Scheduling Workover Rigs for Onshore Oil Production

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Abstract

Many oil wells in Brazilian onshore fields rely on artificial lift methods. Maintenance services such as cleaning, reinstatement, stimulation and others are essential to these wells. These services are performed by workover rigs, which are available on a limited number with respect to the number of wells demanding service. The decision of which workover rig should be sent to perform some maintenance service is based on factors such as the well production, the current location of the workover rig in relation to the demanding well, and the type of service to be performed. The problem of scheduling workover rigs consists in finding the best schedule for the available workover rigs, so as to minimize the production loss associated with the wells awaiting for service. We propose a VNS heuristic for this problem. Computational results on real-life problems are reported and their economic impacts are evaluated.

Key words: Oil production, workover rigs, VNS, heuristics, combinatorial optimization

1 Introduction

Many oil wells in Brazilian fields rely on artificial lift methods to make the oil surface. Oil can be lifted by different techniques, which require specialized equipment operating under difficult conditions for long periods of times. This equipment are assigned to the wells as long as their use is economically profitable. Failures of these equipments over the time require maintenance services such as cleaning, reinstatement, stimulation and others, which are essential to the exploitation of the wells. These services are performed by *workover rigs*, as illustrated in Figure 1. Workover rigs are slow mobile units moving at a speed of approximately 12 mph through a network of roads, as illustrated in Figure 2.

Fig. 1. Workover rig performing a maintenance service

Due to their high operation costs, there are relatively few workover rigs when compared with the number of wells demanding service. As an example, the state owned company Petrobras operates with eight to ten workover rigs in the Potiguar field, located in the Northeastern region of Brazil. The limited number of workover rigs may lead to service delays and inactive wells, with potentially high production loss. The decision of which workover rig should be sent to perform some maintenance service is based on factors such as the well production, the current location of the workover rigs, and the type of maintenance service to be performed.

The problem of scheduling workover rigs (PSWR) consists in finding the best schedule of the workover rigs to attend all wells demanding maintenance services, so as to minimize the oil production loss. The production loss of each idle well is evaluated as its average daily flow rate under regular operation, multiplied by the number of days its production is interrupted.

Fig. 2. Transportation of a workover rig

The mathematical formulation of problem PSWR is given in the next section. A VNS heuristic for this problem is described in Section 3. Computational results on real-life problems are reported in Section 4 and the economical benefits obtained with the use of the proposed approach are assessed. Concluding remarks are drawn in Section 5. This project was sponsored by the Brazilian agency FINEP (*Financiadora de Estudos e Projetos*), in the framework of the CTPETRO Brazilian national plan of science and technology for oil and natural gas, and the associated computer system is under implementation at the state owned company Petrobras.

2 Problem formulation

In this section we present a mathematical formulation for PSWR. The list of wells $j = 1, \ldots, n$ demanding maintenance services is known beforehand. The maintenance services are provided by heterogeneous workover rigs $i = 1, \ldots, m$ whose initial positions are known. The travel times between the wells requiring maintenance services are known, as well as their daily oil production. The rigs can perform different levels of maintenance services depending on their types. A well can be serviced only by rigs whose type is greater than or equal to the level of service required.

The following notation is used:

q_i is the type of rig $i = 1, \ldots, m$;
p_j is the daily oil production of well $j = 1, \ldots, n$;

d_j is the duration of the maintenance service required by well $j = 1, \ldots, n$;
ℓ_j is the level of maintenance service required by well $j = 1, \ldots, n$;
t_{jk} is the travel time between wells $j, k = 1, \ldots, n$, $j \neq k$; and
e_{ij} is the travel time from the initial position of rig i to well j.

We define a non-negative variable x_j associated with the starting time of the maintenance service of well $j = 1, \ldots, n$ and binary variables establishing the order in which the wells are serviced:

$$y_{ij}^k = \begin{cases} 1, & \text{if well } j \text{ is the } k\text{-th one serviced by rig } i, \\ 0, & \text{otherwise.} \end{cases}$$

With this notation, problem PSWR may be formulated as follows:

$$\min \sum_{j=1}^{n} p_j(x_j + d_j) \tag{1}$$

$$\sum_{i=1}^{m} \sum_{k=1}^{n} y_{ij}^k = 1, \qquad \forall j = 1, \ldots, n \tag{2}$$

$$\sum_{j=1}^{n} y_{ij}^k \leq 1, \qquad \forall i = 1, \ldots, m, \ \forall k = 1, \ldots, n \tag{3}$$

$$\sum_{j=1}^{n} y_{ij}^{k+1} \leq \sum_{j=1}^{n} y_{ij}^k, \qquad \forall k = 1, \ldots, n-1, \ \forall i = 1, \ldots, m \tag{4}$$

$$\ell_j \sum_{k=1}^{n} y_{ij}^k \leq q_i, \qquad \forall i = 1, \ldots, m, \forall j = 1, \ldots, n \tag{5}$$

$$\begin{gathered} x_k \geq x_j + d_j + t_{jk} - M(2 - \sum_{r=1}^{s} y_{ij}^r - \sum_{r=s+1}^{n} y_{ik}^r), \\ \forall j, k = 1, \ldots, n, j \neq k, \ \forall s = 1, \ldots, n-1, \ \forall i = 1, \ldots, m \end{gathered} \tag{6}$$

$$x_j \geq \sum_{i=1}^{m} e_{ij} y_{ij}^1, \qquad \forall j = 1, \ldots, n \tag{7}$$

$$x_j \geq 0, \qquad \forall j = 1, \ldots, n \tag{8}$$

$$y_{ij}^k \in \{0, 1\}, \qquad \forall i = 1, \ldots, m, \ \forall j, k = 1, \ldots, n \tag{9}$$

The cost function (1) minimizes the losses in oil production while the wells requiring maintenance are not serviced. Equations (2) establish that each well is serviced by exactly one rig. Constraints (3) ensure that each rig is servicing at most one well at any time. Constraints (4) imply time continuity. Constraints (5) ensure that each well is serviced by a rig with the appropriate type for its service level. Constraints (6) state that if well k is serviced immediately after well j by the same rig, then its starting time x_k must be greater than or equal to the starting time x_j of well j plus the duration d_j plus the travel time t_{jk}. Constraints (7) determine that if well j is the first serviced by rig i, then its starting time must be greater than or equal to the travel time from the initial position of rig i to well j.

The problem has some similarities with the heterogeneous fleet vehicle routing problem discussed e.g. by Gendreau et. al [1]. However, some substantial differences exist. First, the rigs are not initially located at a central depot.

Instead, they are spread in the field, each one at the location of the last well it serviced in the previous schedule. Second, the costs due to losses in oil production at each well are not known beforehand: they depend on the order and time in which the wells are serviced. Finally, in our case heterogeneity is related to the type of maintenance service that can be performed by each rig and not to capacity constraints. The rigs that can be assigned to perform the maintenance service of each well are known beforehand.

3 A VNS heuristic

In this section, we propose a Variable Neighborhood Search (VNS) heuristic for the problem of scheduling workover rigs for onshore oil production. The Variable Neighborhood Search metaheuristic proposed by Hansen and Mladenović [2, 4, 3, 5] is based on the exploration of a dynamic neighborhood model. VNS successively explores increasing order neighborhoods in the search for improving solutions. Each iteration has two main steps: perturbation in the current neighborhood and local search. The main components of the heuristic are described next.

3.1 Initial solutions

Construction heuristics for the problem of scheduling workover rigs have been proposed and evaluated in [6]. Heuristic `H1` will be used to build initial solutions to the VNS heuristic. It adds one well at-a-time to the routes computed for the workover rigs. Its pseudo-code is illustrated in Figure 3. We denote by R the set of wells requesting maintenance services and by S_i the ordered set of wells to be serviced by workover rig $i = 1, \ldots, m$.

The schedule S_i of each workover rig $i = 1, \ldots, m$ is initialized in line 1. The counter of the position *last* in which each well will be assigned is initialized in line 2. The loop in lines 3-10 is performed until all wells demanding maintenance services have been assigned to some workover rig. The loop in lines 4-8 assigns a well to the last position of each workover rig $i = 1, \ldots, m$. The choice of the wells to be assigned to the workover rigs is based on their production losses. For each well $j \in R$ not yet assigned to a workover rig, we compute its production loss $loss_j(i, last)$ in case it is assigned to the last position of workover rig i. The value $loss_j(i, last)$ is equal to the estimated flow rate of well j multiplied by its idle time once it is assigned to the last position of workover rig i. This idle time is equal to the time elapsed until the end of the maintenance of the well assigned to position $last - 1$ of workover rig i plus the traveling time this workover rig will take to reach well j plus the service time of the latter. The well j^* maximizing $loss_j(i, last)$ is selected in line 5. Next, in line 6 it is assigned to the last position of workover rig i. In line 7 it is removed from the list of wells still demanding service. Once one well has been assigned to the last position of each workover rig, the position counter $last$ is increased in line 9 and a new iteration resumes. The algorithm stops when $R = \emptyset$, i.e. all wells have been assigned. Solution $S = \{S_i, i = 1, \ldots, m\}$ is returned in line 11.

```
procedure H1;
1  S_i ← ∅, i = 1, ..., m;
2  last ← 1;
3  while R ≠ ∅ do
4      for i = 1, ..., m and R ≠ ∅ do
5          j* ← max_{j∈R}{loss_j(i, last)};
6          Insert well j* in the last position of S_i;
7          R ← R − {j*};
8      end-for;
9      last ← last + 1;
10 end-while;
11 return S = {S_i, i = 1, ..., m};
end H1;
```

Fig. 3. Pseudo-code of the construction heuristic H1

3.2 Neighborhoods

We conceived nine different neighborhood definitions associated with a solution S to the problem of scheduling workover rigs. Each solution S is represented as a list of workover rigs, each of which is associated with an ordered list (defining a route and a schedule) of wells that it will service.

(1) *Swap routes* (SS): the wells and the associated routes assigned to two workover rigs are swapped, as illustrated in Figure 4 for workover rigs $S1$ and $S2$. Each solution has $m(m-1)/2$ neighbors within this neighborhood.
(2) *Swap wells from the same workover rig* (SWSW): the order in which two wells are serviced by the same workover rig is swapped, as illustrated in Figure 5 for wells $R2$ and $R4$ serviced by workover rig $S1$. Assuming that the n wells are evenly assigned to the m workover rigs, each solution has $n(n-m)/(2m)$ neighbors within this neighborhood.
(3) *Swap wells from different workover rigs* (SWDW): two wells assigned to two different workover rigs are swapped, as illustrated in Figure 6 for wells $R2$ and $R8$ originally assigned respectively to workover rigs $S1$ and

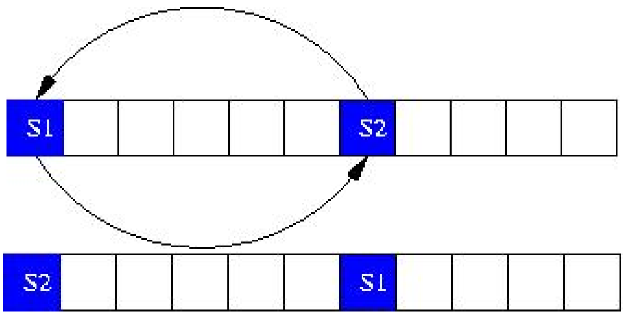

Fig. 4. Neighborhood SW

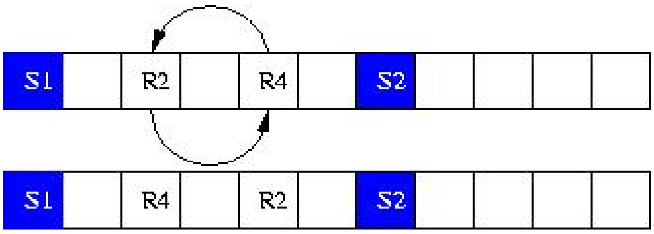

Fig. 5. Neighborhood SWSW

$S2$. Once again assuming that the n wells are evenly assigned to the m workover rigs, each solution has $n^2(m-1)/(2m)$ neighbors within this neighborhood.

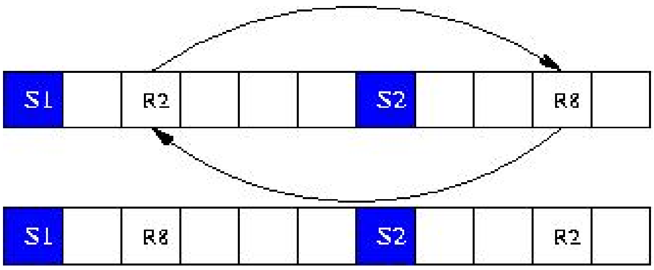

Fig. 6. Neighborhood SWDW

(4) *Add-Drop* (AD): a well assigned to a workover rig is reassigned to any position of the schedule of another workover rig, as illustrated in Figure 7 for well $R2$ which is reassigned from workover rig $S1$ to $S2$. Once again assuming that the n wells are evenly assigned to the m rigs, each solution has also $n^2(m-1)/(2m)$ neighbors within this neighborhood.

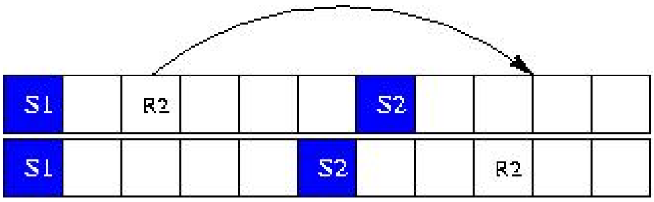

Fig. 7. Neighborhood AD

Five other neighborhoods are defined by successive applications of moves within neighborhoods SSS, SSD, and AD:

(5) SWSW^2: successively apply two moves within neighborhood SWSW
(6) SWDW^2: successively apply two moves within neighborhood SWDW
(7) SWDW^3: successively apply three moves within neighborhood SWDW
(8) AD^2: successively apply two moves within neighborhood AD
(9) AD^3: successively apply three moves within neighborhood AD

3.3 Local search

The local search procedure used at each iteration of the VNS heuristic is based on a swap neighborhood defined by all solutions which can be obtained by the exchange of a pair of wells from the current solution. This neighborhood is equivalent to the union of neighborhoods SWSW and SWDW described in the previous section.

Pairs of wells are examined in circular order. The first improving solution found is made the new current solution. The search stops at the first local optimum, after the full neighborhood of the current solution is investigated (i.e., after a sequence of $n(n-1)/2$ non-improving moves are evaluated).

3.4 VNS heuristic

The nine neighborhoods described in Section 3.2 are not nested. Lower order neighborhoods are characterized by solutions which are closer to the current solution. As the neighborhood order increases, most implementations of VNS progressively investigate solutions which are farther from the current solution. Concerning the problem of scheduling workover rigs and the nine proposed neighborhoods, Add-Drop neighborhoods are the highest order ones, since many elements may change between two neighbor solutions. On the contrary, in the case of swap neighborhoods, only a few solution elements will be changed between two neighbor solutions. Our implementation of the VNS heuristic uses $k_{\max} = 9$ and investigates these neighborhoods in the following order: $N^{(1)} = \text{SS}, N^{(2)} = \text{SWSW}, N^{(3)} = \text{SWDW}, N^{(4)} = \text{SWSW}^2, N^{(5)} = \text{SWDW}^2, N^{(6)} = \text{SWDW}^3, N^{(7)} = \text{AD}, N^{(8)} = \text{AD}^2,$ and $N^{(9)} = \text{AD}^3$.

Figure 8 gives the algorithmic description of procedure `VNSforWorkoverRigs` which implements the VNS metaheuristic for the problem of scheduling workover rigs. A solution S and a neighborhood order k are associated with each VNS iteration. The initial solution is built by the construction heuristic `H1` in line 1. The order k of the initial neighborhood is set to one in line 2. The loop in

```
procedure VNSforWorkoverRigs;
1  Let S be the initial solution built by H1;
2  k ← 1;
3  while k ≤ k_max do;
4      if the time limit is exceeded then return S;
5      Randomly generate S' ∈ N^(k)(S);
6      Obtain S̄ by applying local search to S';
7      if w(S̄) < w(S) then S ← S̄; k ← 1;
8      else k ← k + 1;
9  end-while;
10 Return to step 2;
end VNSforWorkoverRigs.
```

Fig. 8. Pseudo-code of the VNS heuristic for the problem of scheduling workover rigs

lines 3-9 is performed until the complete sequence $N^{(1)}, \ldots, N^{(k_{max})}$ of neighborhoods is explored. If the time limit is attained, the algorithm returns the current solution S in line 4. In line 5, a neighbor solution S' is randomly generated within neighborhood $N^{(k)}$ of solution S. Next, a solution $\bar{S}$ is obtained by applying local search to S' in line 6. If $\bar{S}$ improves the current solution, in line 7 the algorithm resumes the search from this solution using the first neighborhood. Otherwise, the algorithm resumes from S in line 8 using a higher order neighborhood. Once the complete sequence $N^{(1)}, \ldots, N^{(k_{max})}$ of neighborhoods is explored without finding any improving solution, in line 10 the algorithm returns to step 2 to reset the order of the current neighborhood to one and to resume the search from the current solution S.

4 Application to real-life problems

The VNS heuristic was implemented in `C`, using version 2.96 of the `gcc` compiler. The `rand` function was used for the generation of pseudo-random numbers.

We report computational results obtained on eight real-life problems provided by Petrobras, the Brazilian state owned company in charge of oil exploration. The main data characterizing these instances is displayed in Table 1. For each problem we give the date when the scheduling system was activated, the number n of wells requiring maintenance services, the number m of available workover rigs, the average $\overline{d}$ and the maximum d_{max} durations in days of the maintenance services, the average $\overline{t}$ and the maximum t_{max} travel times in hours between the wells requiring service, and the average $\overline{p}$ and the maximum p_{max} oil productions in m^3/day of the wells requiring service.

Instance	date	n	m	$\overline{d}$	d_{max}	$\overline{t}$	t_{max}	$\overline{p}$	p_{max}
BR1	Sep 05, 2002	130	9	4.21	14.60	2.00	5.32	4.22	45.33
BR2	Feb 06, 2003	184	8	4.17	14.75	2.04	5.36	3.19	20.00
BR3	Mar 06, 2003	199	8	4.23	14.90	2.06	5.36	0.92	6.60
BR4	Jan 08, 2003	166	8	4.45	14.72	2.01	5.37	0.86	13.33
BR5	Mar 19, 2003	192	9	4.31	14.75	1.94	5.36	1.53	53.33
BR6	Jan 23, 2003	179	8	4.25	13.00	2.00	5.35	1.01	20.00
BR7	Apr 23, 2003	184	11	4.12	13.00	1.95	5.36	0.96	10.67
BR8	May 05, 2004	99	11	4.45	8.00	1.96	5.41	1.50	41.67

Table 1
Data for real-life instances

To be able to directly compare the results obtained by the VNS heuristic with those obtained by the ad-hoc procedure currently in use by the engineering team of Petrobras, we introduced a small modification in the problem formulation in the context of real-world applications. Instead of finding the best solution such that all wells requiring maintenance services are visited, we search for the best schedule limited to 15 days of operation of the workover rigs.

Table 2 displays the results obtained by the engineering team of Petrobras and those obtained by the new VNS heuristic after ten minutes of processing time on a 1.4 GHz Pentium IV with 256 Mbytes of RAM memory running under version 2.4.18 of Linux. For each problem, we report the total number of wells serviced within the 15-day scheduling period by each approach, together with the total losses in oil production during the same period. We also give the savings due to loss reduction obtained with the VNS heuristic, in percentage terms, in m^3 and in US$ (considering the price of US$ 40 per barrel for the Brent oil in London on July 30, 2004). The new heuristic finds schedules that are clearly better than those obtained by the procedure currently adopted. The losses are reduced by 16.4% in the average, with considerably more wells being serviced and average savings of approximately US$ 107,000 along a 15-day time period over the eigth instances.

5 Concluding remarks

This project was sponsored by the Brazilian agency FINEP (*Financiadora de Estudos e Projetos*), in the framework of the CTPETRO Brazilian national plan of science and technology for oil and natural gas. We comment on the economical impact of the results obtained with the use of the new approach.

	Petrobras		VNS heuristic		savings due to loss reduction		
Instance	wells	losses (m^3)	wells	losses (m^3)	%	m^3	US$
BR1	41	4919.50	62	4810.91	2.21	108.59	27318
BR2	25	7944.13	57	7756.18	2.37	187.95	47283
BR3	32	3980.81	84	3836.31	3.63	144.50	36352
BR4	27	1788.27	69	1387.89	22.39	400.38	100724
BR5	18	3652.53	60	2564.16	29.80	1088.37	273804
BR6	28	2106.07	73	1404.21	33.33	701.86	176568
BR7	31	2186.77	72	1879.33	14.06	310.44	78098
BR8	33	1947.93	57	1491.74	23.42	456.19	114765
				average	16.40	424.79	106864

Table 2
Results for real-life instances for a time period of 15 days

There are usually around ten workover rigs operating full time in the Potiguar field, located in the Northeastern region of Brazil. They are subcontracted from their owners and their rental cost is approximately US$ 10,000,000 per year to Petrobras. We obtained an average increase of 425 m^3 (equivalent to approximately 2673 barrels and US$ 107,000) in oil production due to the reduction in losses along 15 days, corresponding to the difference between the solution obtained by the new heuristic and that computed by Petrobras, as depicted in Table 2. Projected over a 12-month period, this amounts to annual savings in production losses of the order of US$ 2,568,000.

The expected savings in production losses are equivalent to the yearly rental of two to three additional workover rigs. These results have opened the path to preliminary studies to investigate the gains that could be obtained if additional workover rigs were used.

Furthermor, we notice that these savings are significantly larger than the gains expected when this project was contracted, which were originally estimated at 5 to 10% of the yearly rental costs, i.e. US$ 500,000 to 1,000,000 per year. As a consequence, the new heuristic approach is under implementation to be used as an operational scheduling tool at Petrobras.

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