An Auction-based Approach for Decentralized Multi-Project Scheduling

(Doctoral Consortium)

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ABSTRACT

Many scheduling problems in industry practice are considered as Decentralized Resource-Constrained Multi-Project Scheduling Problem (DRCMPSP). Given its characteristics, the problem must be solved in a decentralized manner while respecting information privacy of projects. However, existing approaches fail in satisfying these requirements, and encounter difficulties in dealing with large cases. To this end, we propose a novel approach based on multi-unit combinatorial auction with greedy resource allocation strategy. A bid modification step is also incorporated to provide chances for project agents to improve utilities. This approach does not require private project information, and scales well to large cases. Experiments show that our approach can obtain better solutions compared to state-of-the-art approaches.

Keywords

Multi-Project Scheduling, Multi-Unit Combinatorial Auction, Resource Allocation

1. INTRODUCTION

To schedule multiple projects under limited resource is a common management activity in most business firms. Each of these projects consists of a set of activities with precedence constraints and resource requirements. Traditionally, all projects are controlled by one decision maker and can be scheduled using certain centralized methods. Nowadays, due to active intra- and inter-firm collaborations, multi-project management has entered a new environment where the projects are controlled by different self-interested decision makers with different individual objectives. Usually, to finish their projects, they need to compete for some shared global resources with limited capacities. On the other hand, some information of the projects may be considered as secret since these decision makers could be potential rivals in the same marketplace. Under this background, the *Decentralized Resource-Constrained Multi-Project Scheduling Problem* (DRCMPSP) is formally proposed in [2] to incorporate these new features to the traditional multi-project scheduling problem. DRCMPSP cases widely exist in industry (e.g. airport ground handling service scheduling, aero repair & overhaul scheduling, and supply chain scheduling).

It is well known that the traditional centralized resource-constrained multi-project scheduling is an NP-hard problem. DRCMPSP, as its decentralized version, exhibits new challenges in that it must be solved in a decentralized manner while respecting the privacy requirements of the decision makers. However, current research fails in providing an approach that can produce high quality solution, maintain information privacy, and scale to large problem cases with tens of projects, thousands of activities in total, and several multi-unit shared resources.

In this work, we develop a decentralized approach based on iterative multi-unit combinatorial auction. To simplify the computational burden of agents, we adopt a greedy resource allocation strategy that grants winning bids in each round of auction. We also incorporate a bid modification step to create chances for decision makers to improve utilities. Our approach does not require private project information, and complexity analysis shows that it can scale to large DRCMPSP cases. Experiment results show that our approach is computationally efficient, and produces better results compared to state-of-the-art decentralized approaches.

2. RELATED WORK

The core problem in DRCMPSP is how to allocate the shared global resources to each decision maker in a decentralized manner. Market-based approach, especially combinatorial auction, is an ideal paradigm for solving decentralized resource allocation problem. In [2], a combinatorial auction based approach is proposed to solve simple DRCMPSP cases with several projects, tens of activities in total and one single-unit global resource. However, as our analysis in [4], this approach suffers from scalability issue. When applied to large case, the computational time becomes very long and the solution quality is relatively low.

Recently, several decentralized approaches have been proposed to solve larger cases which involve tens of projects, thousands of activities in total, and several multi-unit global resources, e.g. [1] [5]. However, most of these approaches are based on activity-level adjustment techniques, which inevitably require activity information from each project. In addition, activity-level adjustments are based on estimated individual objectives, which could lower the solution quality.

3. THE PROPOSED APPROACH

In a DRCMPSP case, a set of N projects sharing some global renewable resources need to be scheduled to minimize

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the *Average Project Delay* (APD), defined as:

$$APD = \frac{\sum_{i=1}^{N} \max\{0, (ct_i - dd_i)\}}{N},$$

where ct_i and dd_i are the finish time and due date of project i, respectively. We model DRCMPSP as a mediated multi-agent system, where each project is represented by a Project Agent (PA) and all PAs are coordinated by a Mediator Agent (MA). To make decisions on global resource allocation, the MA conducts a multi-unit combinatorial auction where the PAs play as bidders and the items for sale are the global resources at each scheduling time slot. A bidder i is associated with a valuation function $v_i(\Lambda)$ for each multiset Λ of items, defined according to the schedule with the lowest delay cost assuming it can obtain the amounts of global resources in Λ. Denote an item allocation as $\Lambda = (\Lambda_1, ..., \Lambda_N)$, the auction objective is to find the allocation Λ^* that maximizes social welfare $SW(\Lambda) = \sum_{i=1}^{N} v_i(\Lambda_i)$. Λ^* can be found by solving a *Winner Determination Problem* (WDP).

It is well known that (multi-unit) combinatorial auction is intractable, since the WDP is NP-complete and communication requirement grows exponentially with the total item capacity. However, when apply combinatorial auction to DRCMPSP, additional complexity is introduced. As we show in [4], to compute the value $v_i(\Lambda)$ of a given multiset Λ is intractable, since it is equivalent to solve an NP-hard single Resource-Constrained Project Scheduling Problem (RCPSP). Given these complexities, it is almost impossible to design an optimal algorithm that can scale to large cases. Hence, in this research we aim at designing an inexact polynomial-time approach instead of a complete algorithm.

To simplify agents' computation, our approach employs an iterative auction process with a greedy resource allocation strategy. In addition, a bid modification step is incorporated to compensate the greedy nature of the approach. To be specific, each round of auction contains two consecutive phases. In the first phase, each participating bidder i is asked to submit a bid $B_i =< \Lambda_i, v_i(\Lambda_i) >$, which includes the multiset Λ_i that can (approximately) maximize its valuation under the current item capacities, along with the value $v_i(\Lambda_i)$. The problem of finding B_i is called the *bidding problem*. Then, the MA solves an initial WDP to determine the initial winners, who are intuitively the most "promising" ones given the current resource capacities. The second phase includes a series of final auctions among the initial winners, who are asked to conduct a bid modification step by submitting a bid $B'_i =< \Lambda'_i, v_i(\Lambda'_i) >$, where Λ'_i is different from Λ but with the same value (i.e. $v_i(\Lambda_i) = v_i(\Lambda'_i)$). The problem of finding Λ'_i is called the *bid modification problem*. The MA solves a final WDP in each round of these auctions, immediately allocates global resources to the final winners, and updates the global resource capacities. The final winners will not participate in any auction in the following rounds.

Here we briefly describe how the aforementioned three types of local problems are formulated and solved. As we show in [4], the bidding problem can be transformed to an RCPSP with time-varying resource constraints, where global resource capacities are equal to the current item capacities. Since RCPSP is NP-hard, we design a polynomial-time algorithm based on the priority rule-based schedule generation approach. In terms of the bid modification problem, we first define a demand ratio vector as the ratio of total demand of initial bids to the corresponding resource capacities. This vector will be calculated and published by the MA before the second phase. We then define the resource index as the dot product of a multiset and demand ratio, and formulate the bid modification problem as an RCPSP with the objective of minimizing resource index. To make sure the bidder's utility will not decrease, an additional hard due date constraint is added. This is also an NP-hard problem, hence we design a polynomial-time algorithm based on flexible activity shifting. Finally, we apply a polynomial-time greedy algorithm in [3] to solve all (initial and final) WDPs.

Our complexity analysis in [4] shows that in the worst case, the total number of bids submitted by the bidders is $O(N^2)$, and the total number of WDPs is $O(N)$. Since all local problems are solved in polynomial time, our approach is in general polynomial-time. We also conduct experiments on public benchmark, and compared our approach with existing ones in [2, 1, 5]. Results show that overall our approach improves the best results by nearly 25%, and the computation is very efficient on large cases which contains tens of projects, thousands of activities in total, and several multi-unit global resources.

4. FUTURE RESEARCH

Our research is based on the DRCMPSP model, which is general and can describe a large class of decentralized scheduling problems. However, in reality the problems could be more complex with more constraints (e.g. hierarchical activity structure and additional resource constraints). Hence an immediate direction is to extend our approach to these more complex real-world cases.

In this research we focus on solving a decentralized resource allocation problem. However, one limitation is that bidders are assumed to be truthful, which may not hold in a decentralized environment that involves multiple self-interested agents. In the future, we aim to address the incentive compatibility issue by seeking theoretical support from mechanism design. An important question to ask is that can we develop a payment scheme, along with the proposed allocation approach, to achieve truthful bidding.

REFERENCES

[1] S. Adhau, M. Mittal, and A. Mittal. A multi-agent system for distributed multi-project scheduling: An auction-based negotiation approach. *Engineering Applications of Artificial Intelligence*, 25(8):1738–1751, 2012.

[2] G. Confessore, S. Giordani, and S. Rismondo. A market-based multi-agent system model for decentralized multi-project scheduling. *Annals of Operations Research*, 150(1):115–135, 2007.

[3] R. Gonen and D. Lehmann. Optimal solutions for multi-unit combinatorial auctions: Branch and bound heuristics. In *Proceedings of the 2nd ACM conference on Electronic Commerce (EC'00)*, pages 13–20, 2000.

[4] W. Song, D. Kang, J. Zhang, and H. Xi. Decentralized multi-project scheduling via multi-unit combinatorial auction. In *Proceedings of the 15th International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2016)*, 2016.

[5] Z. Zheng, Z. Guo, Y. Zhu, and X. Zhang. A critical chains based distributed multi-project scheduling approach. *Neurocomputing*, 143:282–293, 2014.