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The impact of fixed and variable costs in a multi-skill project scheduling problem: An empirical study

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ABSTRACT

In this paper, we address a cost-oriented multi-skill project scheduling problem. The project consists on a set of activities such that, for some pairs, a start-to-start time dependency exists. The execution of each activity requires several skills. More than one resource of each skill may be required for processing an activity. A pull of multi-skilled resources is assumed. Costs are associated with resource usage and include fixed and variable costs. The former are incurred simply by using the resources; the latter depend on the final makespan of the project. For this problem, a mathematical programming modeling framework is proposed. The 'natural' model contains a non-linear objective function which, nonetheless, can be linearized at the expense of one additional set of continuous variables. The linearized model is enhanced using several sets of additional inequalities. The results of an extensive set of computational tests performed with the final model are reported. One major goal is to evaluate the possibility of using an off-the-shelf solver for tackling the problem. Another relevant goal is to understand the extent to which a cost-oriented objective influences the solutions obtained. Accordingly, we compare the solutions obtained using such objective with the solutions obtained using the traditional makespan minimization objective, often considered in project scheduling problems.

1. Introduction

In the basic version of a project scheduling problem, a set of time dependent activities has to be scheduled in order to minimize the total time span for executing the project. A well-known extension to this problem is the resource-constrained project scheduling problem (RCPSP). In this case, each activity requires the use of resources which are available in limited quantities. For each activity, in addition to its processing time, we need to consider the corresponding resource requirements. This is a topic which has attracted much attention in the literature. Many variants and extensions of this problem have been studied (the reader should refer to Hartmann & Briskorn (2010), Weglarz, Józefowska, Mika, & Waligóra (2011) and to the references therein).

In the basic setting of the RCPSP, each resource has a single capability or skill. However, in many practical applications, resources are multi-skilled. This is often the case when human resources are involved. The inclusion of this feature in a problem leads to a multi-skill project scheduling problem. In this type of problems, it is assumed that each activity requires several skills. For each skill, it is known the quantity of work necessary to execute each activity. There is a pull of multi-skilled resources that can be allocated to the activities. Each resource has one or several skills. It is usually assumed that in each moment, a resource can contribute with at most one skill to one activity and remains allocated to the activity during its execution. In other words, the activities' skills requirements refer to the presence of a set of resources that possess the necessary capabilities. Additionally, the combined workforce allocated to each activity stays together for the duration of the activity. This is the case, for instance, when one wants to schedule maintenance and installation operations.

Different types of multi-skill project scheduling problems have been addressed in the literature. Bellenguez and Néron (2005), Bellenguez-Morineau (2008) and Bellenguez-Morineau and Néron (2007) study the problem assuming that there are unavailable periods for the resources. The goal in these works is to minimize the project makespan. Additionally, Bellenguez and Néron (2005) consider hierarchical levels for the skills. In particular, different levels of efficiency are associated with each resource for performing each skill. For each activity, not only we need to know the skills it requires but also the execution levels of such skills. More than one resource may be required for each combination skill/level.

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Li and Womer (2009) consider a multi-skill project scheduling problem assuming that each skill required by some activity asks for exactly a single resource. The objective is to minimize the total fixed-cost associated with the resources. Firat and Hurkens (2012) consider a multi-skill work loading problem. Different levels of efficiency are considered for each skill. Each activity has requirements for each skill/level combination. The goal is to determine the workloads of teams so that the number of tasks processed in each workday is maximized. More recently, Correia, Lampreia-Lourenço, and Saldanha-da-Gama (2012) have studied a makespan minimization multi-skill project scheduling problem. Each activity may require any number of skills and for each skill more than one resource may be necessary. Finally, it is worth making a brief reference to the fact that multi-skill resources have also been considered in the context of multi-project problems. Note, however, that this is done is a totally different context. For instance, no sequence decisions are to be made. Works in this direction are those presented by Gutjahr, Katzensteiner, Reiter, Stummer, and Denk (2008) and Heimerl and Kolisch (2010).

In the large majority of the works that can be found in the literature on the above problems, time is the driving factor defining the performance measure to take into account and eventually to optimize. Accordingly, one finds objective functions such as the makespan or the maximum lateness (when due dates are involved). This is true, in particular, for the multi-skill project scheduling problem. However, in practice, although being true that managers consider time as an important aspect, it is also true that they are often more concerned with the costs involved in a project. In this case, labor costs, assume a relevant role.

For the classical RCPSP, the need for a cost-oriented objective function is captured in several works. This is the case with the so-called resource investment problem introduced by Möhring (1984). The problem consists in allocating resources to a project in such a way that a given deadline is satisfied. The objective is to minimize the costs associated with the resources which are assumed to be renewable. This problem was studied by other authors namely by Drexl and Kimms (2001), Neumann and Zimmermann (2000), Neumann, Schwindt, and Zimmermann (2002), Ranjbar, Kianfar, and Shadrokh (2008) and Yamashita, Armentano, and Laguna (2007). Nübel (2001) proposed the so-called resource renting problem in which renewable resources have to be rented. In particular, for each resource the author considers the existence of a (fixed) procurement costs and a (variable) renting cost. The objective is to minimize the total resource availability costs (which include procurement and renting). A deadline is prescribed for the project conclusion. By setting the renting costs to zero the problem reduces to the resource investment problem.

In the context of multi-skill project scheduling problems, to the best knowledge of the authors, Li and Womer (2009) is the only work addressing a cost-oriented problem. Fixed costs are associated with the resources. In the computational experiments these costs are set to 1, i.e., the number of resources used in the project is to be minimized. Therefore, the impact of considering different cost structures is neglected.

In this paper, we aim at deepening the knowledge on cost minimization multi-skill project scheduling problems. We consider the basic situation in which each activity requires one or several resources for each skill that must be considered for performing the activity. We assume fixed and variable costs associated with the resources. For each resource, the variable cost is a means for weighting the total time that the resource is involved in the project. Furthermore, resources are assumed to be distinct in terms of the variable costs. For instance, resources with more skills may be more costly than resources with less skills. The goal in this problem is to schedule the activities and allocate resources to them in order to minimize the total cost associated with resource usage. A constraint is considered assuring that the total time span for executing the project stays below a prescribed deadline. The motivation for doing so, is the well-known fact in the area of project management and scheduling that no clear trade-off exists between time and cost. In fact, these two factors are often conflicting and one possibility for overcoming this conflict is exactly to minimize the cost but imposing a constraint on the total duration of the project. This way, a useful tool is given to the decision maker allowing a deeper insight on how time and costs relate with each other.

The general framework just described is illustrated in Fig. 1 and is motivated by the need felt by many companies (construction, software development, etc.) to contract workforce for undertaking a specific project. The major goal in such cases is to minimize the labor cost assuring an acceptable execution time for the entire project.

We consider a mixed-integer linear programming approach for the problem. Initially, a 'natural' non-linear mathematical programming formulation is proposed and discussed. We show that the non-linearities can be removed at the expense of a new set of continuous variables. Several sets of inequalities are discussed for enhancing the model. The possibility of using a commercial solver for tackling the problem is explored as this is a tool available to the common decision maker in a company. An extensive set of computational experiments is reported and analyzed in order to give a clear perception on how the different types of costs considered influence the solutions obtained. Furthermore, we compare the solutions obtained with those resulting from a classical makespan minimization objective.

The current paper goes beyond the existing literature on multi-skill project scheduling problems by considering a general cost-oriented objective function comprising fixed and variable costs. As mentioned above, non-linearities arise, which nonetheless, can be removed but at the expense of an extra set of continuous variables. The modeling considerations presented are of great relevance for practitioners who wish to solve real world problems. We perform an extensive empirical study for evaluating (i) the tractability of the enhanced mixed-integer linear programming formulation proposed using an off-the-shelf solver, (ii) the impact of the different types of costs (alone and combined) on the difficulty in solving the problem (iii) the extent to which the solutions change by considering a cost-oriented objective instead of a makespan one, (iv) the extent to which different economies of scale in the costs influence the results. We use as a basis for making comparisons, the solutions obtained by Correia et al. (2012) for a makespan minimization problem.

The remainder of the paper is organized as follows. In Section 2 a mathematical programming modeling framework is proposed for

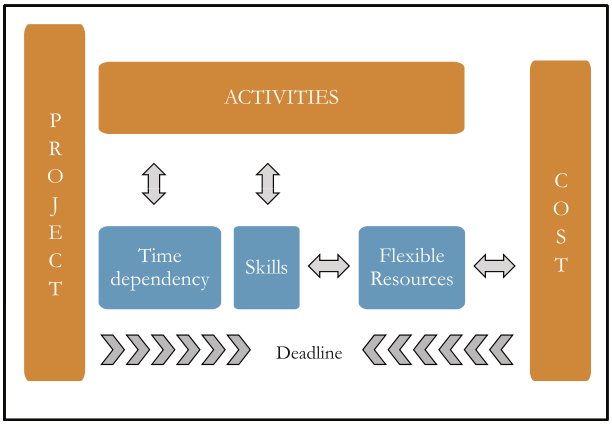

Fig. 1. General underlying framework for a cost minimization multi-skill project scheduling problems.