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Solution methods for scheduling of heterogeneous parallel machines applied to the workover rig problem

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A B S T R A C T

We take into account a parallel heterogenous machine scheduling problem arising in maintenance planning of heterogeneous wells. This problem particularly arises in the context of workover rig scheduling. The oil wells need regular maintenance to ensure an optimal level of production. After oil production being decreased at some wells, appropriate workover rigs with compatible service capacity, are deployed to serve the wells at discrete locations. Every well needs a certain level of maintenance and rehabilitation services that can only be offered by compatible workover rigs. A new mixed integer linear programming model is propose for this problem that is an arc-time-indexed formulation. We propose a heuristic selection type hyper-heuristic algorithm, which is guided by a learning mechanism resulting in a clever choice of moves in the space of heuristics that are applied to solve the problem. The output is then used to warm start a branch, price and cut algorithm. Our numerical experiments are conducted on instances of a case study of Petrobras, the Brazilian National Petroleum Corporation. The computational experiments prove the efficiency of our hyper-heuristic in searching the right part of the search space using the right alternation among different heuristics and confirms the high quality of solutions obtained by our hyper-heuristic.

1. Introduction

One of the most important natural resources of the world since late XIX century is oil, which shapes our lives in many ways, not only by being the main energy source of our era, but also its uses on plastics, road construction, pharmaceuticals drugs, etc. The process of finding, drilling, producing, transporting and refining oil provides a wide range of research fields, from geology to biochemistry and so on.

Many land (onshore) oil fields are composed of many wells, which are distributed geographically. Occasionally, failures happen on these wells, requiring an intervention inside them to return to their original condition. Such operation normally includes substituting the production equipments (cleaning) or stimulating the reservoir itself (stimulation), to name a few. Those interventions require the use of *workover rigs*, big structures that can be dismounted, transported and mounted from one well to another, providing safety and accuracy conditions to the intervention. Renting of workover rigs come at great cost, thus having them at stand-by availability is expensive. This paper boards the problem of prioritizing onshore interventions using workover rigs to minimize production loss associated with the wells awaiting service. The problem in study here can be classified like a particular case of machine scheduling problem.

A classical problem of machine scheduling represents a set of tasks (or jobs) to be processed, where each task consists of a sequence of operations to be performed using a given number of machines. The processing of an operation requires the use of a specific machine for a particular processing time, and each operation must be executed in the order given by the sequence.

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Each machine must process only one operation at a time. The objective is to arrange the wells so that the global performance measures can be optimized.

A vast body of literature is dedicated to the classical problems of scheduling (job-shop and flow-shop), but in specific applications, the quantity of publications is rather limited. Two well-known samples of historical papers for the classical problems are related to the problems with 10 wells and 10 workover rigs proposed by Muth (1963), which was only solved 26 years later by Carlier and Pinson (1989). In this problem, each task has to be processed on each of the given workover rigs exactly once —classical job-shop scheduling problem.

This paper presents a particular case of machine scheduling, an application to the problem of *Workover Rigs Scheduling (WRS)* for maintenance services in oil wells of onshore fields. The problem consists in finding the best schedule for a small number of workover rigs to minimize the production loss, associated with a large number of wells waiting for service. This paper is structured as following: In Section 2, we review the relevant literature and in Section 3, a precise problem description is given. In Section 4, a mathematical model as well as several classes of valid inequalities are proposed. Two solution methods are proposed in Section 5 and numerical results are reported in Section 6. Finally, we summarize and conclude the work and propose some further research directions.

2. Literature review

Smith (1956) showed that if the problem has only one rig and no time windows, the optimal sequencing is obtained, independent of the quantity of wells, by sorting the wells in an increasing order of value $\frac{P_i}{Et_i}$, where P_i is the rate of daily production loss of well *i* and Et_i is the estimated maintenance service time of well *i*.

Barnes, Brennan, and Knap (1977) provided lower bounds for workover rigs problem. The authors consider *m* rigs and *n* wells, and show that a lower bound can be obtained as $Max\{B(1), B(n)\}$ where $B(n)$ is the total production loss with *n* rigs and $B(1) = \frac{1}{2m}[(m-1)B(n) + 2B(1)]$ is the total production loss with only one single rig.

Noronha et al. (2001) presented a greedy heuristic algorithm for the workover rigs problem. The authors consider priorities for the wells as $G_{ij} = \frac{P_i}{T_{ij}}$, where, P_i is the daily rate of production loss of well *i*, and T_{ij} is the estimated maintenance service time of the well *i* by the rig *j*. In their greedy approach, the authors consider also the environmental risks corresponding to the service. The proposed algorithm was later used a constructive phase of a GRASP metaheuristic.

Aloise et al. (2006) proposed a variable neighborhood search (VNS) metaheuristic. In the VNS algorithm the authors, have used the constructive heuristic $H1$, proposed by Noronha et al. (2001), which adds one well at-a-time to the routes computed for the workover rigs. The local search procedure proposed for the VNS 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. The numerical experiments was performed with real-life instances showing a loss reduction of 16.4% on average. This VNS metaheuristic approach is currently being used as an operational scheduling tool at Petrobras S. A (Brazilian National Petroleum Corporation).

Mattos Ribeiro, Regis Mauri, and Antonio Nogueira Lorena (2011) proposed a simulated annealing (SA) for a variant of the WRS where the travel time is not considered. The authors have used CPLEX 12.1 (IBM, 2009) to solve instances with up to 50 wells. They have also reported that the proposed SA presents a low deviation (the worst case, 0.037%) from optimality and takes, approximately, 10 s for solving real-life instances composed of 25, 50, 75, 100 and 125 wells, with 2, 4, 6, 8 and 10 rigs.

In Duhamel, Cynthia Santos, and Moreira Guedes (2012), three mixed integer linear models are proposed. The first model improves an existing scheduling-based formulation. The second one, uses an open vehicle routing approach and the third one is an extended model for which a column generation strategy is developed. The models were tested using CPLEX 12.0 under default parameters and the instances were composed with up to 60 wells, the number of rigs varies from 2 to 5 and the time horizon is set to 15 days. The authors report optimal values for medium-size instances of WRS.

Ribeiro, Laporte, and Mauri (2012b) presented the WRS as a workover rig routing problem, a particular case of vehicle routing problem with time windows, in context of the operations of onshore oil fields. The authors have proposed three metaheuristics for the problem: an iterated local search, a clustering search, and an adaptive large neighborhood search (ALNS). They have carried out experiments with 50, 100 and 500 wells, and 5 and 10 rigs, testing a total of 60 instances. The authors reported a superior performance of ALNS on larger instances.

Mattos Ribeiro, Desaulniers, and Desrosiers (2012), in this work the authors propose a branch, price and cut algorithm as the first exact algorithm for the WRS, which is modeled as a workover rig routing problem. The computational experiments relies on a set of 40 instances (with 100 and 200 wells, 5 and 10 rigs, and 200–300 units of time for the horizon). For the larger instances (200 wells), 12 of the 40 instances could not be solved, in particular, all instances with 200 wells,10 rigs, and horizon time of 300 h were unsolvable.

Ribeiro, Desaulniers, and Desrosiers (2012a) look at the problem as a routing problem and proposes a branch, price and cut algorithm for solving instances of this problem up to 200 wells and 10 rigs. Recently, Ribeiro, Desaulniers, Desrosiers, Vidal, and Vieira (2014) proposed three different heuristics such as branch-price-and-cut (BPC) heuristic version of Ribeiro et al. (2012a), an adaptive large neighborhood search (ALNS), and a hybrid genetic algorithm (HGA). They managed to solve up to 10 rigs and 300 wells.

2.1. Objective and contribution

We propose a new model, which is based on an arc-time-indexed formulation inspired by the work in Pessoa, Uchoa, de Aragão, and Rodrigues (2010). We also propose several classes of valid inequalities in order for tightening the MIP polytope. The model is well-designed in such a way that a particular relaxation of this model allows a decomposition of the relaxed model per rigs thus reducing the computational difficulties in resolution. A branch, price and cut is proposed that is capable of solving instances of moderate size to optimality.

The work was motivated by the industrial application and the need for efficient and scalable solution framework that can exploit the knowledge hidden in all the heuristics proposed for the problem at hand and show how the output solution can be checked in a branch, price and cut for accelerate the algorithm and determining the solution quality.

The main part of this article is presenting a two-phase algorithm. In the first phase, a heuristic selection type of hyper-heuristics is proposed, which is a self-adaptive mechanism in the sense that the selection of heuristic algorithm (chosen from a pool of constructive, improvement and destructive ones) iteratively applied to the problem is based on a proposed learning method. We then warm start our using the best-found solution of our hyper-heuristic and show that the proposed solutions are actually very close to optimals. Our main goal is to show that the self-adap-