Planning of an Offshore Well Plugging Campaign: A Vehicle Routing Approach

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Abstract. When a petroleum well no longer serves its purpose, the operator is required to plug and abandon (P&A) the well to avoid contamination of reservoir fluids. An increasing number of offshore wells needs to be P&A'd in the near future, and the costs of these operations are substantial. Research on planning methods in order to allocate vessels that are required to perform these operations in a cost-efficient manner is therefore essential. We use an optimization approach and propose a mixed integer linear programming model based on a variant of the uncapacitated vehicle routing problem that includes precedence and non-concurrence constraints to plan a plugging campaign. P&A costs are minimized by creating optimal routes for a set of vessels, such that all operations that are needed to P&A a set of development wells are executed. In a case study, we show that our proposed optimization approach may lead to significant cost savings compared to traditional planning methods and is well suited for P&A planning purposes on a tactical level.

Keywords: Routing, Plug and Abandonment, Plugging Campaign

1 Introduction

An active petroleum well goes through different phases: exploration, production, and injection. After the well has served its purpose, and is no longer profitable, it must be plugged and abandoned. According to [13, Chapter 9], Plug and Abandonment (P&A) is the process of securing a well by installing required well barriers (plugs) such that the well will be permanently abandoned and cannot be used or re-entered again. We refer to P&A as the permanent abandonment of the well, as opposed to temporary P&A, where the well may be re-entered. Permanently plugged wells shall be abandoned with an eternal perspective taking into account the effects of any foreseeable chemical and geological processes. This definition holds for offshore and onshore wells, but in this paper we consider solely the former. Moreover, we only focus on development wells (consisting of production and injection wells), as exploration wells are P&A'd immediately after drilling.

To give an impression of the magnitude of future P&A work, [12] forecast a total of $1,800$ development wells to be P&A'd the next decade on the United

Kingdom and Norwegian Continental Shelf. The average P&A cost per well in the same period and regions is estimated to be around £5 − 15 million. Currently, approximately 50% of the costs of decommissioning, which also takes into account removal of installations, is related to P&A. On the United States Outer Continental Shelf, which most notably consists of the Gulf of Mexico, there are at present 5, 082 production wells and 3, 220 temporarily plugged wells, that are in need of permanent plugging [3].

The high costs related to these operations and opportunity costs of the vessels required to perform these operations (e.g. exploration or drilling activities), makes this topic highly relevant for research on efficient resource allocation and scheduling of P&A operations.

In this paper, we look at a tactical time horizon for the planning and scheduling of P&A operations for a number of subsea wells in which the production systems are located on the seabed. In this respect, a *P&A campaign* is an allocation of *vessels* (ships and rigs) to perform plugging operations on a set of wells.

As P&A costs derive mainly from renting vessels, cost savings can be achieved by, e.g., developing new or improving existing techniques such that the durations of the operations are reduced. When taking a system perspective, savings may also be obtained by optimizing routing of vessels and scheduling of operations. These cost savings might result from, for example, decreased sailing time or more use of vessels with a low day-rate. Here lies the basis for developing and demonstrating how an optimization approach based on vehicle routing theory may be used to reap these rewards.

In view of this, we propose an optimization model for the tactical planning problem concerned with P&A campaigns. We refer to this problem as the P&A Campaign Problem (PACP).

Even though optimization has been extensively applied to the petroleum industry (e.g. [10, 6]), literature on the use of optimization in P&A planning is, to the best of our knowledge, scarce. The only application of optimization to P&A that we are aware of is [1].

The planning of a P&A Campaign can be considered to be a vehicle routing problem (VRP). In this context, "routing" can be defined as the assignment of sequences of operations to be performed by vessels. The term "scheduling" is then used when the timing aspect is brought into routing. Therefore, scheduling includes the timing of the various events along a vessel's route. [4] give a review of ship routing and scheduling problems within maritime transportation, categorized on the basis of strategic, tactical and operational planning levels. An optimization model for maintenance routing and scheduling for offshore wind farms, based on a VRP with pick-up and delivery, is proposed in [7]. This model has similar features as the PACP. However, just like most maritime transportation problems, it involves cargo or inventory considerations.

The PACP can be represented as an extension of the Uncapacitated Vehicle Routing Problem (u-VRP) or Multiple Traveling Salesman Problem (m-TSP) with precedence and non-concurrence constraints, a heterogeneous fleet of vessels and the possibility of multiple routes, see [14]. Related work is done in [5] and

[2]. The former paper considers an extension of the traveling salesman problem (TSP) with precedence constraints applied to ship scheduling and presents other related work on TSPs, whereas the latter contains a review of literature on the m-TSP and practical applications.

There are several ways in which the PACP problem can be formulated. We have investigated using a time-indexed mixed-integer programming formulation. However, as P&A campaigns are characterized by both a long time horizon (1-2 years) and a fine time resolution for individual operations (hours/days), this formulation leads to a large number of binary variables. As a result, the model quickly becomes intractable, even for toy-sized problems. Therefore, we formulate the model using an arc-flow formulation, treating time as continuous. This formulation requires significantly less binary variables and is capable of solving larger instances of the problem.

We extend current literature on vehicle routing problems by introducing a new practical application of an u-VRP, besides proposing 'non-concurrence' constraints, which are required when considering multilateral wells.

The remainder of this paper is structured as follows. We start by giving a problem description in Section 2 and provide a model formulation in Section 3. A case study consisting of three wells is then described in Section 4, of which the computational as well as economical results are presented in Section 5. The results are compared with other realistic routing alternatives. The paper concludes with Section 6, which summarizes the main findings from this work as well as suggesting the direction future research could take.

2 Problem Description

Offshore petroleum wells can be distinguished by being connected to either a subsea or platform installation, where the wells are usually clustered in *templates*. In order to P&A an offshore well, several operations have to be performed in a strictly ordered sequence. These operations consist of amongst others preparatory work, the setting of plugs and removal of the wellhead. Subsea wells need vessels to perform these operations. There are several classes of vessels that are able to carry out these operations. In general, Mobile Offshore Drilling Units (MODUs), also called rigs, can conduct all types of operations. This class of vessels includes jackup rigs, semi-submersible rigs (SSRs) and drillships. Another class consisting of lighter vessels such as light well intervention vessels (LWIVs) and light construction vessels (LCVs) can only perform a subset of operations, but have a cheaper day-rate compared to rigs.

A categorization of these different operations into phases is given by [11], which is also extensively used by the industry. Based on this categorization, we define four operation types, or phases, which will be used more explicitly in the case study in Section 4. Phase 0 consists of preparatory work, which can, in general, be executed by all vessels. Phase 1 comprises the cutting and pulling of casing and tubing and setting of primary and secondary barriers, which requires a rig. Phase 2 again requires a rig and includes the setting of a surface plug.

Finally, phase 3, removal of the conductor and well head, might be performed from some lighter vessels. An overview of compatibilities between phases and vessel classes is given in Table 1.

Note that this categorization is constructed for wells in the North Sea, and need not necessarily hold for wells under different regulatory regimes. Still, it is a good representation that is useful in showing the traits of the model.

Table 1. Compatibility of phases and vessel classes

Phase	SSR	LWIV	LCV
0	X	X	X
1	X	-	-
2	X	-	-
3	X	X	-

Besides traditional wells with a single wellbore, there also exist wells with multiple wellbores connected to a common wellhead. These wells are known as multilateral wells. To give an example, Figure 1 shows a multilateral well with three lateral wellbores and a mainbore. The nodes represent operations in the wellbores that have to be performed to P&A the well. Multilateral wells are designed to reduce construction costs and increase production from a reservoir. Operations in different lateral wellbores cannot be performed simultaneously, as these wellbores must be entered through the same mainbore.

P&A operations are in general not time-critical, which means that wells can be left temporarily or partially plugged, as long as the wells are continuously monitored. Nonetheless, there might be reasons to include time windows for the operations. This might be due to legal issues, such as the expiry of a lease contract, or plans made by the operators. Vessel-use can also be limited due to contractual issues, alternative usage such as exploration or drilling, or other conditions like harsh weather.

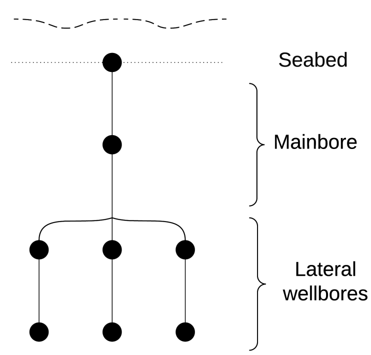


Fig. 1. Diagram of a multilateral well

Based on these different aspects of the P&A process we are able to formulate a general optimization model that minimizes the total costs related to a P&A campaign. The decision variables consist of binary variables determining the routes of the vessels and continuous variables specifying start times of operations. The constraints in the model are related to timing, precedence, non-concurrence and legal routes for vessels. The objective of the model is to minimize total rental costs, which is constructed based on time usage and day-rates of the different vessels.

3 Mathematical Formulation

In this section, we present the Mixed Integer Linear Programming (MILP) Model for the PACP. We explain the notation (sets, indices, parameters and variables) used in the model and we provide the mathematical formulation of the constraints and objective functions.

3.1 Sets and Indices

To P&A a well, a certain number of operations have to be executed. These operations might be represented by the previously defined phases, but can be more or less detailed. We therefore define the set $\mathcal{N} = \left\{1, ..., N^{OPS}\right\}$, which consists of all the operations required to be executed on all wells. The set $\mathcal{K} = \{k_1, ..., k_{N^{VES}}\}$ consists of N^{VES} heterogeneous vessel that are available to perform these P&A operations. For every vessel $k \in \mathcal{K}$, we define $\mathcal{N}_k \subseteq \mathcal{N}$ to be the set of operations that vessel k can perform. We define origin and destination vertices $o(k)$ and $d(k)$, which represent locations such as harbours, where the vessels are situated at the start and end of the planning period, respectively. We model routing options as arcs, and P&A operations as vertices. Let $\mathcal{A}_k = \{(i, j) : i, j \in \mathcal{V}_k\}$ represent the arc set corresponding to vessel $k \in \mathcal{K}$, where $\mathcal{V}_k = \mathcal{N}_k \cup \{o(k), d(k)\}$ is the vertex set of vessel k. The precedence set $\mathcal{P}$, consists of pairs (i, j) with $i, j \in \mathcal{N}$, for which operation i should precede operation j. This set is included to ensure correct sequencing of operations. Some operations are prevented, due to technical reasons, from being executed simultaneously. Therefore, we let $\mathcal{S}$ consist of pairs of operations (i, j) with $i, j \in \mathcal{N}$ that cannot be executed simultaneously.

Moreover, given vertex i, $\delta^+_k(i)$ is defined as the set of vertices j such that arc $(i, j) \in \mathcal{A}_k$. That is, the set of possible vertices j that vessel k can visit after visiting vertex i. Similarly, given vertex i, $\delta^-_k(i)$ is defined as the set of vertices j such that $(j, i) \in \mathcal{A}_k$, i.e. the set of possible vertices j that a vessel k may have visited before visiting vertex i. The term "visit" is used to include operations as well as leaving the origin or entering the destination.

The PACP is now defined on the directed graphs $G_k = (\mathcal{V}_k, \mathcal{A}_k)$ for all $k \in \mathcal{K}$.

3.2 Parameters

For each vessel $k \in \mathcal{K}$, non-negative durations T^S_{ijk} and T^{EX}_{ik} representing sailing and execution times, are associated with each arc $(i, j) \in \mathcal{A}_k$ and vertex $i \in \mathcal{V}_k$, respectively. Sailing times equal zero for arcs between operations in the same well and otherwise consist of (de-)mobilization time and actual sailing time between wells. For every vertex $i \in \bigcup\limits_{k \in \mathcal{K}} \mathcal{V}_k$ we associate a time window $\left[\underline{T}_i, \overline{T}_i\right]$, where $\underline{T}_i$ and $\overline{T}_i$ represent earliest start time and latest completion time of the corresponding operation in vertex i, respectively.

Non-negative day-rates C_k are defined for each vessel $k \in \mathcal{K}$. When using an alternative objective function which depends on vessel usage, we make use of varying day-rates C^{EX}_k, C^S_k, C^{SB}_k, for execution, sailing, and stand-by time, respectively.

3.3 Variables

The aim of the PACP is to find a collection of feasible vessel routes that minimizes total cost. We present this problem using an arc-flow formulation. We define a binary flow variable x_{ijk} for each vessel $k \in \mathcal{K}$ and arc $(i,j) \in \mathcal{A}_k$; equaling 1 if vessel k traverses arc (i,j) in the optimal solution, and 0 otherwise. Moreover, we define the continuous time variables t_{ik}, for each $k \in \mathcal{K}, i \in \mathcal{V}_k$, specifying the start-time of operation i by vessel k. We also introduce auxiliary variables, y_{ij}, for all $(i,j) \in \mathcal{S}$, taking the value 1 if operation i is executed before operation j, to deal with non-concurrence in multilateral wells.

3.4 Constraints

The constraints defining the MILP are treated below.

Operations. To P&A all wells under consideration, all corresponding operations have to be executed. This is ensured by the following constraints:

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

These constraints also restrict the assignment of each operation to exactly one vessel.

Routing. The following sets of constraints define the possible routes that the vessels are allowed to take. First, we make sure that a vessel's route starts at its origin, and performs only one route:

$$\sum_{j \in \delta_k^+(o(k))} x_{o(k)jk} = 1, \quad k \in \mathcal{K}. \tag{2}$$

The inclusion of an arc between the origin and destination with zero cost gives the option not to make use of a vessel. Then, we assure that each vessel ends its route in its destination:

$$\sum_{i \in \delta_k^-(d(k))} x_{id(k)k} = 1, \quad k \in \mathcal{K}. \tag{3}$$

Finally, we have flow balance constraints ensuring feasible routing, stating that if a vessel is used to perform a P&A operation, it must move to another operation (in the same or any other well), or to the destination:

$$\sum_{i \in \delta_k^-(j)} x_{ijk} - \sum_{i \in \delta_k^+(j)} x_{jik} = 0, \quad k \in \mathcal{K}, j \in \mathcal{N}_k. \tag{4}$$

Multiple Routes. The previous constraints force the number of times a vessel can be used to one, assuming that when a vessel has left its origin to perform P&A operations, it must perform all its planned operations on that one route. This is a reasonable assumption if vessels are committed to a project for a longer time and vessel rent has to be payed throughout this whole period, independent on whether it is executing an operation or remains idle. However, if a vessel is allowed to return to a harbour where rental costs are not incurred, the possibility of multiple trips should be taken into account. This can be done by redefining the set $\mathcal{K}$. We include copies of the vessels if multiple routes are allowed. Formally, this leads to the following. First, we define $\mathcal{R}_k := \left\{1, .., N_k^R\right\}, k \in \mathcal{K}$, where N_k^R equals the maximum allowed number of routes for vessel k. Now, let $\tilde{\mathcal{K}} = \left\{\tilde{k}_{kr} : k \in \mathcal{K}, r \in \mathcal{R}_k\right\}$. To make sure that the routes are then planned in correct order we define the following constraints:

$$t_{d(\tilde{k}_{kr})\tilde{k}_{kr}} \leq t_{o(\tilde{k}_{kr'})\tilde{k}_{kr'}}, \quad k \in \mathcal{K}, \quad r, r' \in \mathcal{R}_k \mid r' - r = 1. \tag{5}$$

That is, if we have two subsequent routes for a vessel, then the former route should be finished before the latter can start. The model now allows for multiple routes by replacing $\mathcal{K}$ with $\tilde{\mathcal{K}}$.

Timing. The time constraints ensure schedule feasibility with respect to start times of the operations. If a vessel performs an operation on a well (or enters its destination), it must have completed its previous operation (or left its origin) and travelled to the current location:

$$x_{ijk}\left(t_{ik} + T_{ik}^{EX} + T_{ijk}^{S} - t_{jk}\right) \leq 0, \quad k \in \mathcal{K}, (i,j) \in \mathcal{A}_k. \tag{6a}$$

This can be linearized as

$$t_{ik} + T_{ik}^{EX} + T_{ijk}^{S} - t_{jk} \leq M_{ijk}(1 - x_{ijk}) \quad k \in \mathcal{K}, (i,j) \in \mathcal{A}_k, \tag{6b}$$

where $M_{ijk} = \overline{T}_i + T_{ijk}^S - \underline{T}_j$.
Time windows for operations are defined by the following constraints:

$$\underline{T}_i \sum_{j \in \delta_k^+(i)} x_{ijk} \leq t_{ik} \leq (\overline{T}_i - T_{ik}^{EX}) \sum_{j \in \delta_k^+(i)} x_{ijk}, \quad k \in \mathcal{K}, i \in \mathcal{N}_k. \tag{7}$$

If a vessel does not perform a certain operation, then these constraints force the corresponding time variable to zero.

We also impose time windows for the origin and destination vertices, representing limitations in vessel use:

$$\underline{T}_i \leq t_{ik} \leq \overline{T}_i, \quad k \in \mathcal{K}, i \in \bigcup_{k \in \mathcal{K}} \{o(k), d(k)\}. \tag{8}$$

Precedence. As explained in Section 2, there exists a strict ordering in the sequence in which operations have to be performed within a well. This ordering is guaranteed to hold by the following precedence constraints:

$$\sum_{k\in\mathcal{K}} t_{ik} + \sum_{k\in\mathcal{K}} \sum_{l\in\delta_k^+(i)} T_{ik}^{EX} \cdot x_{ilk} - \sum_{k\in\mathcal{K}} t_{jk} \leq 0, \quad (i,j) \in \mathcal{P}. \tag{9}$$

Non-concurrence. The precedence constraints control the order in which operations in the same wellbore are being executed, but they cannot deal with the fact that operations from different lateral wellbores cannot be performed simultaneously. This phenomenon arises when considering multilateral wells. We refer to the constraints that arise in this situation as non-concurrence constraints. The following constraints enforce that for all non-concurrence pairs $(i,j) \in \mathcal{S}$ we have that either operation i is performed before operation j ($y_{ij} = 1$), or vice versa ($y_{ij} = 0$).:

$$\sum_{k\in\mathcal{K}} t_{ik} + \sum_{k\in\mathcal{K}} \sum_{l\in\delta_k^+(i)} T_{ik}^{EX} \cdot x_{ilk} - \sum_{k\in\mathcal{K}} t_{jk} \leq M_{ji}(1 - y_{ij}), \quad (i,j) \in \mathcal{S}, \tag{10a}$$

$$\sum_{k\in\mathcal{K}} t_{jk} + \sum_{k\in\mathcal{K}} \sum_{l\in\delta_k^+(j)} T_{jk}^{EX} \cdot x_{jlk} - \sum_{k\in\mathcal{K}} t_{ik} \leq M_{ij} y_{ij}, \quad (i,j) \in \mathcal{S}, \tag{10b}$$

where $M_{ij} = \overline{T}_j - \underline{T}_i$.

Alternatively, one can represent multilateral wells in a more restricted way, such that constraints (10) are not necessary. We can obtain this by either bundling operations that have the same phase but are in different wellbores or imposing an order for the execution of operations in the different lateral wellbores. This approach leads to a reduction in the number of constraints and integer variables, but might lead to sub-optimality.

3.5 Objective Functions

Differences in the construction of P&A contracts leads to the need to model different types of objective functions. To illustrate this, we present two exemplifying objective functions. When service companies perform P&A operations for operators, contracts are usually written on a day rate or turnkey basis [8]. Day rates are made up of, amongst others, vessel rent and personnel and equipment costs. Specification of turnkey contracts needs a precise breakdown of P&A costs, which leads to an analysis of the same cost factors. Therefore, we formulate the objective function in its most basic form as the sum of individual day-rates multiplied by total time the vessels are used offshore:

$$\min \sum_{k\in\mathcal{K}} C_k (t_{d(k)k} - t_{o(k)k}). \tag{11}$$

Some contracts specify varying day rates, such as operating, sailing and stand-by rates (C_k^{EX}, C_k^S, C^{SB}, respectively), which can easily be taken into account by the following objective function:

$$\min \sum_{k \in \mathcal{K}} \left(C_k^{EX} t_k^{EX} + C_k^S t_k^S + C_k^{SB} t_k^{SB} \right), \tag{12}$$

with:

$$t_k^{EX} = \sum_{i \in \mathcal{N}_k} T_{ik}^{EX} \sum_{j \in \delta_k^+(i)} x_{ijk}, \qquad k \in \mathcal{K}, \tag{13}$$

$$t_k^S = \sum_{(i,j) \in \mathcal{A}_k} T_{ijk}^S x_{ijk}, \qquad k \in \mathcal{K}, \tag{14}$$

$$t_k^{SB} = t_{d(k)k} - t_{o(k)k} - t_k^S - t_k^{EX}, \qquad k \in \mathcal{K}, \tag{15}$$

where t_k^{EX}, t_k^S and t_k^{SB} denote the execution, sailing, and stand-by time, respectively.

In some cases, large operating companies perform the P&A operations themselves. They usually have entered into long-term contracts with ship companies to rent vessels, which are used for multiple purposes. In this situation, the objective function might reflect opportunity costs arising from alternative uses of the vessel, such as exploration or well development.

3.6 Variable Domains

The domains of the variables used in the aforementioned constraints and objective functions are declared below:

$$x_{ijk} \in \{0, 1\}, \quad k \in \mathcal{K}, (i,j) \in \mathcal{A}_k, \tag{16}$$

$$t_{ik} \in \mathbb{R}_0^+, \quad k \in \mathcal{K}, i \in \mathcal{N}_k, \tag{17}$$

$$y_{ij} \in \{0, 1\}, \quad (i,j) \in \mathcal{S}. \tag{18}$$

Thus, the PACP model used in the case study in this paper consist of constraints (1) - (10b), variables (16) - (18), and objective function (11).

4 Case Study

To test the functioning and show possible benefits of the model, we run the model under several scenarios. We then compare these results with the results resulting from the use of simple plugging strategies, reflecting different ways in which plugging campaigns currently are, or could be, executed. The scenarios consist of one base case scenario, and five alternative scenarios that are derived by changing some parameters of the base case scenario. In the base case, we consider three subsea wells (denoted by W1, W2 and W3) on which operations have to be performed such that all wells will be permanently P&A'd. We assume that the vessels under consideration are located at the same harbour at the beginning of the planning period, and that this harbour is also the destination. The wells have a single wellbore and are located on the same field, of which W2 and W3 are located on the same template. We assume that all wells are at a distance of 150 kilometers from the harbour and W1 is 5 kilometers apart from W2 and W3. The locations and distances between wells are taken from existing wells on the Alvheim field in the North Sea. We use the four phases as described in Section 2 as a categorization of the P&A operations for each well. We assume that two different vessels are available to carry out the operations: a Semi-Submersible Rig (SSR), that can perform operations in all phases, and a Light Well Intervention Vessel (LWIV), that can perform operations in phase 0 and 3. Both vessels have a fixed day-rate, independent of the activity (executing P&A operations, sailing, or stand-by). Input data to the model, retrieved from the P&A database as described in [9], is given in Table 2. Note that the execution

Table 2. Summary of input data for SSR and LWIV.

	Execution time (days)				Day Rate	Speed	(de-) Mobilization
Phase:	0	1	2	3	(k$)	(knots)	(days)
SSR	11.9	8.85	5.63	0.75	700	5	2.5
LWIV	11.9	-	-	0.75	450	15	0.2

times are the same for all wells, as we assume that all wells are similar. However, the model allows for unique values for execution times in the case where well specific duration estimates are available. Sailing times consist of actual sailing times (calculated based on distances between the wells and speeds of the different vessels), as well as mobilization and de-mobilization time. As opposed to LWIVs, some SSRs require anchor handling, which leads to a significant difference in (de-)mobilization time. We note that when a vessel moves between wells on the same template, no anchor handling is required.

4.1 Scenarios

We perform a sensitivity analysis in which we, ceteris parabus, change some of the parameters of the base case as defined above (*SCEN1*). As an LWIV is more sensitive to bad weather than a SSR, we look at the scenarios where we increase the execution times for the LWIV. To investigate this effect we multiply the duration of phase 0, when using a LWIV, by arbitrary factors 1.5 and 2 given in scenarios *SCEN2* and *SCEN3* respectively. In the fourth and fifth scenario (*SCEN4* and *SCEN5*), we multiply the duration of phase 3 by factors 1.5 and 2 as well, when executed by a LWIV.

Finally, in the sixth scenario (*SCEN6*) the execution time of phase 3 for both LWIV and SSR is multiplied by a factor of 2. This scenario is chosen to reflect a case where it is optimal to perform all possible operations using a LWIV in two separate trips.

4.2 Strategies

We now define five different strategies that might be employed to perform a plugging campaign. The first strategy is simply the optimal outcome suggested by the model (OPT), whereas the last four strategies are examples of how different P&A campaigns can be planned manually. Traditionally, P&A operations are performed by a single rig, which is characterised by *STRAT1*. The optimal solution in this case is to execute all operations in a well consecutively and find the optimal sequence of wells to visit for the rig. More recently, cheaper light vessels are being used to perform light P&A operations that do not require a drilling rig. This might be optimal from a well perspective, but not necessarily from a system perspective. Different variations of vessel use are given in *STRAT2*, *STRAT3* and *STRAT4*. We refer to these strategies as manual strategies, even though we solve restricted versions of the optimization model. The five strategies are now given by:

- OPT: In this case, we allow the model to find the optimal allocation of vessels to P&A operations. The SSR may perform all operations in all phases (but must perform all operations in phases 1 and 2. The LWIV may perform any operations in phases 0 and 3. Finally, the LWIV is allowed to perform two routes. That is, it can return to the harbour once, where it does not incur rental costs.
- *STRAT1:* We restrict the model only to make use of the SSR to perform all the P&A operations on the wells.
- *STRAT2:* We require that all phase 0 operations are performed by the LWIV, and that the remaining operations are done by the SSR. The LWIV is only allowed to perform one route.
- *STRAT3:* Same as *STRAT2*, but we also require that all operations in phase 3 are performed by the LWIV.
- *STRAT4:* Same as *STRAT3*, however this strategy allows the LWIV to perform two routes. This reflects the possibility to do all preparatory work with a light vessel (after which the vessel goes back to the harbour), then use a rig to perform the cutting and pulling operations in phase 1 and 2, and finally use the light vessel to perform phase 3.

5 Results

In this section, we present results from running the model for the different strategies and scenarios set out in Section 4. The model has been implemented in the Mosel programming language, and solved with FICO Xpress version 8.0.4. The analyses have been carried out on a HP dl165 G5 computer with an AMD Opteron 2431, 2,4 GHz processor, 24Gb RAM running Red Hat Linux v4.4.

Table 3. Cost increase (in percentage) for the different strategies compared to the optimal cost (in million dollars) and start- and end-times for the routes in the optimal strategy (second route in parenthesis).

			Scenario					
			1	2	3	4	5	6
Cost ($M\$$)	Optimal		55.32	63.16	63.65	55.41	55.42	56.55
Cost increase (%)	Strategy	1	15.06	0.77	0.00	14.87	14.86	15.34
		2	0.17	0.44	12.30	0.00	0.00	0.77
		3	15.79	8.80	20.59	15.90	16.20	13.87
		4	0.39	0.64	12.49	1.14	2.06	0.00
Start- and end-times (days)	SSR	start	9.1	19.4	0	9.1	9.1	9.1
		end	63.5	73.2	90.9	64.3	64.3	62.0
	LWIV	start	0	0	-	0	0	0 (54.7)
		end	38.2	56.8	-	37.2	37.2	37.2 (60.7)

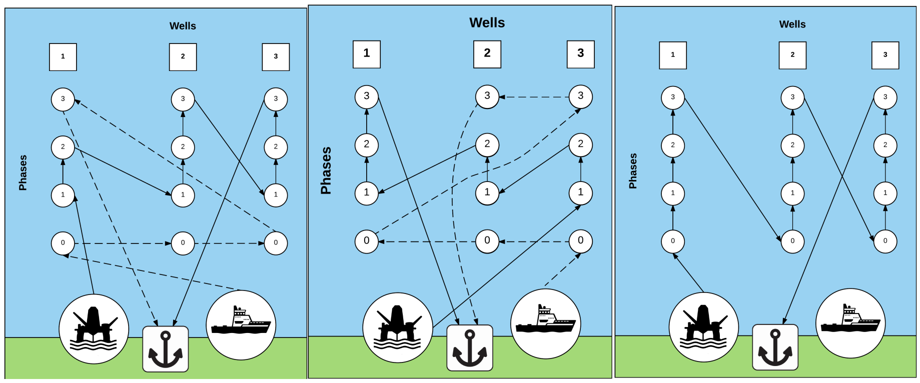
Table 3 shows numerical results for the different strategies and scenarios, whereas Figure 2 illustrates the optimal routes for each of the five scenarios.

There are several observations we can make based on these figures. To begin with, we see from Figure 2 that each scenario results in a different optimal routing (except for *SCEN4* and *SCEN5*), despite the differences between the scenarios being small. As the LWIV cannot perform operations in phases 1 and 2, the main differences between the optimal routing strategies become apparent in the choice of vessel to perform phased 0 and 3. Looking at Table 3, in the first two scenarios, none of the defined manual strategies is optimal (even though strategies 2 and 4 result in objective function values that are close to the optimal value). For each of the last four scenarios, one of the manually defined strategies is optimal, however none of these strategies performs well under all scenarios. Based upon the data input, the performance might even get arbitrarily bad. *STRAT3* performs worst under all scenarios. In this strategy we commit the LWIV to perform the operations in phases 0 and 4. But, since the LWIV cannot start operations in phase 4 before the SSR is done with phase 3, this strategy leads to an increase in costs due to idle time of the LWIV.

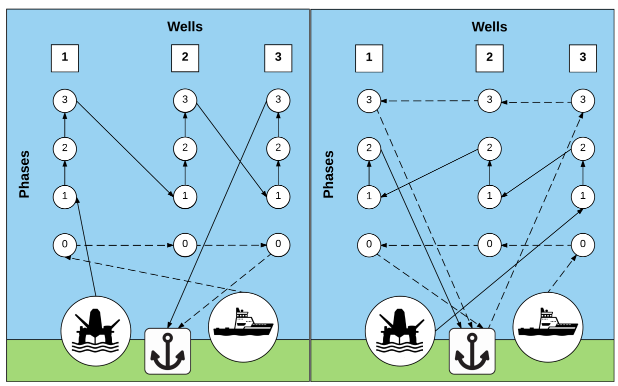
The dynamics in scenarios 1 to 3 are also worth mentioning. In the base case, the LWIV only performs phase 3 on one well. When it takes more time (factor 1.5, scenario 2) to perform phase 0, the LWIV no longer has to wait to perform an additional phase 3 operation. However, when the duration of phase 0 doubles (scenario 3), using the LWIV is no longer optimal at all.

The differences between scenario 4 and 5 are small as phase 3 has a relatively short duration

We conclude that the optimal routes depend heavily on differences in travel distance, execution times and day rates for the different vessels. Based on our inputs, assumptions, and choice of case study, we see that the optimal solution



(a) *SCEN1* (b) *SCEN2* (c) *SCEN3*



(d) *SCEN4* and *SCEN5* (e) *SCEN6*

Fig. 2. Optimal vessel routes for the six different scenarios. The solid and dashed routes correspond to the SSR and LWIV respectively.

might represent cost savings in the order of magnitude of US$ million compared to other and more conventional planning methods, represented by the manually defined strategies. This shows the strength of the application of an optimization model in planning of a P&A campaign.

Considering that the scenario in question consists of three wells, it is reasonable to assume that cost savings will be significant when including more wells.

The case study we considered consisted of three wells that needed to be P&A'd, which is a realistic sized problem. However, depending on the case, P&A campaigns on larger sets of wells can be planned, and might result in other system effects. We therefore perform a computational study, to investigate the scalability of the model. We take the previously defined case study with two vessels (SSR and LWIV) and three wells as base case. We then add wells that are located on the same field and are in need of P&A, and try to solve the model to optimality. The results are given in Table 4. The maximum run time is set to 24 hours, which is reached in the case with 7 wells. Since the addition of one extra well implies adding four different operations or vertices, we clearly see an exponential increase in the solution time. Moreover, we observe very slow convergence of the lower bound.

Non-concurrence in Multilateral Wells. In the following example we show the importance of including the non-concurrence constraints (10) as opposed to using a simplification. We consider a multilateral well that needs to be P&A'd. The well has one mainbore and three lateral wellbores, as represented in Figure 1. We assume that the well is located on the same field as in the case study, and we make use of the same vessels (i.e. a LWIV and SSR). Now assume that the LWIV is only available in the first month. Embracing the formulation with non-concurrence constraints, this leads to an optimal solution where the LWIV performs phase 0 operations in two lateral wellbores, after which the SSR performs the remaining operations. This results in an objective value of 47.806 million dollars. In a more restricted version of the model with an imposed order for the execution of operations in the different lateral wellbores, in the optimal solution, the SSR performs all operations and the LWIV is not being used. This leads to an objective function value of 53.116 million dollars. So, in this example, not including the non-concurrence constraints leads to an additional cost of approximately 5 million dollars. The simplified model consists of 61 binary variables and 124 constraints. Inclusion of non-concurrence constraints leads to an additional number of binary variables equal to the cardinality of the set $\mathcal{S}$ (denoted by $|\mathcal{S}|$) and $2 \cdot |\mathcal{S}|$ extra constraints. In the example above we have $|\mathcal{S}| = 12$, which does not lead to a significant increase in solution time.

6 Conclusions

The main contribution in this paper is a novel formulation of an optimization model for a P&A campaign. This is a field where, to the extent of our knowledge, optimization techniques so far have not been applied. In the case study, we show that there might be significant benefits from using this optimization model in monetary terms. Small changes in the data basis may lead to highly differing optimal routes. The manually defined planning strategies are therefore not robust to such changes in the data. Moreover, we show that the inclusion of non-concurrence constraints is preferred over a simplified representation of multilateral wells. As a result, the model may serve as

Table 4. Computational results

Wells	Time (sec)	MIP-Gap (%)
3	0.51	0
4	2.52	0
5	46.14	0
6	900.74	0
7	86401.50	0.48

decision support to decision makers. Nonetheless, we recommend to run more extensive case analyses, to evaluate alternative campaigns and discover general rules that can be used when planning P&A campaigns. The model can then also be used to run different scenario analyses to evaluate the effect of changes in parameters or definition of phases due to, for example, new technology.

The major challenge is related to scalability of the model. In order to solve more realistic cases, future research might therefor be conducted into several directions. To begin with, the literature suggests the implementation of decomposition techniques, such as column-generation, and inclusion of valid inequalities. Alternatively, when taking a non-exact approach, heuristics mights be developed for the problem, which however cannot guarantee that the obtained solution is optimal. Still, routes obtained from a heuristic approach might perform significantly better than existing planning approaches. Moreover, the case study in this paper did not define specific start and completion times for the individual operations and vessels. Inclusion of such time-windows might decrease computation time as well.

Another aspect worth looking at is the possible inclusion of a learning effect. Industry actors have observed that dedicated vessels performing operations during a P&A campaign have a significant reduction in execution times. The inclusion of such an effect is however challenging, and would lead to endogenous execution times.

Finally, there is a lot of uncertainty in the execution times of operations, due to unknown well conditions. Schedules and routes resulting from the deterministic model formulated in this paper might therefore be non-optimal when uncertainty is taken into account. Future work might therefore also focus on the application of stochastic programming to this problem.

References

1. Aarlott, M.M.: Cost Analysis of Plug and Abandonment Operations on the Norwegian Continental Shelf Mats Mathisen Aarlott. Master thesis, Norwegian University of Science and Technology (2016)
2. Bektas, T.: The multiple traveling salesman problem: An overview of formulations and solution procedures. Omega 34(3), 209–219 (2006)
3. Bureau of Safety and Environmental Enforcement: BSEE Well Database (2017), https://www.data.bsee.gov/homepg/data_center/well/borehole/master.asp
4. Christiansen, M., Fagerholt, K., Ronen, D.: Ship Routing and Scheduling: Status and Perspectives. Transportation Science 38(1), 1–18 (2004)
5. Fagerholt, K., Christiansen, M.: A travelling salesman problem with allocation, time window and precedence constraints an application to ship scheduling. International Transactions in Operational Research 7(3), 231–244 (2000)
6. van den Heever, S.A., Grossmann, I.E., Vasantharajan, S., Edwards, K.: A Lagrangean Decomposition Heuristic for the Design and Planning of Offshore Hydrocarbon Field Infrastructures with Complex Economic Objectives. Industrial & Engineering Chemistry Research 40(13), 2857–2875 (2001), http://pubs.acs.org/doi/abs/10.1021/ie000755e

7. Irawan, C., Ouelhadj, D., Jones, D., Stålhane, M., Sperstad, I.: Optimisation of maintenance routing and scheduling for offshore wind farms. European Journal of Operational Research 39(1), 15–30 (2015)
8. Kaiser, M.J.: Offshore Decommissioning Cost Estimation in the Gulf of Mexico. Journal of Construction Engineering and Management 132(March), 249–258 (2006)
9. Myrseth, V., Perez-Valdes, G.A., Bakker, S.J., Midthun, K.T., Torsæter, M.: Norwegian Open Source P&A Database. In: SPE Bergen One Day Seminar, 20 April, Grieghallen, Bergen, Norway. Society of Petroleum Engineers (2016)
10. Nygreen, B., Christiansen, M., Haugen, K., Bjørkvoll, T., Kristiansen, Ø.: Modeling Norwegian petroleum production and transportation. Annals of Operations Research 82, 251–268 (1998)
11. Oil & Gas UK: Guidelines for the Abandonment of Wells. Tech. rep. (2015)
12. Oil & Gas UK: Decommissioning Insight 2016. Tech. rep. (2016)
13. Standards Norway: NORSOK Standard D-010: Well integrity in drilling and well operations (2013)
14. Toth, P., Vigo, D. (eds.): The Vehicle Routing Problem. Society for Industrial and Applied Mathematics (2002)