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Minimizing average project team size given multi-skilled workers with heterogeneous skill levels

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ABSTRACT

Many firms face the challenging task of staffing concurrent projects such that the skill requirements of each project can be satisfied by the respective team of workers. We consider a staffing problem where each worker can be assigned to several projects at a time. A high total number of assignments implies large project teams and scattering of workers across projects. Large teams come along with productivity losses due to increased coordination effort and social loafing while scattering incurs losses due to frequent switching between projects. To curb these inefficiencies, we formulate a mixed-integer linear program that minimizes average project team size and, thus, scattering. The program accounts for multi-skilled workers with heterogeneous skill levels who must also fulfill duties within their departments. We prove that the problem is NP-hard in the strong sense and outline valid inequalities that accelerate the solution by a commercial branch-and-cut solver. For large-scale instances, we devise three construction heuristics, each of which is embedded in a multi-pass procedure. Our performance analysis reveals that a heuristic based on the drop principle offers the best compromise between solution quality and computation time. Limitations of the proposed approach, managerial insights, and areas of application are discussed.

1. Introduction

Multi-project management and human resource management are crucial for the prosperity of many firms. The share of goods and services that is provided in the form of project deliverables continues to rise and in some branches such as construction or consulting, virtually all revenues are generated through projects [1, pp. 47–63 and 25–27, respectively]. In many types of projects, e.g., in consulting, auditing, and information technology (IT) projects, skilled personnel is the most important resource, whose efficient employment is critical for a firm's success. Today, human resource management is challenging because the demand for high-skilled workers has risen disproportionately over the last decades making them a scarce resource in some fields of business, especially in project-driven organizations with many non-routine tasks [2]. Hence, these organizations must care about the well-being of their workers in order to reduce labor turnover.

The realms of multi-project and human resource management intersect when it comes to project staffing. The task of project staffing is to compose project teams such that the skills and availabilities of team members meet the requirements of the respective project. For this task, sociologists and psychologists make two recommendations. First, they advise to keep team size as small as possible because inefficiencies that are inherent in teamwork such as social loafing grow with increasing team size. Second, they advise to avoid the inefficient scattering of workers across projects and to let workers concentrate on only a few projects to guarantee job satisfaction. Both recommendations can be met by minimizing the total number of assignments of workers to projects because this minimization is equivalent to minimizing average project team size and also equivalent to minimizing the average number of project assignments per worker when a constant number of projects and workers is assumed. So far, however, quantitative methods that support human resource managers to form small teams in a typical multi-project environment are missing.

In this paper, we set out to fill this gap. We consider a firm that has to staff a set of projects with multi-skilled workers who differ in their skill levels. Heterogeneous skill levels imply that some workers need more time to accomplish a skill requirement than others. We assume that projects have already been scheduled. For each project, skill requirements arise in the periods of its execution. Workload does not only originate from projects but also

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arises within the departments of the firm. Departmental workload must be accomplished in each period of the planning horizon by the workers who belong to the corresponding department. Each worker belongs to exactly one department. Hence, we presume a matrix organization that features functional or product-oriented departments, for example, and potentially cross-departmental project teams. Our goal is to find an assignment of workers to projects and to allocate project workload such that all requirements of projects and departments are satisfied and such that average project team size is minimized.

For staffing concurrent projects, project team size and the number of project assignments per worker are crucial design variables. In regard to team size, small teams have several advantages. By *small* we mean small in relation to project workload but large enough to accomplish this workload. The smaller a team is, the weaker is the Ringelmann effect, which describes rising losses in individual productivity of team members with increasing team size [3]. These losses rise due to growing coordination problems and decreasing motivation [4,5]. The phenomenon that individuals are less motivated and expend less effort when they work in a group than when working alone, is termed *social loafing* [6]. Social loafing tends to increase with group size. This increase can be ascribed to greater opportunities to "hide in the crowd" [7, p. 72] and to free ride but also to feeling "lost in the crowd" [5, p. 830] due to a perceived lack of influence on the group outcome, for instance. Furthermore, a small team eases communication within the team and with stakeholders outside the team. More frequent communication between team members improves cohesion and cooperation [8].

In regard to the number of project assignments per worker, workers usually prefer a moderate number of simultaneous project assignments as it enables them to keep their focus on a few activities. A small number of assignments also stems productivity losses from switching between projects. Switching is time-consuming because a worker must reacquaint herself with her task and the current project status when she resumes interrupted project work [9, Section 4.1].

Small project teams in conjunction with a small number of project assignments per worker generally enable a team member to apply many of her skills and, hence, to experience task variety within a project. A worker can make a significant and, thus, satisfying contribution to each of her projects. Additionally, our staffing goal results in project teams with a quite stable team composition over the course of the project. A relatively large project team tends to be a so-called *fluid team* with unstable team membership as many workers contribute to the project only for a short period of time and team members wax and wane [10]. Bushe and Chu [10] point to several problems caused by high turnover in teams, e.g., lack of team spirit and loss of know-how when a worker leaves a team. The authors propose organizational arrangements to encounter the problems. Our quantitative approach, which tries to avoid high fluctuation in the first place, complements their techniques and may even render some of their proposed arrangements dispensable.

The call for small teams has echoed through the literature for a long time. Already in 1975, Brooks [11] pointed out that growing team size hampers project progress due to increased communication needs. Brooks [11, p. 25] had observed that "adding manpower to a late software project makes it later" because new team members must be introduced by existing ones. Hammer and Champy [12, p. 144] demanded that "as few people as possible should be involved in the performance of a process" in order to prevent unnecessary handoffs. In view of social loafing, Hackman [13, p. 27] advised that teams should be "just large enough to do the work". Likewise, Liden et al. [14, p. 299] concluded from an investigation of work groups in two U.S. firms that "organizations will recognize the need … to keep group size down to a minimum in combating social loafing". Especially for multi-project environments, Hendriks et al. [15] introduced the *project scatter factor*, which measures the number of workers that are assigned to one man-year of project workload. As scattering workload across many workers and scattering workers across many projects is inefficient, Hendriks et al. [15] recommend a small project scatter factor, i.e., small teams.

Up to now, only a few quantitative approaches take team size or the number of project assignments per worker into account. Team or workforce size is mainly considered for the single-project case [cf. 16–19, for example]. For a multi-project environment, Patanakul et al. [20] and Certa et al. [21] limit the number of assignments via constraints what can drastically shrink the solution space and may even leave no feasible solution. Only the model of Grunow et al. [22], which addresses staffing clinical studies, minimizes average team size. However, in contrast to our approach, they assume that the number of workers required for a task is prespecified, they do not distinguish different skill levels, and they do not provide heuristic solution methods although their problem is NP-hard in the strong sense (for a proof see Walter [23, Section 5.2]). The work of Grunow et al. [22] and the other mentioned works will be considered in more detail in Section 4. Aspects of the staffing problem that is tackled in the paper at hand have been presented in Walter and Zimmermann [24,25]. A hierarchic approach that comprises project selection, the staffing problem, and workload leveling is outlined in Walter [23].

The remainder of this paper is organized as follows. In Section 2, we introduce the notation for our staffing problem and formulate a mixed-integer linear program (MIP) for this problem. In Section 3, we show that the problem is NP-hard in the strong sense. Work that is related to our staffing problem is presented in Section 4. Valid inequalities that support the solution process of a branch-and-cut solver are outlined in Section 5, before we devise three construction heuristics in Section 6. In Section 7, we report how we generated test instances and present computational results obtained from the solver Cplex and from multi-pass implementations of our heuristics. The results are discussed in Section 8, in which we also point to limitations of our approach, managerial insights, and areas of application. A summary and an outlook conclude this paper in Section 9.

2. Problem formulation

We consider a firm that intends to carry out a set of projects within the upcoming planning horizon. The link between the firm and the projects are skills that are mastered by the workers of the firm and that are required by the projects. The firm wants to allocate project workload to its workers such that average team size is minimized.

The planning horizon of the firm spans the set $\mathcal{T}=\{1,\dots,T\}$ of T periods. In a typical setting, the length of the planning horizon is one year and the length of each period $t\in\mathcal{T}$ is one month.

The workforce of the firm is denoted by $\mathcal{K}=\{1,\dots,K\}$, i.e., it comprises K workers. For each worker $k\in\mathcal{K}$, his availability R_{kt} is given for each period $t\in\mathcal{T}$. The availability is measured in hours and may amount to 160 h for a full-time worker in a one-month period, for example.

The long-term organizational structure of the firm is reflected by a set $\mathcal{D}=\{1,\dots,D\}$ of D departments. Each worker $k\in\mathcal{K}$ is a member of exactly one department. Let $\mathcal{K}_d\subseteq\mathcal{K}$, $d\in\mathcal{D}$, denote the workers that belong to department d. In each department $d\in\mathcal{D}$, a departmental work requirement rd_{dt} has to be accomplished in each period $t\in\mathcal{T}$ by the staff $\mathcal{K}_d$ of department d. Departmental work requirements are expressed in man-hours; so a requirement