Engineering Applications of Artificial Intelligence 25 (2012) 1738–1751

Contents lists available at SciVerse ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

A multi-agent system for distributed multi-project scheduling: An auction-based negotiation approach

Sunil Adhau *, M.L. Mittal, Abhinav Mittal

Department of Mechanical Engineering, Malaviya National Institute of Technology, Jaipur 302017, Rajasthan, India

ARTICLE INFO

Article history:
Received 25 July 2011
Received in revised form
27 October 2011
Accepted 20 December 2011
Available online 12 January 2012

Keywords:
Distributed multi-project scheduling
Multi-agent system
Heuristic algorithms
Auction-based negotiation

ABSTRACT

Simultaneously running multiple projects are quite common in industries. These projects require local (always available to the concerned project) and global (shared among the projects) resources that are available in limited quantity. The limited availability of the global resources coupled with compelling schedule requirements at different projects leads to resource conflicts among projects. Effectively resolving these resource conflicts is a challenging task for practicing managers. This paper proposes a novel distributed multi-agent system using auctions based negotiation (DMAS/ABN) approach for resolving the resource conflicts and allocating multiple different types of shared resources amongst multiple competing projects. The existing multi-agent system (MAS) using auction makes use of exact methods (e.g. dynamic programming relaxation) for solving winner determination problem to resolve resource conflicts and allocation of single unit of only one type of shared resource. Consequently these methods fail to converge for some multi-project instances and unsuitable for real life large problems. In this paper the multi-unit combinatorial auction is proposed and winner determination problem is solved by efficient new heuristic.

The proposed approach can solve complex large-sized multi-project instances without any limiting assumptions regarding the number of activities, shared resources or the number of projects. Additionally our approach further allows to random project release-time of projects which arrives dynamically over the planning horizon. The DMAS/ABN is tested on standard set of 140 problem instances. The results obtained are benchmarked against the three state-of-the-art decentralized algorithms and two existing centralized methods. For 82 of 140 instances DMAS/ABN found new best solutions with respect to average project delay (APD) and produced schedules on an average 16.79% (with maximum 57.09%) lower APD than all the five methods for solving the same class of problems.

1. Introduction

In business organizations it is quite common to have multiple projects executed simultaneously at one location or at different locations. These projects need local (always available to the concerned project) and/or global (shared among the projects) resources, generally available in limited quantity, for their completion. Typical examples are found in the automobile supply chains where a supplier carries out several engineering projects for different automobile manufacturers or original equipment manufacturers (OEMs) and in construction where one contractor is executing projects for more than one customer at different sites. The problem of scheduling of these multiple projects is called resource constrained multi-project scheduling problem (RCMPSP) in literature.

Traditionally the RCMPSPs were solved with the assumption of centralized decision making in which the resource allocation and scheduling decisions were made centrally in an integrated manner. In practice, however, the resource allocation and scheduling functions are generally performed in a decentralized manner. Typically, a project manager competes with other project managers for the required global resources. In such cases the global resources are first allocated to the competing project managers and then the project managers schedule activities of their projects. The allocation of the limited resources to the competing projects is a combinatorial problem challenging the OR community. The problem of resource allocation and scheduling assuming decentralized decision making environment is termed as distributed resource constrained multi-project scheduling problem (DRCMPSP) in literature.

* Corresponding author. Permanent address: Government Polytechnic, Pune, University Road, Pune (M.S)-411016, India. Tel.: +91 9887577991; fax: +91 141 2713294.
E-mail addresses: suniladhau@gmail.com (S. Adhau), mlmittal.mnit@gmail.com (M.L. Mittal), abhinav.krishan.mittal@gmail.com (A. Mittal).

0952-1976/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.engappai.2011.12.003

In recent years multi-agent systems (MAS) have gained tremendous popularity in providing solution to the distributed decision making problems in different domains of industrial life. Some of the examples are multi-plant production scheduling (Alvarez, 2007); real-time distributed manufacturing and control (Leitao, 2009; Jason et al., 2011); e-manufacturing (Tiwari et al., 2010); dynamic supply chain (Wang et al., 2009); bus maintenance scheduling (Zhou et al., 2004), etc. The term agent in MAS refers to a software entity which is autonomous, proactive, social (Sandholm, 2001; Wooldridge, 2009) and having its own execution environment and decision powers. In MAS, each agent is independent and capable of making decisions according to his own beliefs, desires and intensions (Jennings and Wooldridge, 1995).

This paper is concerned with developing a new multi-agent based system for distributed resource constrained multi-project scheduling problem that arise in companies running multiple parallel industrial projects. We propose a distributed multi-agent system auction-based negotiation approach denoted as DMAS/ABN. The proposed multi-agent system is mapped on coarse grain structure of autonomous, self-interested competitive agents called as decision maker and assumes an asymmetric distribution of information. The blackboard agent architecture is used which consist of project agents (PA) as many as the active projects, a resource agent and an exchange agent. In order to resolve the resource conflicts and allocating multiple different types of global resources across multiple competing projects a new distributed multi-unit combinatorial auction-based coordination mechanism is developed. The auction problem for global resource assignment is formulated as an integer linear programming model but due to NP hardness of the problem it is impractical to solve large multi-project instances in polynomial time. The DMAS/ABN uses a new heuristic procedure for solving auction problems. The bidding process requires project agents (PAs) to submit separate bids for the eligible activities requiring global resources. The utility of a time slot of the resources for an activity is calculated as the cost of not getting these resources. The local decision making algorithm (PALDM) run by project agents is developed to calculate bid price (utility of an activity) by virtually scheduling the project at current time. The exchange agent (EA) that runs the iterative bidding/auction mechanism determines the winners by iterative winner determination heuristic and notify the resource agent (RA) to transfer global resources from his pool to the winning PAs. After receiving the shared resources, the scheduler encapsulated in each PA generates the schedules.

The uniqueness of this work with respect to other state-of-the-art approaches is that our approach allows dealing with complex large-sized multi-project instances without any limiting assumptions regarding the number of activities, shared resources or the number of projects. The existing other MAS approaches that use auctions (e.g. Lee et al., 2003; Confessor et al., 2007; Arauzo et al., 2010) for a DRCMPSP problem, however, suffer from the drawback of considering single unit of only one type of shared resource while there is hardly any project that is completed with only one type of resource in single unit. Our approach further allows random project release-times for the projects that arrive at any time over the planning horizon which is exclusive and rarely considered in existing state-of-the-art algorithms.

The DMAS/ABN scheduling system has been implemented in Java on the JADE Agent Development platform. The proposed multi-agent system is tested on standard set of 140 problem instances from literature and compared with the similar existing systems for solving DRCMPSP. The results thus obtained are benchmarked against the three state-of-the-art decentralized algorithms and two existing centralizes methods for large DRCMPSP instances. For 82 of 140 instances DMAS/ABN found new best solutions with respect to average project delay (APD). It is observed that DMAS/ABN provides the minimum value (126.36) of average APD over the 140 problems. It also outperforms in producing schedule with lower total makespan (TMS) with respect to a well-known centralized approach-shortest activity from shortest project (SASP) and decentralized method of MAS which uses a centrally imposed coordination (MAS/CI). The results show that the decentralized DMAS/ABN can compete with the published MAS and centralized procedures.

The remainder of this paper is organized as follows: Section 2 summarizes existing related work on decentralized multi-project scheduling problems and MAS. Section 3 formally defines the problem. Section 4 describes the multi-agent system architecture and agents' interaction protocols. Section 5 presents the proposed combinatorial auction based negotiation algorithm and describes its implementation mechanism. Section 6 presents an illustrative example. Computational experimentation and analysis of results are presented in Section 7. Concluding remarks and some ideas for future research are put forth in Section 8.

2. Related work

Scheduling of multiple projects with limited resource availability has been an active area of research for more than the last four decades. In most of the existing research (e.g. Pritsker et al., 1969; Kurtulus and Davis, 1982; Mohanty and Siddiq, 1989; Lova and Tormos, 2001; Gonçalves et al., 2008; Mittal and Kanda, 2009) a centralized decision making environment is assumed in which a central authority is responsible for all decisions regarding allocation of scares global resources to the projects and their scheduling. The assumption of centralized decision making is quite restrictive for their use in practice especially in complex dynamic setting. Multi-agent systems have been developed to facilitate distributed decision making in resource allocation and scheduling of multiple projects.

The work on application of MAS to DRCMPSP started during end of the 20th century. In one such early work Yan et al. (2000) use MAS as a technique to support project management for resource allocation in a distributed environment. The scheduling of projects is performed by message passing and negotiation among activity agents and resource agents. Following the same research line Knotts et al. (2000) develop eight agent-based algorithms for solving the multimode, resource-constrained project scheduling problem. Both study considered decentralized scheduling of large resource constrained single-project problem (RCPSP). Kim (2001) developed a new distributed coordination framework for project schedule changes (DCPSC) and a novel agent-based compensatory negotiation (ABCN) methodology for construction supply chains. The optimality of the final schedule is not guaranteed and their work does not consider capacity constraints of resources.

Lee et al. (2003) make use of a 'fine grained' agent architecture consisting of schedule agents, task agents and resource agents and propose a dynamic economy model and a market based control mechanism for resource allocation to multiple projects. The authors consider only single unit of each of the four types of shared resources in the problems and report experimentation on small problems of up to nine projects of 15 activities. Confessore et al. (2002, 2007) consider 'coarse-grained' MAS structure consisting of several bidding agents representing project managers and an auctioneer agent and develop an iterative combinatorial auction for resolving resource conflicts among the projects. The authors report experimentation with small multi-project instances (with up to five projects and 18 activities) with resource availability to single unit of only one type of shared resource.