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Multi-mode resource-constrained project scheduling problem with alternative project structures

Sha Tao[a], Zhijie Sasha Dong[b,*]

[a] School of Management and Engineering, Nanjing University, Nanjing 210093, China
[b] Industrial Engineering Program, Ingram School of Engineering, Texas State University, San Marcos, TX 78666, United States

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ABSTRACT

This paper proposes to consider alternative project structures when dealing with the multi-mode resource-constrained project scheduling problem. An AND-OR network is used to present this alternative project structures innovatively. The problem is formulated as a bi-objective linear integer program, which minimizes the makespan and total cost. A hybrid metaheuristic is developed based on AND-OR network to solve this NP-hard problem efficiently, which nests adapted Tabu Search (outer layer) and NSGA-II algorithm (inner layer). A large amount of computational experiments of different sizes are conducted, and compared with solutions generated by CPLEX, traditional Tabu Search, enumeration-based method and single-layer NSGA-II. The experimental results show the advantages of the proposed model and method, especially with large-size problems.

1. Introduction

Project scheduling problems are the problems of allocating scarce resources over time to perform a given set of activities. They have received wide attention since 1970s when researchers and practitioners found out that various resources problems appeared during project scheduling (Balas, 1971; Cooper, 1976; Icmeli, Erengüc, & Zappe, 1993). For example, activities cannot be completed on time because some resources (e.g., manpower, material) are not available at that time. Motivated by taking fully advantage of scare resources, the resource-constrained project scheduling problem (RCPSP) arose, which considers resources of limited availability and activities of known durations and resource requirements. The multi-mode resource-constrained project scheduling problem (MRCPSP) is an important generalization of RCPSP, where each activity can be implemented in one out of several execution modes.

MRCPSP (also RCPSP) always assumes that each activity must be implemented with fixed precedence relations. However, it is not the case in practice, and Kellenbrink and Helber (2015) described the aircraft turnaround process at an airport as an example. In reality, there exist a lot of alternatives in project structure. For example, a construction project always involves several alternative methods and only one method can be chosen. If it is a bridge construction, it usually involves two methods for constructing pier shaft: Precast and Cast-in-site. Each method is realized by a specific process pattern consisting of a set of activities and precedence relations which connect these activities (Wu, Borrmann, Beißert, König, & Rank, 2010).

Therefore, to deal with these alternatives in the project structure, we propose an extension of MRCPSP where the project network would not be given and fixed (as in the traditional MRCPSP) but should be selected according to certain rules. Thus, the traditional MRCPSP is a special case of the problem we propose here since it has only one project network. In this problem which named MRCPSP with alternative project structures, only a part of activities should be implemented and the precedence relations only take effect for the selected activities. We utilize the AND-OR network created by Tao and Dong (2017) to represent this problem because it defines the logical relations among activities, which is beyond the capability of the classical project representation network. The activities are required to be selected based on the definitions of AND/OR nodes. We formulate the proposed problem as a bi-objective integer linear programming model by integrating new features of alternative project structures. We develop a two-layer metaheuristic algorithm with a combination of adapted Tabu Search and NSGA-II by taking advantage of properties of this problem. A set of computational experiments from Project Scheduling Problem LIBrary are conducted to demonstrate the efficiency of our designed algorithm as well as the utilization of AND-OR network. Some managerial insights have been suggested based on the computational results.

This paper is organized as follows. Section 2 reviews relevant literature. Section 3 describes this problem in detail with practical

* Corresponding author.
E-mail address: sasha.dong@txstate.edu (Z.S. Dong).

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examples. Section 4 introduces the AND-OR network presentation and shows how to formulate this problem as a bi-objective linear integer programming model. Then the hybrid metaheuristic is developed in Section 5 and computational experiments are used to demonstrate efficiency of the proposed model and method in Section 6. Finally, Section 7 offers several managerial insights, concludes our work in this paper and points out future research directions.

2. Literature review

2.1. Resource-constrained project scheduling problem (RCPSP)

There are numerous studies to summarize the literature on RCPSP including surveys by Özdamar and Ulusoy (1995), Herroelen, Reyck, and Demeulemeester (1998), Brucker, Drexl, Möhring, Neumann, and Pesch (1999), Demeulemeester and Herroelen (2002), Hartmann and Briskorn (2010) and Weglarz, Józefowska, Mika, and Waligóra (2011). Most of the previous work focused on two directions. One is to propose various extensions and variants of the RCPSP because assumptions of this basic model are too restrictive for many real-world applications. For example, the deterministic RCPSP is extended to be stochastic RCPSP (Fu, Lau, & Varakantham, 2015; Rostami, Creemers, & Leus, 2017) by taking stochastic activity duration or resource requirement into consideration. Besides the finish-start (FS) precedence relations, the RCPSP with more generalized and practical precedence relations including finish-start (FS), start-start (SS), finish-finish (FF), start-finish (SF) is investigated by many researchers (Tritschler, Naber, & Kolisch, 2017). The multi-mode resource-constrained project scheduling problem (MRCPSP) is one of the most extensively studied generalizations (Hartmann, 2001; Alcaraz, Maroto, & Ruiz, 2003), where each activity can be implemented in one out of several execution modes. Each execution mode of one activity represents a combination of resource requirements and a duration for that activity. The standard RCPSP is a special case of the MRCPSP with one mode per activity. Because the RCPSP and its variations are NP-hard, the other research direction is to develop efficient heuristic and metaheuristic solution approaches. Recent work include Fang and Wang (2012), Koulinas, Kotsikas, and Anagnostopoulos (2014), Bettemir and Sonmez (2014), Messelis and Causmaecker (2014), Zheng and Wang (2015), and Sonmez and Gürel (2016). Regardless of which direction, in these problems it is assumed that all activities and precedence constraints are known and all activities must be implemented (Kellenbrink and Helber, 2015). In our paper, we propose a problem that considers such alternative project structures, and formulate this problem with two conflicting objectives by extending the work on AND-OR networks by Tao and Dong (2017). Kellenbrink and Helber (2015) investigated a similar problem with an example of aircraft turnaround process, but they only focused on minimizing the project makespan.

2.2. AND-OR networks

Similar AND-OR networks were proposed by Belhe and Kusiak (1995), Gillies and Liu (1995), Stork (2001), Kääb (2003) and Mohring, Skutella, and Stork (2004). However, all these networks introduced logical relations among activities from precedence constraints, so they were not able to describe alternative project structures. This restriction also explains why all the previous research only focused on the limited time when scheduling rather than limited resources. Kellenbrink and Helber (2015) worked on the resource-constrained project scheduling problem with a flexible project structure (RCPSP-PS). However, the network representation they used is not intuitive to demonstrate the flexible project structure. Besides, the mathematical model they presented only attempted to minimize the project makespan without considering other factors. Project scheduling is an inherently multi-objective problem because it involves various types of trade-offs among limited resources. The most important trade-off is the balance between time and cost. Therefore, it is more reasonable to formulate the scheduling problem with two objective functions. The key to strike a balance between these two conflicting objective functions is to find a set of Pareto optimal solutions, and many achievements have been made in the area of metaheuristics. Most recent work include hybrid bidirectional ant-based approach for the assignment and scheduling problem (Dridi, Krichen, & Guitouni, 2014), and a hybrid of particle swarm optimization and differential evolution algorithm for the MRCPSP (Zhang, Luo, & Zhang, 2015). Interested readers can refer to the literature reviews on the RCPSP mentioned earlier as well as Ballestin and Blanco's (2011) paper on multi-objective RCPSPs. In our paper, we investigate project scheduling with alternative project structures and develop a hybrid metaheuristic approach of adapted Tabu Search and NSGA-II to explore solutions efficiently.

Another shortcoming of previous AND-OR networks is that they are too theoretical to be applied in practice. For example, Belhe and Kusiak (1995) had to reduce their "design activity network" to a smaller network and develop a complicated algorithm for solving it. Stork (2001) had to check the feasibility of a given set of AND/OR precedence constraints by constructing a linear realization in a greedy way. Using the AND-OR network proposed by Tao and Dong (2017) would avoid this limitation, and it helps formulate the RCPSP with alternatives in project structure and develop an efficient algorithm. The power of this AND-OR network will be demonstrated by specific examples in this paper.

3. Problem description

The striking feature of the project scheduling problem investigated here is the alternative project structure. As mentioned earlier, many traditional project scheduling studies always assume a given project structures, which means certain activities with certain precedence relations. However, real-world projects usually have alternatives. In this case, the project structure is variant and how to choose project structures is a significant decision for the scheduling problem. Therefore, we study the coupled problem called project scheduling problem with alternative project structures, which integrates project structure selection into project scheduling.

To help understand the concept of the alternative project structure, we use the bridge construction project from Wu et al. (2010) as an illustrative example (as shown in Fig. 1). This project involves a series of alternative method selections. When a choice being made, this selection will trigger a corresponding construction process. A construction process is consisted of activities or sub-processes and precedence relations linked between them. Different choices always lead to different processes with different associated labors, machines, and other resources. This case involves three construction method choices, namely bridge construction method selection, piers construction method selection, and pier shaft construction method selection. The relation among these three choices is that the selection of bridge construction method of *In-Situ Casting on Standard Falsework* triggers sub-process 1, and then the activity *Construct piers* in sub-process 1 triggers piers construction method selection. For piers construction method selection problem, when *Reinforced Concrete* is selected, it triggers sub-process 2. Next, the activity *Construct pier shaft* in sub-process 2 triggers pier shaft construction method selection. At last, *Cast-in-Site method* is selected and this triggers the sub-process 3. The sub-process triggered by other unselected methods, e.g. *Balanced Cantilever*, *Steel Structure*, will not be elaborated in our paper.

Another very useful example is aircraft turnaround process, and interested readers can refer to the paper of Kellenbrink and Helber (2015). Two common and significant characteristics can be found from these engineering projects. First, not all the activities are mandatory, and sometimes decisions have to be made about whether to perform some specific activities. Second, choices among these optional activities will impose different precedence constraints by triggering different