Plant shut-down maintenance workforce allocation and job scheduling

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Abstract. An important and challenging real-life problem is considered, involving workforce allocation and job scheduling for shut-down maintenance in a large oil refinery. A limited number of maintenance employees must be divided into several teams that work in parallel on different maintenance tasks. Since shut-down is costly, the aim is to minimize the total shut-down period, i.e., the time to complete all the maintenance tasks. Different team sizes are possible, and the size of the given team determines the speed of finishing the assigned maintenance tasks. Constraints include the total workforce size, the allowed team sizes, job availability (arrival) times, and precedence relations between different jobs. This problem can be considered as a resource-constrained parallel-machine scheduling problem, in which the objective is to minimize the makespan, and both the number and the speeds of the individual machines are decision variables. Optimization models and effective heuristic algorithms are developed for this NP-hard scheduling problem.

Keywords: Maintenance scheduling, parallel machine scheduling, makespan, resource-constrained scheduling

1 Introduction

The real-life problem considered in this paper is the optimum scheduling of shut-down maintenance activities in a large oil refinery. Shut-down maintenance is performed by a limited number of skilled workers supplied by a contractor at a high daily rate. These workers have to be divided into several work teams that work in parallel on different maintenance tasks. The number of workers in each team, which is subject to certain restrictions, determines the speed of completing each maintenance task assigned to the team. Models are formulated to determine the number of work teams, the size of each team, the jobs assigned to each team, and the sequence of processing these jobs. The objective is to minimize the time needed to complete all jobs, i.e., the shut-down duration, in order to reduce the cost of lost revenue and the cost of contract workers.

The problem analyzed in this paper can be considered as a resource-constrained parallel-machine scheduling problem, in which the limited resource is the maintenance workforce, and the parallel machines are the different maintenance teams. In machine scheduling terms, the objective is to minimize the makespan, and both the number and the speeds of the individual machines are decision variables. The proposed machine scheduling problem involves resource constraints, precedence constraints, a variable number of machines, and variable machine speeds. This is a unique problem that has not been considered previously in scientific literature. It is also a challenging NP-hard scheduling problem, which is very hard to solve to optimality. An integer programming model is formulated to solve smaller instances of this problem. In order to solve larger real-life instances, an effective heuristic solution algorithm is developed and evaluated using a large number of test problems.

Remaining sections of this paper are organized as follows. Relevant recent literature is reviewed in section 2. The integer programming model is formulated in section 3. The heuristic solution is described in section 4. Finally, conclusions and suggestions are provided in section 5.

2 Relevant literature

Three aspects of the problem have been separately considered in prior literature: plant maintenance workforce scheduling, plant shut-down maintenance scheduling, and resource-constrained parallel machine scheduling. Relevant recent literature on these aspects is reviewed below.

Several integer programming models have been proposed for plant maintenance workforce scheduling. Alfares and Emovon (2007) use integer programming to compare alternative maintenance work schedules at a power station. The objective is to satisfy workload requirements with minimum cost and highest efficiency. Safaei et al. (2011) present a bi-objective mixed-integer programming model for workforce-constrained maintenance scheduling in a steel plant. The first objective is to minimize the total workforce requirements, and the second is to maximize the equipment availability. Koochaki et al. (2013) analyze the impact on maintenance workforce scheduling of two plant maintenance policies, namely condition-based maintenance and age-based maintenance. Leite and Vellasco (2020) adapt the particle swarm optimization (PSO) algorithm to schedule offshore maintenance activities and staff in order to maximize profitability.

Plant shut-down maintenance scheduling has been well studied in the literature. Castro et al. (2014) analyze long-term shut-down maintenance scheduling in a power plant with time restrictions on labor availability, demand variability, and price variability. A generalized disjunctive programming model is developed to maximize the revenue by maximizing labor utilization and minimizing shut-downs during high-price seasons. Adhikary et al. (2016) construct a nonlinear optimization model for preventive maintenance in continuous operating systems with two objectives: maximizing system availability and minimizing maintenance cost. To solve the model, a dual-objective genetic algorithm is developed and applied to optimize preventive maintenance in a real power plant.

The resource-constrained parallel machine scheduling problem, which is analogous to the maintenance scheduling problem analyzed in this paper, has received considerable attention in the literature. Edis et al. (2013) review and classify the literature on parallel machine scheduling where additional resources are required, such as operators, tools, fixtures, and robots. Fanjul-Peyro et al. (2017) propose two integer programming models to minimize makespan for parallel machine scheduling with limited resources. Assuming the amounts of required resources depend on the job-machine assignment, three heuristics are developed to solve the two optimization models. Zheng and Wang (2018) analyze a resource-constrained parallel machine scheduling problem, aiming to minimize both the makespan and the total carbon emission. A multi-objective fruit fly optimization algorithm is used to determine the optimum job schedule and the speed of each machine.

Compared to previous work, this paper presents a new scheduling problem. If considered as a machine scheduling problem, it would have a variable number of parallel machines, variable machine speeds, resource-dependent job processing times, resource limitations, and precedence relations. As far as the author knows, this is the first paper in which the number of machines is itself a decision variable.

3 Model description

In the problem under study, a limited number of maintenance employees are available to perform a given set of maintenance jobs. These employees must be divided into several groups (work teams) that work in parallel on different subsets of the maintenance jobs, in order to finish all jobs in the minimum time duration. Therefore, the proposed maintenance scheduling problem involves employee team formation, job-team assignment, and job sequencing for each team. The aim is to minimize the makespan (time interval) needed to complete the shut-down maintenance. The binary integer programming model presented below is formulated to represent and optimally solve this problem.

3.1 Assumptions

The assumptions used to define the problem and construct the optimization model are listed below.

1. The maintenance workforce is homogeneous and composed of multi-skilled employees who are equally qualified to work on any maintenance job.
2. The size (number of employees) of any employee group (team) is limited to a given set of feasible values. Usually, two team sizes are specified: a standard (smaller) team size, and a rush (larger) team size.
3. The processing time of each job depends on the size of the group assigned to do the job. Usually, two processing time durations are possible for each job: a normal (longer) time by the smaller team size, and a crash (shorter) time by the larger team size.
4. Precedence relations exist between certain pairs of jobs, where a job cannot be started before the completion of its predecessor job(s).
5. A job cannot be started before its arrival time. Some jobs have an arrival delay period after which they become available for maintenance.

3.2 Decision variables

C = makespan, i.e., completion time of the last maintenance job
N = number of groups (work teams)

$$Q_g = \begin{cases} 1 \text{ if group } g \text{ is active} \\ 0 \text{ otherwise} \end{cases}$$
$g = 1,\ldots, G$

$$Y_{gk} = \begin{cases} 1 \text{ if the size of group } g \text{ is } s_k \text{ employees} \\ 0 \text{ otherwise} \end{cases}$$
$g = 1,\ldots, G$, $k = 1,\ldots, K$

$$X_{jgkt} = \begin{cases} 1 \text{ if job } j \text{ is assigned to group } g, \text{ of size } s_k, \text{ and started on day } t \\ 0 \text{ otherwise} \end{cases}$$
$j = 1,\ldots, J$, $g = 1,\ldots, G$, $k = 1,\ldots, K$, $t = 1,\ldots, T$

3.3 Structure of the integer programming model

A pure-integer linear programming (ILP) model is developed to represent and optimally solve the problem. is linear, All the decision variables are integer, and all of them except C and N are binary. The objective of the model is to minimize the makespan C , i.e., the total shut-down duration, subject to the following constraints:

1. Unique job scheduling constraints: ensure that each job j is assigned to one group g of one size s_k and has one start time t. Job-to-group and employee-to-group assignments are fixed during the shut-down maintenance period.
2. Unique job assignment constraints: assure that, for each work group, no more than one job is assigned in each time period.
3. Precedence constraints: guarantee that each job can start only after the completion time of all its predecessors.
4. Makespan constraints: set the makespan to be greater than or equal to the finish time of all jobs.
5. Logical constraints: relate the decision variables X_{jgkt} and Y_{gt}, by assigning jobs only to the active groups with the correct size.
6. Workforce constraint: ensure that the sum of group sizes does not exceed the available workforce size W.
7. Unique team size constraints: to guarantee that only one size is selected for each active group.
8. Number of teams' constraint: to equate the number of groups to the sum of active groups.

4 Heuristic solution method

Obtaining the optimum solution of the ILP model defined above is very difficult, especially for large problem sizes. The number of decision variables, especially X_{jgkt}, grows very rapidly with increasing problem size. To effectively solve larger sizes of this workforce allocation and job scheduling problem, the unique problem structure was utilized to develop an efficient two-stage heuristic. First, ignoring job sequencing and precedence constraints, a simplified ILP model is used to assign jobs to teams. Next, jobs are sequenced for their respective assigned teams to incorporate arrival and precedence constraints.

In order to assess the real-world effectiveness of proposed heuristic, its performance has been verified assuming different problem characteristics. Therefore, to compare the heuristic solution with the optimum ILP solution, computational experiments were carried out using a wide variety of randomly generated test problems. The heuristic method has been shown to produce optimal solutions for all test problems significantly faster than the ILP model.

5 Conclusions

This paper presented a model for scheduling employees and tasks in plant shut-down maintenance. Given a limited number of maintenance employees and a set of maintenance tasks, the employees are divided into several teams of specific sizes such that each team is responsible for a given subset of the tasks. This allows several maintenance activities to be processed simultaneously (in parallel) by the different workforce teams. Naturally, the speed of processing each task depends on the size of the maintenance team assigned to perform it. Considering the work teams as machines, this problem can be presented as a resource-constrained parallel-machine scheduling model. As a parallel machine scheduling problem, this model is unique because both the number and the capacities of the machines are decision variables. The model has been successfully applied in a real-life shut-down maintenance scheduling problem in a large oil refinery. A heuristic algorithm is developed and shown to efficiently solve this scheduling problem.

6 References

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