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Multi-skill project scheduling in a nuclear research facility

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1 Introduction

This paper addresses the weekly scheduling of the activities within one of the research facilities of the French Alternative Energies and Atomic Energy Commission (CEA in short for French). After analyzing the operations and characteristics of the studied laboratory, we conclude that the problem under consideration amounts to an extension of the classical Resource-Constrained Project Scheduling Problem (RCPSP).

The RCPSP is a combinatorial optimization problem that covers a wide range of scheduling situations. The problem consists in scheduling non-preemptive tasks on limited renewable resources. These tasks are linked together by precedence relationships (task i cannot start while task l is in process, $\forall(l, i) \in E$). Usually, the objective is to find a solution that minimizes the makespan of the project, while complying both the precedence constraints and the resource constraints.

Even if the standard version of the RCPSP allows the modeling of a broad spectrum of scheduling problems, it may not cover all the situations that can be found in real-life problems. Extended versions of the RCPSP are then necessary. For a more exhaustive lecture about the variants and extensions of the resource-constrained project scheduling problem, we refer to the survey on this topic published by Orji and Wei (2013). Among all the existing extended versions, we distinguish two that are of great interest for the modeling of the studied problem: the Preemptive RCPSP and the Multi-Skill Project Scheduling Problem (MSPSP). A first attempt to combine these two models for scheduling research activities can be found in Polo Mejia et al. (2017), where a pure preemptive MSPSP with multi-skilled resources is proposed. However, an intensive analysis of the laboratory under study highlighted the need to develop a more extended version in order to have a better representation of the reality. That is why we propose in this paper a new extended variant of the RCPSP: MSPSP with partial preemption.

The remainder of the paper is as follows. In the next section, we briefly describe the problem under consideration. In Section 3, we present the mixed integer linear programming model representing the partially preemptive MSPSP and some computational experiments carried out. Finally, in the last section, we conclude and discuss future research.

2 Problem description

The classical version of the RCPSP is supposed to be non-preemptive, that means, once started an activity must run continuously until its completeness. However, in some practical applications as in the case of scheduling research or engineering activities, it may be interesting to allow the preemption. Allowing preemption may lead to a reduced makespan of the project, especially when resource availability is very limited. On the other

hand, it increases the number of possible solutions and consequently the computational complexity of the problem (Herroelen et al. 1998).

Traditionally in the preemptive RCPSP, the preemption is allowed for all the activities. However, due to some safety and operational constraints, proper to nuclear regulation, we must forbid the preemption of a subset of activities. Another hypothesis of this variant is the release of all resources during the preemption periods. When scheduling research activities, we may be interested in avoiding the release of some equipment or resource having an important setup time for some activities. That is why we propose to work with a variant allowing the partial release of resources according to the characteristics of the activities. We must indicate for each activity what resource can be released during the preemption periods.

Other assumption of the RCPSP is that each resource has specific functions, or in other words the resources are supposed mono-skilled. This hypothesis can become false when we are also studying the allocation of human resources working in the project. In our study case, some resources could perform several functions leading us to a multi-skill RCPSP (MSPSP). In the MSPSP, a resource is therefore characterized by the set of skills it possesses; and a task is no longer only defined by the quantities required of each resource, but also by the number of resources with a specific competence. This variant acquires great importance for scheduling activities in very specific fields, such as pharmaceutical, chemical and nuclear, where the regulation requires the presence of a group of technicians having a set of well-defined competences for the execution of an activity.

In the MSPSP, as defined by Montoya et al. (2014), technicians can only respond to one skill requirement per activity. However, in our practical case, technicians may respond to more than one skill requirement per activity. Additionally, due to operational and safety reasons, we need to guarantee a minimal number of technicians present during the execution of the activity.

Keeping in mind all the aforementioned characteristics, and looking for the most realistic model, we decided to develop an extended variant of RCPSP combining the characteristics of the MSPSP and the preemptive RCPSP. In the proposed variant, that we called MSPSP with partial preemption, the objective is to find the best schedule for a set of activities on renewable multi-skilled resources with limited capacity, being able to respond to more than one skill requirement per activity. An activity is now defined by its duration, precedence relationships and constant requirements of both resources and skills. Preemption is now handled in three levels according to the activities characteristics: 1) Non-preemption, for activities where none of the resources can be preempted; 2) Partial preemption, for activities where a subset of resources can be preempted; and 3) Full preemption, for activities where all resources can be preempted. In our practical case, activities may be subject to a release date and to a deadline (activities in the subset B) or due date (this is determined by the importance of the activity). Additionally, due to the durations of some activities (larger than technicians' work shifts), we need to relax the constraint stating that the same technician execute the totality of the activity.

For establishing the complexity of the MSPSP with partial preemption, we use as a starting point the classical RCPSP. For each instance of the RCPSP we can match an instance of the MSPSP with partial preemption, where all resources are mono-skilled and none of the resources can be preempted. So, we can see the RCPSP as a particular case of the MSPSP with partial preemption. The RCPSP has been proved to be strongly NP-hard (Blazewicz et al. 1983); we can therefore infer that the MSPSP with partial preemption is also strongly NP-hard. Once defined the characteristics and the complexity of the proposed problem, we proceed to formalize the problem using a mixed integer linear programming model that we discuss in the next section.

3 Modeling

The RCPSP can be modeled using different approaches: continuous time-based models based on flows, discrete-time mixed integer linear programming (MILP) formulations, or event-based MILP formulations. Among the discrete-time formulations, more precisely the time-indexed formulations, we find the so-called on/off formulation. This formulation uses binary variables $Y_{i,t}$, where $Y_{i,t} = 1$ if activity i is in progress at time t and $Y_{i,t} = 0$ otherwise. This formulation, which seems to be the most suitable for the preemptive case, has been the basic formulation for the construction of tested models.

In order to choose an effective model, we tested two models, that are similar in essence, constructed using the on/off formulation. In both models, most restrictions are modeled in the same way. The main difference lies in the way in which we handle the preemption periods. For testing these models, we generated a set of instances inspired by real data using the method proposed in Polo Mejia et al. (2017). After computational experiments, one of the models showed significantly better results, and it is presented below.

In the model $DO_{j,t}$ is the operator's availability over the time. $Br_{i,k}$ represents the resource requirements. $DR_{k,t}$ indicates the resource capacities. Parameter $PR_{i,k}$ indicates whether the resource k can be preempted ($PR_{i,k}=0$) or not ($PR_{i,k}=1$). Skill requirements are given in parameter $Bc_{i,c}$. $CO_{j,c}$ indicates the set of skills of technicians ($CO_{j,c} = 1$ if technician j has the competence c , 0 otherwise). Parameter Pc_i indicates whether technicians can be preempted ($Pc_i=0$) or not ($Pc_i=1$). The minimal number of required technicians is given in Nt_i . D_i represents the duration of activities. Parameters dl_i and r_i are the deadlines and release dates.

- $Y_{i,t} \in \{0, 1\}$, $Y_{i,t} = 1 \iff$ activity i is in progress at time t
- $O_{j,i,t} \in \{0, 1\}$, $O_{j,i,t} = 1 \iff$ technician j is allocated to activity i at time t
- $Z_{i,t} \in \{0, 1\}$, $Z_{i,t} = 1 \iff$ activity i starts at time t or before
- $W_{i,t} \in \{0, 1\}$, $W_{i,t} = 1 \iff$ activity i ends at time t or after
- $Pp_{i,t} \in \{0, 1\}$, $Pp_{i,t} = 1 \iff$ activity i is preempted at time t
- $Tard_i \in \mathbb{Z}_{\geq 0}$: Tardiness of activity i

$$\min \quad \sum_i Tard_i + \sum_i \sum_t t * Y_{i,t} \quad (1)$$

$$s.t. \quad \sum_i O_{j,i,t} \leq DO_{j,t} \quad \forall j, \forall t \quad (2)$$

$$\sum_i ((Y_{i,t} + PR_{i,k} * Pp_{i,t}) * Br_{i,k}) \leq DR_{k,t} \quad \forall t, \forall k \quad (3)$$

$$(Y_{i,t} + Pc_i * Pp_{i,t}) * Bc_{i,c} \leq \sum_j (O_{j,i,t} * CO_{j,c}) \quad \forall i, \forall t, \forall c \quad (4)$$

$$\sum_j O_{j,i,t} \geq (Y_{i,t} + Pc_i * Pp_{i,t}) * Nt_i \quad \forall t, \forall i \quad (5)$$

$$\sum_t Y_{i,t} \geq D_i \quad \forall i \quad (6)$$

$$D_l * (1 - Y_{i,t}) \geq \sum_{t'=t}^T Y_{l,t'} \quad \forall (l, i) \in E, \forall t \quad (7)$$

$$\sum_{t=dl_i+1}^T Y_{i,t} \leq 0 \quad \forall i \in B \quad (8)$$

$$\sum_{t=1}^{r_i-1} Y_{i,t} \leq 0 \quad \forall i \quad (9)$$

$$Pp_{i,t} \geq Z_{i,t} + W_{i,t} - Y_{i,t} - 1 \quad \forall i, \forall t \quad (10)$$

$$Z_{i,t} \geq Y_{i,t'} \quad \forall i, \forall t, \forall t' \leq t \quad (11)$$

$$W_{i,t} \geq Y_{i,t'} \quad \forall i, \forall t, \forall t' \geq t \quad (12)$$

$$Z_{i,t} \leq \sum_{t'=1}^t Y_{i,t'} \quad \forall i, \forall t \quad (13)$$

$$W_{i,t} \leq \sum_{t'=t}^T Y_{i,t'} \quad \forall i, \forall t \quad (14)$$

$$Tard_i \geq t * Y_{i,t} - dl_i \quad \forall i, \forall t \quad (15)$$

The objective in (1) represents the minimization of the tardiness and also ensures the scheduling of units of duration of each activity as soon as possible. Equations (2) ensure that operator's capacities are satisfied. In equations (3), we ensure that all resource requirements are satisfied respecting the resource capacities. Equations (4) ensure the respect of skill requirements taking into account the set of skills of technicians. The constraints given in (5) and (6) ensure the respect of the minimal number of technicians and duration of activities. Precedence constraints are given in (7). Inequalities (8) and (9) are the constraints for deadlines and release dates. Equations (10) determine whether an activity is preempted or not. Inequalities (11) to (14) are constraints for getting the values of variables $Z_{i,t}$ and $W_{i,t}$. Finally, inequalities (15) calculate the tardiness.

Using CPLEX, this model allows us to solve optimally a set of small instances (20 activities with duration between 1 and 10 units of time and a mean of 4 precedence relationships, 13 skills) within a mean time of 7.23 seconds. For a set of larger instances (20 activities with duration between 5 and 20 units of time and a mean of 6 precedence relationships, 13 skills), we were not able to solve them optimally after 2 hours of computing having final gap between 3-15%. By conference time, heuristic methods capable of obtaining good answers in reduced times for large instances will be presented.

4 Conclusions

In this paper we show how operations research techniques can be applied to schedule research activities within a nuclear facility. Reducing the scheduling horizon allows us to manage the inherent variability of research activities and hence to treat the scheduling problem as a traditional one. The application of operations research techniques to the scheduling process of research activities can reduce the time spent by researchers in the planning of activities, giving them more time to devote to research. Additionally, using these techniques in the nuclear field increase the safety on the facility by ensuring the respect of all technical constraints.

The RCPSP has been shown to be a very powerful model, being able to represent a huge amount of real-life problems. However, for some complex systems, the classical RCPSP may not take into consideration some very important aspects. We then proposed in this paper the multi-skill project scheduling problem with partial preemption and an MILP formulation for formalizing the problem.

As future work, we must study ways to improve the proposed model in terms of the quality of the linear relaxation and time solving. We also need to develop new heuristics allowing us to have good solutions in reasonable times. In order to develop algorithms for exact solving, approaches for calculating good lower bounds will be studied.

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