future anticipated pressures
2	Intermediate abandonment	Remove casing strings (if necessary), install primary and secondary barriers towards potential flow zones in overburden, install surface plug
3	Wellhead and conductor removal	Cut conductor and casing strings below seabed to avoid interference with marine activity, retrieve casing strings, conductor and wellhead

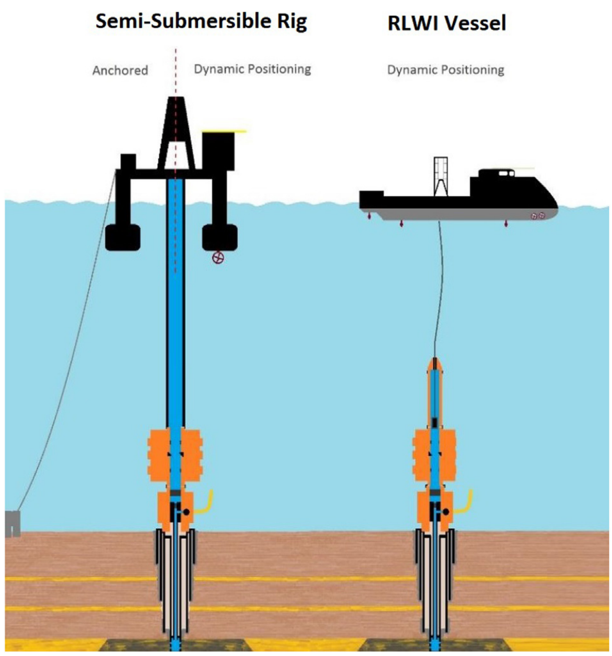


Fig. 2. Illustration of subsea P&A with an SSR with a workover riser (left) and an RLWI vessel with a riserless system (right), Øia et al. (2018).

2.2. P&A campaign planning

When several wells are plugged and abandoned together, making use of one or several MOUs, it can be called a "P&A campaign". As subsea wells are located at different locations around the seabed, the MOUs must physically move from well to well to perform the plugging operations. The routing of MOUs is time-consuming and hence significant cost savings can be achieved by plugging subsea wells together in campaigns. Wells do not have to be plugged in one go, and different MOUs can be used to perform different phases. So, additional savings can be achieved by performing part of the campaign with light vessels, instead of the more expensive SSRs.

As an example, Sørheim et al. (2011) conducted an analysis where they showed that when at least two wellheads are removed in a plugging campaign, it is beneficial to use a dedicated light vessel to perform the Phase 3 operations, while using a rig for the other operations. Similarly, Varne et al. (2017) show in two case studies that the deployment of an RLWI vessel for Phase 0 (pre-P&A) operations can provide considerable cost savings, compared to only making use of a dedicated rig. Finally, Clyne & Jackson (2014) describes the planning and execution of Australia's largest subsea well abandonment campaign to date, which consisted of 19 wells, where they stress the importance of using light vessels to perform Phase 0 and Phase 3 operations. These findings have been quantitatively verified by Moeinikia et al. (2014a, b, 2015a, b, c). However, these studies do not describe a way to optimally plan plugging campaigns that take into account relevant constraints.

P&A decisions are taken on a field level by the responsible operator/license holders. When planning for a P&A campaign, in which several wells will be plugged with multiple MOUs, the scope is therefore restricted by the number of wells on the field under consideration. Subsea wells may be found individually (single satellite) or clustered on a template. Multi-well templates might consist of several wellheads and have the advantage that vessels don't have to be relocated when performing operations on the same template. In general, as long as the operator has well-control and there are no integrity issues, P&A operations are not time-critical. However, a well might have to be plugged and abandoned within a particular time-window, due to, for example, regulations.

We consider the situation where an operator has multiple subsea wells that have ceased production and have to be permanently plugged and abandoned within a time-horizon. On each well or template, several operations must be performed to permanently plug the well. We consider the previously defined phases as operations, however any other mutually exclusive and collectively exhaustive separation of operations can be used. The objective of planning a P&A campaign is therefore to find the most cost-efficient routes and schedules for a set of vessels to carry out P&A-operations on a given number of wells or templates in a tactical planning horizon, typically ranging up to 2 years, while satisfying a set of (time-)constraints.

3. Optimization

The problem of planning a P&A campaign can be addressed using the field of operations research (OR), also knowns as optimization. This problem contains elements of routing and scheduling and can be viewed as an uncapacitated Vehicle Routing Problem with Time-Windows (u-VRPTW), which has received a lot of attention from the OR community throughout the years. The problem is also known as the multiple Traveling Salesman Problem with Time Windows (m-TSPTW), see Toth and Vigo (2002). A review of formulations and applications to the m-TSPTW is given in Bektas (2006). In this context, Bakker et al. (2017) present a mixed-integer linear programming (MILP) model for planning relatively small plugging campaigns. But, we are not aware of any other research that combines the field of optimization with P&A. Nonetheless, there is a lot of research that applies OR to the (upstream) petroleum industry that can be related to our problem.

Notable examples of MILP models applied to upstream petroleum problems are the following. Iyer and Grossmann (1998); Goel and Grossmann (2004); Gupta and Grossmann (2014) developed MILP models for the planning and scheduling of investment and operation in offshore oilfield development. Another multi-period MILP model that focuses on investment planning for offshore fields is presented in Nygreen et al. (1998). This model has been extensively used by the Norwegian Petroleum Directorate, showing the practical relevance of using optimization models in the petroleum industry. A more recent contribution is from Rodrigues et al. (2016), in which a MILP is developed to minimize development costs by picking the optimal number and location of wells as well locations and capacities of production platforms. When focusing on the production phase, Ulstein et al. (2007) used optimization models for tactical planning of petroleum production in fields.

4. Model

In this section, we present the optimization model, which is a a Mixed Integer Linear Programming (MILP) Model, that is used for the problem of finding the most cost-effective plan to plug and abandon a given number of subsea wells within given time-horizons, using a set of heterogeneous MOUs.

A P&A plan consists of a collection of feasible routes and schedules for the different MOUs, such that all plugging operations are performed. A first model for this problem has been presented in Bakker et al. (2017), which formulates a m-TSPTW and adapts a Miller, Tucker and Zemlin formulation. We improve this model in several ways. To begin with, we switch to a commodity flow type formulation, which is known to lead to a tighter model formulation (Öncan et al. (2009)). This in turn allows for larger problems to be solved. Moreover, we change the way in which we allow MOUs to take multiple routes, which also reduces the size of the model. Finally, we take into account the restricted operability of lighter vessels during the winter season.

We note that we do not consider capacity restrictions in our problem. The reason being that fluid returns are stored in storage tanks and can be drained offshore by supply vessels of which the day rates are significantly lower than the vessels used to perform P&A operations.

Moreover, when making use of rigs, anchor handling vessels are required to perform anchor handling operations such as transporting and deploying the anchors (Tjøm et al., 2010). Nevertheless, we have decided to keep these vessels out of the model. The aim of the model is to optimize the planning, routing and scheduling of the MOUs that perform the plugging operations. The model is not developed to obtain a cost-estimate of the whole plugging campaign. As anchor handling vessels are only required for a subset of wells, we consider the cost resulting from renting these vessels as a fixed cost, which we do not consider in the model. Nonetheless, these extra costs can be added to the total campaign costs if required.

We start by defining the notation and components being used in the model, after which the objective function and constraints that constitute the model are presented in a stepwise fashion.

4.1. Formulation

To find the optimal plan in a P&A campaign, we present a model that is a an extension of an m-TSPTW with precedence constraints, where we adapt an arc-flow formulation. An overview over all the sets, parameters and variables that are used in the model is given in Appendix B.

The set $\mathcal{N}$, indexed by i or j, consists of all the operations that have to be performed to plug all the wells that are considered in the P&A campaign. A single operation in this set is also referred to as a node. The MOUs that can perform these operations are collected in the set $\mathcal{K}$ and $\mathcal{N}_k$ consists of the subset of operations that unit $k \in \mathcal{K}$ can perform. Moreover, the cost of renting these MOUs is represented by the day rate for each vessel, C_k^{DAY}.

The time it takes for vessel k to perform operation i, also referred to as the execution time, is denoted by T_{ik}^{EX}. Each unit k starts and finishes in a location, referred to as its origin $o(k)$ and destination $d(k)$ respectively. These locations do not necessarily need to be equal. Moreover, the MOUs might have the opportunity to return to a harbor $h(k)$. This allows for MOUs to be used in separate campaigns and is alternatively referred to as multiple trips. The problem is defined on the directed graphs $G_k = (\mathcal{V}_k, \mathcal{A}_k)$, where the node set of unit k is given by $\mathcal{V}_k = \mathcal{N}_k \cup \{o(k), d(k), h(k)\}$ and the arc set $\mathcal{A}_k$ consists of feasible pairs (i, j) for which $i, j \in \mathcal{V}_k$, for all $k \in \mathcal{K}$.

In this context, we define binary routing variables x_{ijk} for all $(i, j) \in \mathcal{A}_k$ and $k \in \mathcal{K}$, equaling 1 if unit k performs operation j after operation i and zero otherwise. In addition, we will make use of the continuous variables t_{ik} and w_{ik}, for $i \in \mathcal{V}_k$ and $k \in \mathcal{K}$, representing the time when unit k arrives at node i and the time it waits there respectively. Finally, we let the continuous variables $\tilde{t}_{ijk}$ be defined as follows:

$$\tilde{t}_{ijk} = \begin{cases} t_{jk} & \text{if } x_{ijk} = 1, \\ 0 & \text{if } x_{ijk} = 0, \end{cases}$$

where $k \in \mathcal{K}$ and $(i, j) \in \mathcal{A}_k$. These variables are commodity flow variables, where the commodity can be considered to be the start time of the operations.

Lastly, we define sailing time parameters T_{ijk}^S for all $(i, j) \in \mathcal{A}_k$ and $k \in \mathcal{K}$. These sailing times equal zero when operation i and j are located on the same template or well and are otherwise equal to the sailing time between operation i and j for unit k, possibly increased with anchor handling time in the case of rigs. We note that this is the extra time the rig needs in the anchor handling process and does not reflect the need for anchor handling vessels.

4.1.1. Discussion on P&A operations

The operations in the set $\mathcal{N}$ can be defined in several ways and can have different levels of detail. To begin with, we work with a categorization of operations based on the four phases that where defined in Section 2.1. We consider the set of phases $\mathcal{P} = \{p0, p1 + p2, p3\}$, where phase 1 and phase 2 are merged, as it is assumed in this study that these phases only can be executed by a rig. When a rig performs a phase 1

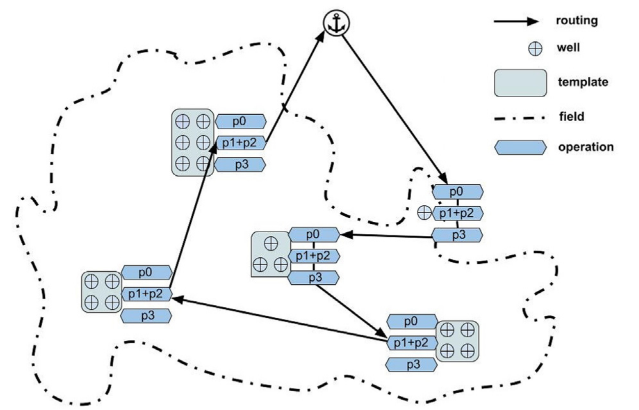


Fig. 3. Visualization of the operations that an SSR performs along its route.

operation, it is natural that it continues with phase 2 as well. Moreover, the operations can be defined on a well or template level. For single satellite wells, we are always on a well level. However, when several wells are clustered on a template, an MOU does not have to move when performing operations on these wells. In this situation, we assume that one would always use the same MOU to perform operations of the same phase. Operations can hence be defined on a template level, which reduces the complexity of the problem.

As an example, Fig. 3 visualizes the operations an SSR performs along a particular route. It first visits a single satellite well, where it performs all operations, after which it moves to a template consisting of three wells, where it again performs all operations. On the last three templates it only performs operations in $p1 + p2$. For the campaign to be finished, another MOU must perform the remaining operations on the last three wells.

4.2. Constraints

4.2.1. Objective function

The aim of this work is to construct P&A campaigns that minimize total plugging costs, which mainly arises from renting MOUs. Operators that are planning P&A campaigns have to rent these rigs and vessels for the duration of the planned campaign. Although rig and vessel contracts might have different structures, typically, a day rate is specified. This day rate might be differentiated based on the type of activity, such as execution, sailing or waiting. Alternatively, operators might already have long-term contracts for some rigs and vessels that are being used for other purposes such as exploration and development/drilling activities. When using these MOUs in a plugging campaign, this leads to an opportunity cost, which can be represented by a specific day rate.

The objective of the problem is to minimize the sum of the rents for the MOUs, which is given by the product of the day rate of an MOU (C_k^{DAY}) and the duration it is being used. The duration a vessel is being used is given by the difference between the time the vessel enters the destination ($t_{d(k)}$) and leaves the origin ($t_{o(k)}$), subtracted with the time it possibly waits in the harbor ($w_{h(k)}$). The objective function is now given by:

$$\min \sum_{k \in \mathcal{K}} C_k^{DAY} (t_{d(k)} - t_{o(k)} - w_{h(k)}). \tag{1}$$

We note that various objective functions can be used. Bakker et al. (2017) shows that when considering different rates for distinctive activities this would still lead to an additive and linear objective function. However, as publicly available data on MOU rent typically is given using a single day-rate, we choose to present the objective function in this way.

Moreover, we assume that the MOUs do not incur any rental costs in the harbor, as we subtract the waiting time in the harbor from the total time usage.

4.2.2. Degree

The following constraints are known as degree constraints in the optimization literature. They contribute to the construction of feasible routes for each of the MOUs.

To begin with, we must ensure that all operations are being executed by exactly one MOU:

$$\sum_{k\in\mathscr{K}}\sum_{j\in\delta_k^+(i)} x_{ijk} = 1, \quad i\in\mathscr{N} \tag{2}$$

Here, $\delta_k^+(i)$ is defined as the set of operations j such that arc $(i, j)\in\mathscr{A}_k$. In other words, the set of operations j that unit k can perform after executing operation i. Similarly, given operation i, $\delta_k^-(i)$ is defined as the set of operations j such that $(j, i)\in\mathscr{A}_k$. Hence, Equation (2) ensures that for all operations $i\in\mathscr{N}$, there is exactly one MOU ($k\in\mathscr{K}$) that performs this operation and moves on to perform some other operation j.

Constraints (3) and (4) make sure that the routes of all MOUs start in their origins and finish in their destinations respectively:

$$\sum_{j\in\delta_k^+(o(k))} x_{o(k)jk} = 1, \quad k\in\mathscr{K} \tag{3}$$

$$\sum_{i\in\delta_k^-(d(k))} x_{id(k)k} = 1, \quad k\in\mathscr{K} \tag{4}$$

The inclusion of an arc between the origin and destination with zero travel time, allows for MOUs not to be used in the plan.

Finally, constraint (5) states that the flow into a node j ($\sum_{i\in\delta_k^-(j)} x_{ijk}$) should equal the flow out of a node j ($\sum_{i\in\delta_k^+(j)} x_{ijk}$) for each MOU:

$$\sum_{i\in\delta_k^-(j)} x_{ijk} = \sum_{i\in\delta_k^+(j)} x_{jik}, \quad j\in\mathscr{N}_k, k\in\mathscr{K} \tag{5}$$

So, if MOU k executes operation j, then the flow into and out of that node will both be equal to one.

4.2.3. Timing of operations

Constraint (6) ensures correct timing of all operations. It states that if unit k performs operation j after i, then, the start time of operation j should equal the start time of operation i increased with the execution time of operation i (T_{ik}^{EX}) and waiting time at i (w_{ik}) and the sailing time from i to j (T_{ijk}^{S}):

$$t_{ik} + \left(\sum_{j\in\delta_k^-(i)} x_{jik}\, T_{ik}^{EX}\right) + w_{ik} = \sum_{j\in\delta_k^+(i)} (\tilde{t}_{ijk} - x_{ijk}\, T_{ijk}^{S}),$$
$$i\in\mathscr{N}_k, k\in\mathscr{K} \tag{6}$$

Together with the degree constraints (2)–(5), this constraint eliminates subtours.

Moreover, we have to relate the start time variables t_{ik} with the commodity flow variables $\tilde{t}_{ijk}$. That is:

$$t_{ik} = \sum_{l\in\delta_k^-(i)} \tilde{t}_{lik}, \quad i\in\mathscr{N}_k\cup\{d(k)\}, k\in\mathscr{K} \tag{7}$$

$$t_{ik} = \sum_{j\in\delta_k^+(i)} (\tilde{t}_{ijk} - x_{ijk}\, T_{ijk}^{S}), \quad i = o(k), k\in\mathscr{K} \tag{8}$$

4.2.4. Precedence

Plugging operations on a single well or template have to be performed in a strictly ordered sequence, but not necessarily directly after each other. To control for this, we make use of the set $\mathscr{R}$, which consists of pairs (i, j) for $i, j\in\mathscr{N}$, for which operation i has to be performed before operation j. The precedence constraints read:

$$\sum_{k\in\mathscr{K}}\left(t_{ik} + \sum_{l\in\delta_k^-(l)} x_{lik}\, T_{ik}^{EX}\right) \le \sum_{k\in\mathscr{K}} t_{jk}, \quad (i, j)\in\mathscr{R} \tag{9}$$

That is, operation j should be started after operation i is finished.

The precedence relations that we use are based on the different phases that have to be performed. So, on an individual well or template, $p0$ has to be performed, before one can start executing $p1 + p2$.

4.2.5. Time-windows for operations

Operations can have time windows for when they must be performed. Examples of situations where time-windows might arise are the following. A well that is producing during part of the planning horizon cannot be plugged during that period and a well with integrity issues might need plugging operations within a short time-horizon and. Moreover, regulatory regimes might set time-windows for when a well has to be abandoned. For example, on the Norwegian Continental Shelf, a temporarily plugged and abandoned well that does not have access to a monitoring system must be permanently plugged and abandoned within three years (Standards Norway (2013)). To allow for these restrictions, we include the following constraint:

$$x_{ijk}\underline{T}_j \le \tilde{t}_{ijk} \le x_{ijk}\bar{T}_j, \quad (i, j)\in\mathscr{A}_k, k\in\mathscr{K}|j\in\mathscr{N}_k \tag{10}$$

However, we note that in this application the time-windows tend to be fairly loose.

Besides, satisfying time-windows, equation (10) forces $\tilde{t}_{ijk}$ to zero, when unit k does not move from node i to j.

4.2.6. MOUs

MOUs might have restrictions on when they can be used due to other planned activities or restricted rental periods. This leads to the following constraints:

$$\underline{T}_k^{MOU} \le t_{ik} \le \bar{T}_k^{MOU}, \quad i\in\{o(k), d(k)\}, k\in\mathscr{K} \tag{11}$$

In contrast to SSRs, RLWIs and LCVs cannot be used al year round due to rough weather conditions. During the winter months, these vessels therefore have to go back to the harbor. This is incorporated in the following way:

$$t_{h(k)k} \le \underline{T}_k^{WINTER}, \quad k\in\mathscr{K}^{WINTER} \tag{12}$$

$$t_{h(k)k} + w_{h(k)k} \ge \bar{T}_k^{WINTER}, \quad k\in\mathscr{K}^{WINTER} \tag{13}$$

So, vessel k has to arrive in the harbor before the start of the winter, where it has to wait until the end of the winter season.

4.2.7. Domains of the variables

Finally, the variables have the following domains:

$$x_{ijk}\in\{0,1\}, \tilde{t}_{ijk}\in\mathbb{R}_0^+, \quad (i, j)\in\mathscr{A}_k, k\in\mathscr{K} \tag{14}$$

$$t_{ik}, w_{ik}\in\mathbb{R}_0^+, \quad i\in\mathscr{N}_k, k\in\mathscr{K} \tag{15}$$

This means that all the variables are nonnegative and continuous, except for the routing variables which are binary.

5. Case study

A case study has been developed to demonstrate the potential of the optimization model. The case study consists of synthetically constructed subsea fields based upon realistic data and well locations, so that the field examples resemble typical Norwegian subsea fields.

5.1. Data

Input data on time durations for P&A operations have been obtained from Øia et al. (2018), who provide a thorough description of operational procedures for both SSRs and RLWI vessels, as well as presenting

Table 2
Durations (in days) of the different phases for different complexities when performed by SSRs or RLWI vessels. Based upon Øia et al. (2018).

	SSR			RLWI		
Phase	Low	Medium	High	Low	Medium	High
	5.29	4.71	4.58	3.33	4.81	8.33
	8.75	9.52	14.21	–	–	–
	1.38	1.38	0.88	1.38	0.96	1.38

duration estimates for three types of subsea wells (low, medium and high complex wells). These estimates are on a low level, and within each phase, multiple operations are defined. For use in our model, we aggregate the durations within each phase. An overview over the resulting data is given in Table 2.

Data on durations for LCVs are not presented in Øia et al. (2018), but since LCVs and RLWI vessels have similar capabilities, we assume that the durations of phase 3 are equal for these two vessel types. In the case study, each well is assigned a complexity, to account for the variations between wells.

As we want to test the performance of the model for different problem sizes, we have constructed 10 different cases. The optimization literature usually refers to a specific case of a problem as an instance. Nevertheless, we make use of the more general term 'case'. To generate these cases we have made use of an extensive publicly available dataset by Norwegian Petroleum Directorate (2019), that contains data on all the wellbores on the NCS. All cases are inspired by the topology, number of wells and templates on existing fields on the NCS. So, all the cases are based upon realistic data, but do not reflect any particular real life plugging campaigns. Descriptive statistics for the different cases are given in Table 3.

As one can see, the cases vary in size and differ in terms of the number of wells (ranging from 8 to 44), well complexities, templates, fields (and locations). As the size of a plugging campaign is in general bound from above by the maximum number of wells that can be plugged on a particular field, we had to add wells from neighboring fields to create the largest cases.

As an example, Fig. 3 shows a stylized visualization of case 3, which contains eighteen subsea wells spread out over four templates and one single satellite well. Of these 18 wells, 14 wells have medium complexity and 4 wells have a high complexity. Moreover, a possible route for an SSR is depicted, starting and finishing in the harbor.

The horizon of the cases is assumed to span two years and start in spring. We assume that the length of the winter season is four months (ranging from November to February), during which the lighter vessels must stay in the harbor. Moreover, since we know that we in general have loose time-windows, we have divided the wells into groups based on whether they have to be plugged during the first year, second year, or can be plugged at any time during the planning horizon.

Finally, in the analyses, we consider three MOUs (SSR, RLWI, LCV) that can be used during disjoint periods of time. The use of extra MOUs would be redundant, as it would never be optimal to make use of multiple MOUs of the same type in the problems that we consider.

The travel time between operations on two different templates comprises the physical moving time and possible demobilization and

Table 3
Count on the number of templates and wells (for each complexity) for the ten different cases.

Case		1	2	3	4	5	6	7	8	9	10
Number of Templates		4	5	5	8	8	11	11	14	14	16
Number of Wells		8	14	18	13	25	29	32	32	33	44
Complexity	Low	2	9	0	5	2	15	17	12	7	16
	Medium	6	5	14	6	19	6	5	10	20	22
	High	0	0	4	2	4	8	10	10	6	6

Table 4
Speed, day rate, (de)mobilization- and anchor handling-durations for the different vessel types.

Type	Speed (knots)	Day Rate (k$)	Harbor		Offshore	
			Mob	DeMob	Ancher	DeMob
			Durations (days)			
SSR	5	275	5	2	3	0.2
RLWI	11	230	3	2	0.1	0.1
LCV	11	200	2	2	0.1	0.1

mobilization times. The distances between all the wells are calculated using the coordinates of the wells in the different cases, taken from the Norwegian Petroleum Directorate (2019) database. Together with MOU speed, this gives us the physical travel time. Mobilization and demobilization times are defined when an MOU leaves or enters the harbor, as well as when it performs operations offshore. The offshore mobilization time of SSRs might be increased with the time required for anchor handling operations Tjøm et al. (2010), when the template is located at a water depth less than 190 m.

Day rates for MOUs are very volatile and depend on many factors such as type of unit, whether the unit has been in use recently (warm unit), whether it is a short or long contract, changes in oil and gas prices and/or demand for the units in general (Osmundsen et al. (2012)). We have chosen to work with the spread rate estimates from Øia et al. (2018). These spread rates include a daily rate and an approximation of the costs of the main equipment used. We note that changes in the spread/day rates give rise to different optimal solutions and plans, which makes this model a useful tool for engineers planning P&A operations.

An overview over MOU data that is used in the case study is given in Table 4.

5.2. Strategies

To demonstrate the usefulness of the model, we test the optimal solution found by the model, against several different *strategies*. The optimal solution is referred to as strategy 0, the base strategy. Inspired by the campaigns in Sørheim et al. (2011); Clyne and Jackson (2014); Varne et al. (2017), we define three additional strategies that operators might adopt. Using the first strategy, a campaign is planned where the operator only makes use of an SSR. This can be considered to be the traditional way of planning plugging operations. The second and third strategy, on the other hand, make use of an LCV to perform all Phase 3 operations, whereas the third strategy also uses makes use of an RLWI vessel to perform the Phase 0 operations. When solving the models using these strategies, we only fix the assignments of MOUs to operations. The routing and scheduling decisions are still chosen in an optimal way by the model. Hence, these strategies give lower bounds on the optimal values of the campaigns that would be constructed manually by engineers planning P&A operations. An overview over the different strategies is given in Table 5.

Table 5
Overview over the different planning strategies.

Strategy	Description
0	Optimal strategy, no restrictions
1	All rig
2	LCV for $p3$
3	RLWI for $p0$, LCV for $p3$

Table 6
A summary of the results for the different cases. We present the percentage increase of the objective functions for the different strategies compared to the cost of the best known solution that uses the optimal strategy ($s0$), besides the optimality gap for $s0$.

Case	Cost $s0$(mil$)	Optimality	Percentage cost increase		
			$s1$	$s2$	$s3$
1	36.88	opt.	7.12%	8.57%	1.71%
2	56.29	opt.	12.45%	12.33%	0.25%
3	83.42	opt.	6.91%	6.85%	3.41%
4	56.59	0.65%	8.49%	9.03%	3.24%
5	109.73	0.19%	9.14%	8.65%	2.60%
6	133.60	0.28%	9.05%	8.77%	4.20%
7	140.67	1.19%	8.60%	8.61%	6.21%
8	143.95	2.49%	6.37%	6.39%	4.88%
9	143.11	1.00%	9.31%	9.42%	3.02%
10	186.14	0.88%	infeas.	infeas.	3.33%

6. Results

6.1. Computational issues

The model has been implemented in Python 3.5.3, formulated using Pyomo 5.1.1 and is being solved with CPLEX version 12.7. The analyses have been carried out on a HP EliteDesk 800 G1 computer with an Intel Core i7-4790S CPU, 3.2 GHz processor, 16 Gb RAM, running Windows 10. All the cases are run with a time limit of 1 h. If a particular case has not been solved to optimality within this time limit, we present the relative optimality gap. The optimality gap is defined as the gap between the best known (integer) solution (BKS) and a lower bound on the optimal value. This is a measure of the amount by which the BKS possibly might increase. As we can see from Table 6, the BKSs are either optimal or close to optimal, with optimality gaps lower than 2.5%. This means that we can generate good solutions for all realistically sized cases within a reasonable amount of time, using an exact approach.

6.2. Value of the optimization model

To show the value of the optimization model, we compare the objective functions and plans for the best known solution ($s0$), with the ones resulting from the three different strategies. Fig. 4 shows the costs in million dollars for the different strategies and cases, while Table 6 shows the percentage increase in the objective function value, when embracing the 'manual' strategies instead of the plan suggested by the model without any restrictions ($s0$).

We note that the manual strategies all could be solved to optimality, except for strategy 1 and 2 in case 10. In this case, the problem turned out to be infeasible, since the time-horizon is too short.

We see that the costs for the optimal P&A campaigns ($s0$) range from 37 to 186 million dollars. The gains of using the optimal plan instead of the manual strategies are in the order of several million dollars for all the cases. Only for case 2 and when embracing strategy 3, we find that the objective function values are relatively close and differ by only 0.25%. Moreover, we observe that when embracing either strategy 1 (all rig) or 2 (inclusion of LCV) in an optimal way, this would lead to an increase in P&A costs ranging from 6% to 12% compared to the best known solution. In the case of strategy 3, the increase is between 0.25% and 6.2%.

To highlight the differences between the strategies, we take case three as an example. Fig. 5 shows the optimal plans for the four different strategies for case 3. We see that the savings between 3.41% and 6.91% are obtained by using a mixture of strategy 1 and strategy 3. That is, for the first three templates, an RLWI vessel and LCV are used for the $p0$ and $p3$ operations respectively, while on the last two templates the rig performs all operations.

6.3. Optimal plans

The optimal plans for the different cases all share similar features. To illustrate, Gantt charts representing the optimal plans for cases 2,4,8 and 8 are given in Fig. 6, while Gantt charts for the remaining cases are given in Figure C.7 in the Appendix. When studying these plans, we can make several observations. We know that the rig always performs $p1 + p2$, but we see that the plans differ in which MOU performs $p0$ and $p3$ operations.

To begin with, we observe that the RLWI vessel is being used in all cases to perform preparatory work on the majority of wells. After having done the $p0$ operations, the vessel might continue performing $p3$ operations on some of the wells, if it does not have to wait for it. This feature is displayed in the optimal plans for case 1,2,4 and 10.

In addition, we observe that, in general, the LCV is used in the campaigns to perform the majority of $p3$ operations. However, for smaller cases (that is 1,2 and 4), it is not beneficial to make use of such an MOU.

Finally, a vessel campaign might be split by the winter period, as can be seen in case 8 (for the RLWI vessel) and case 9 (for the LCV).

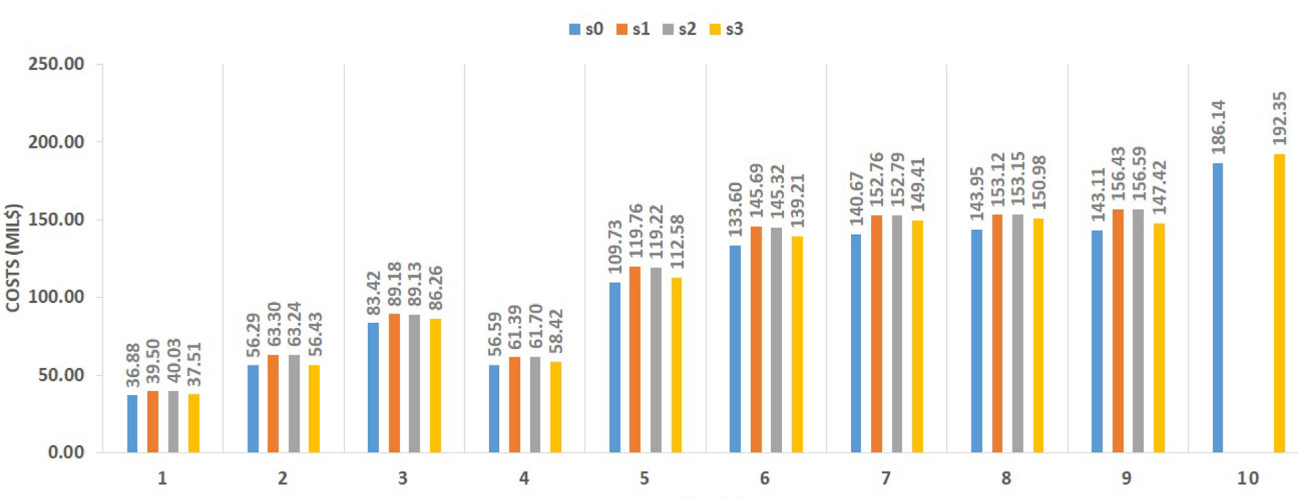
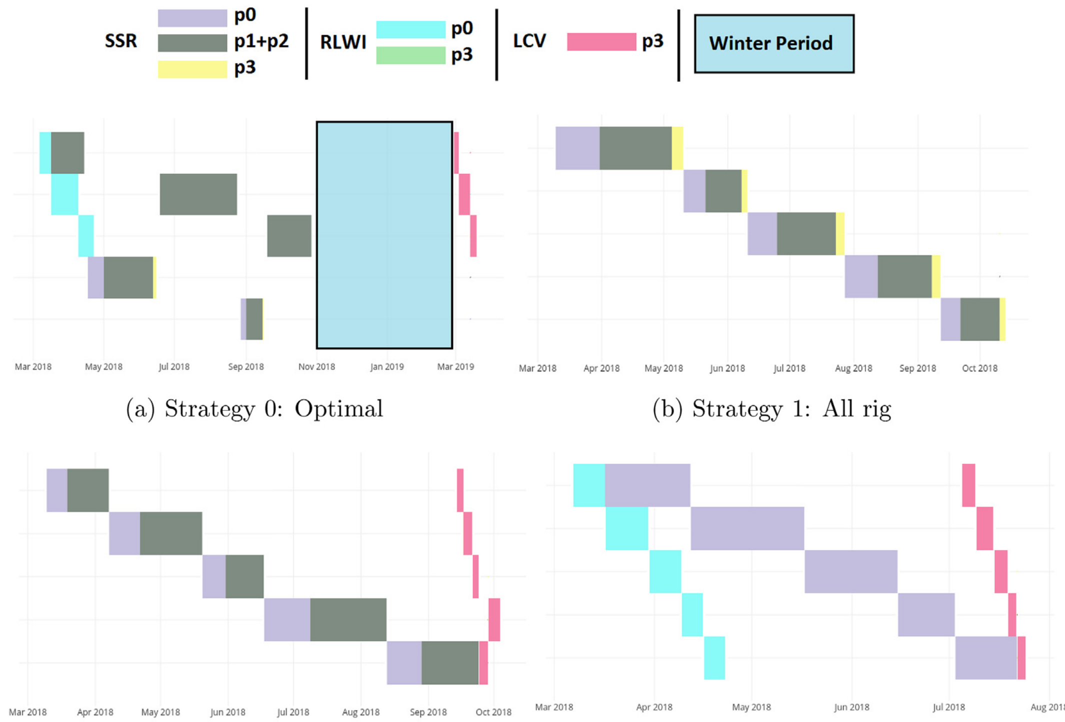


Fig. 4. Campaign costs (in million dollars) for the different cases and strategies.



(a) Strategy 0: Optimal (b) Strategy 1: All rig

(c) Strategy 2: LCV for $p3$ (d) Strategy 3: RLWI for $p0$, LCV for $p3$

Fig. 5. Gantt charts representing the different strategies for case 3.

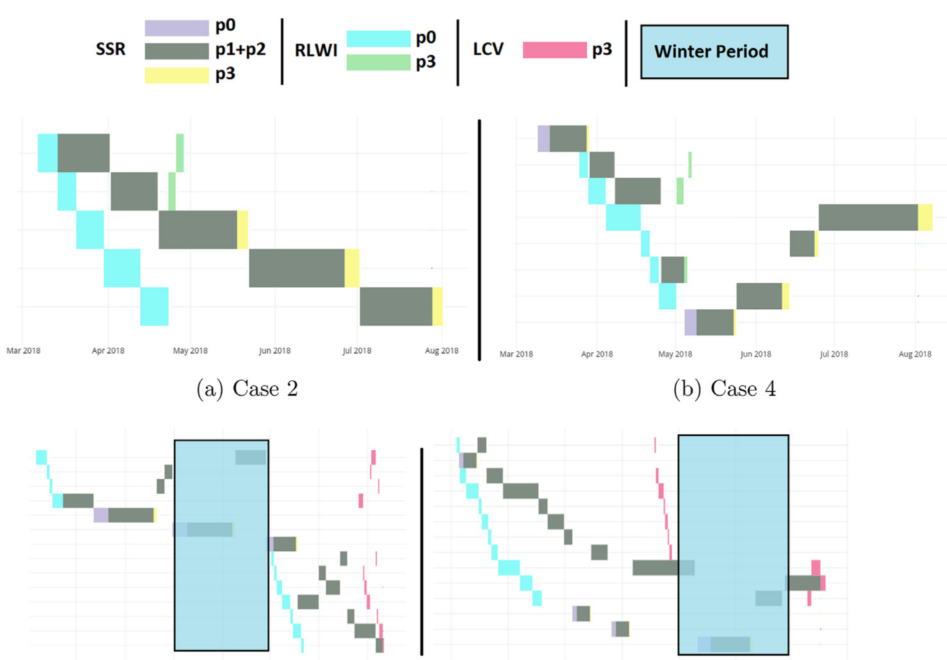
6.4. Value of cooperation

Each of the cases 5,7,9 and 10 is made up from wells belonging to two different fields. In practice, these fields will most likely be plugged in separate campaigns. When operators cooperate between licenses and fields and plan campaigns together, additional savings can be made. To quantify this effect, we present the costs for the separate campaigns in Table 7.

We present the objective function values of the optimal plans for the complete campaign or two separate campaigns. We see that planning for individual campaigns leads to relative cost increases between 3% and 5%, which equals somewhere between 4 and 6 million dollar for each case.

6.5. Sensitivity analysis

During the analyses we observed that the optimal solutions and plans are dependent on data input such as well complexity or spread



(a) Case 2 (b) Case 4

(c) Case 8 (d) Case 9

Fig. 6. Gantt charts representing the optimal plans for case 2,4,8,9 and 10.

Table 7
P&A Campaign Costs for the cases consisting of two fields when planned in one complete campaign, or for the two fields separate.

	P&A Campaign Costs (mil$)			Cost increase
Case	Complete	Field 1	Field 2	
6	109.73	31.47	83.42	4.70%
8	140.67	56.29	89.44	3.60%
10	143.11	83.42	64.05	3.05%
11	186.14	121.87	70.14	3.15%

rate. This means that the optimization model can be a useful tool for P&A campaign planners and/or rig/vessel contractors. With use of the model, they can quickly find out which campaign is optimal under different data inputs. To highlight this point, we investigate two scenarios.

While in a normal campaign one would expect to encounter wells of different complexities, we did not have data on this distribution. In the analyses performed so far, we worked with a random distribution of well complexities. The two extreme scenarios that we consider consist therefore of wells that all either have a low or high complexity.

For the high complex well scenario, we find that the optimal strategy is to only make use of an SSR in all the cases under consideration, whereas in the low complex well scenario the optimal plans change for each of the cases, while still having either one of the structures as described in Section 6.3.

7. Conclusions

In this article an optimization model has been developed for planning P&A campaigns. As planning such a campaign is a complex problem involving many constraints and combinatorics, this optimization model can be a useful tool for P&A planners. The methodology allows planners to find optimal solutions for many different cases and perform scenario analyses.

We developed ten different synthetic cases, generated from realistic data, to test the performance of the model. Even though the case study is based on data from the Norwegian Continental Shelf, the model can be applied to different countries and regulatory regimes. The results from the case study show the following. With our model formulation, we can solve realistically sized cases consisting of at least 44 wells. The optimal plans generated differ from strategies mimicking the behavior of actual planned campaigns. Depending on the case, the optimal plans make use of RLWI vessels and/or LCVs, to perform phase 0 and phase 3 operations. We find that for all 10 cases, savings can be made that are in the order of millions of dollars when adopting the optimal plans instead of the ‘manual’ strategies. On top of this, we show that there is significant value for operators from different fields to cooperate and combine their forces in one large plugging campaign.

Acknowledgments

This paper was prepared as a part of the project “Economic Analysis of Coordinated Plug and Abandonment Operations” (ECOPA), financed by the Research Council of Norway through the PETROSAM2 and PETROMAKS2 programs (p-nr: 247589).

Appendices

A. Abbreviations

LCV	Light Construction Vessel
MOU	Mobile Offshore Unit
MILP	Mixed-Integer Linear Programming
NCS	Norwegian Continental Shelf
OR	Operations Research
P&A	Plug and Abandonment
RLWI	Riserless Light Well Intervention
SSR	Semi-Submersible Rig
u-VRPTW	uncapacitated Vehicle Routing Problem with Time Windows
m-TSPTW	multiple Traveling Salesman Problem with Time Windows

B. Nomenclature

B.1. Sets and Indices

$\mathscr{K}$	set of MOUs that are available to perform the plugging operations, indexed by k
$\mathscr{K}^{WINTER}$	set of MOUs that cannot be used during the winter months. This includes the RLWI vessels and LCVs
$\mathscr{N}$	set of operations that have to be executed to plug all the wells, indexed by i, j
$\mathscr{N}_k$	subset of operations that unit k can perform
o_k, d_k	origin and destination nodes for unit k, which represent the locations (harbours) where the MOUs are located at the start and end of the planning horizon respectively
h_k	harbor node for MOU k, where $k \in \mathscr{K}^H$
$\mathscr{V}_k$	node set for unit k, defined as $\mathscr{V}_k = \mathscr{N}_k \cup \{o(k), d(k)\}$
$\mathscr{A}_k$	set of feasible arcs for unit k, defined as $\mathscr{A}_k = \{(i, j): i, j \in \mathscr{V}_k \text{ and } (i, j) \text{ feasible}\}$
$\delta_k^+(i)$	set consisting of nodes j, for which arc (i, j) is in the arc set $\mathscr{A}_k$
$\delta_k^-(i)$	set consisting of nodes j, for which arc (j, i) is in the arc set $\mathscr{A}_k$
$\mathscr{R}$	set of precedence pairs. Consists of pairs (i, j), for which operation i should precede operation j

B.2. Parameters

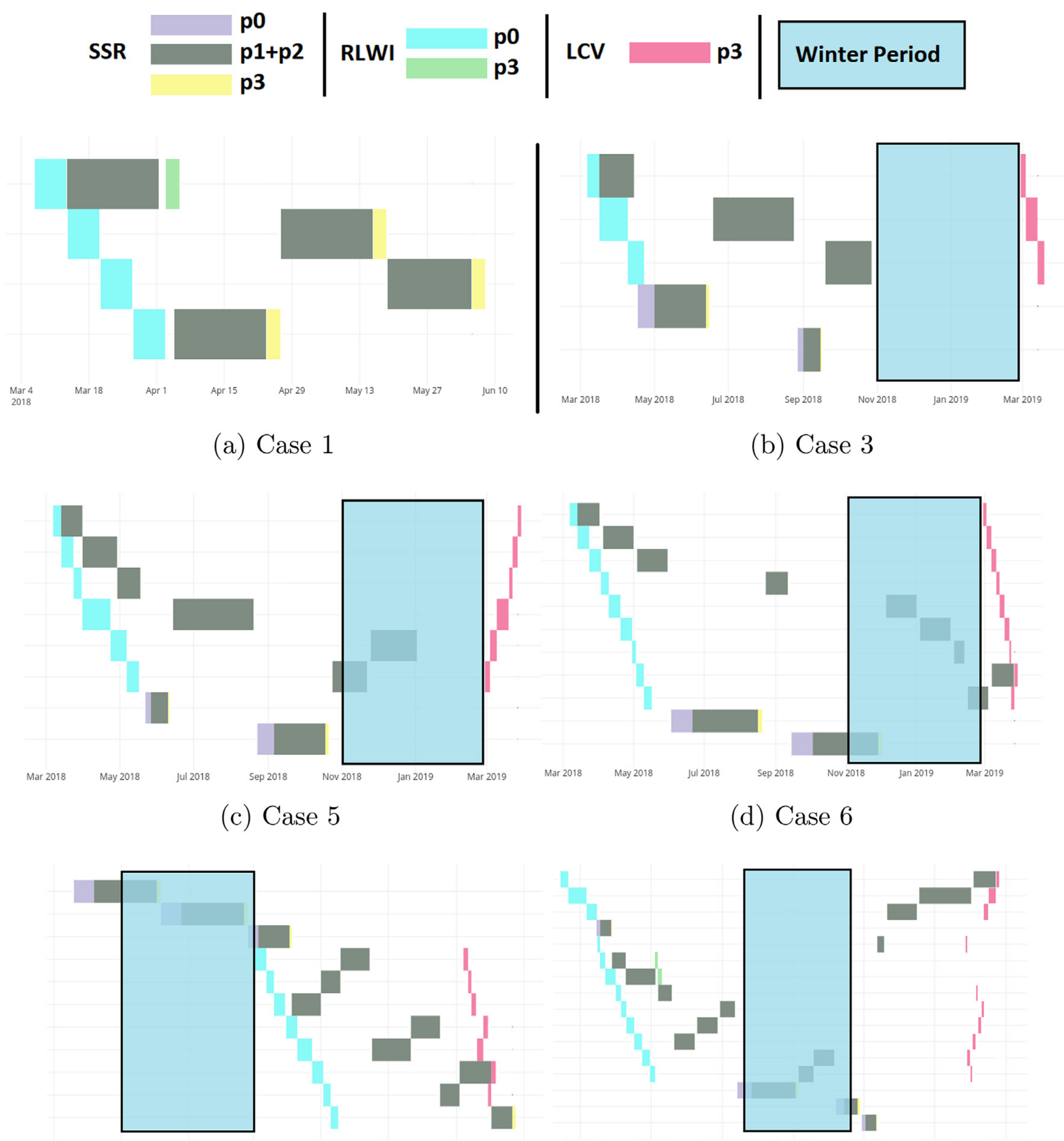
T_{ijk}^S	Sailing time of vessel k, when moving from node i to j

T_{ik}^{EX} Execution time of operation i, when performed by vessel k
C_k^{DAY} Day rate for vessel k
$\underline{T}_i$ $\bar{T}_i$ Time Window during which operation i has to be started
$\underline{T}_k^{MOU}$ $\bar{T}_k^{MOU}$ Time Window during which vessel k can be used
$\underline{T}_k^{WINTER}$ $\bar{T}_k^{WINTER}$ Time Window representing the period during which vessel k cannot be used

B.3. Variables

x_{ijk} Routing variable, equaling 1 if unit k moves from operation i to j
t_{ik} Start time of operation i for unit k
$\tilde{t}_{ijk}$ Commodity flow variable, equaling the start time t_{ik} when $x_{ijk} = 1 w_{ik}$ Waiting time for unit k in node i

C. Optimal Plans



(a) Case 1 (b) Case 3

(c) Case 5 (d) Case 6

(e) Case 7 (f) Case 10

Fig. C.7. Gantt charts representing the optimal plans for case 1,3,5,6,7 and 10.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.petrol.2019.05.042.

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