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Agent-based fuzzy constraint-directed negotiation mechanism for distributed job shop scheduling

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ABSTRACT

This paper presents an agent-based fuzzy constraint-directed negotiation (AFCN) mechanism to solve distributed job shop scheduling problems (JSSPs). The scheduling problem is modelled as a set of fuzzy constraint satisfaction problems (FCSPs), interlinked by inter-agent constraints. Each FCSP represents the perspective of the participants and is governed by autonomous agents. The novelty of the proposed AFCN is to bring the concept of a fuzzy membership function to represent the imprecise preferences of task start time for job and resource agents. This added information sharing is crucial for the effectiveness of distributed coordination. It not only can speed up the convergence, but also enforce a global consistency through iterative exchange of offers and counter-offers. The AFCN mechanism can also flexibly adopt different negotiation strategies, such as competitive, win–win, and collaborative strategies, for different production environments. The experimental results demonstrate that the proposed model can provide not only high-quality and cost-effective job shop scheduling (i.e., comparable to that of centralized methods) but also superior performance in terms of the makespan and average flow time compared with other negotiation models for agent-based manufacturing scheduling. As a result, the proposed AFCN mechanism is flexible and useful for distributed manufacturing scheduling with unforeseen disturbances.

1. Introduction

Manufacturing scheduling problems involve many parallel and sequential activities allocated over time with a capacity limitation on production resources. Typically, most manufacturing scheduling problems are modelled in terms of one monolithic centralized optimisation structure with slow response times. This centralized method lacks flexibility and adaptability when updated information is obtained from each manufacturing environment on the shop floor. Therefore, distributed scheduling has become a promising means of optimising job shop scheduling problems (JSSPs) in flexible manufacturing environments (Chun and Wong, 2003; Dewan and Joshi, 2002; Lin and Solberg, 1992; Siwamogsatham and Saygin, 2004).

Two major classes of methodologies have been proposed to solve distributed scheduling problems, namely, distributed problem solving (DPS) and the agent-based approach (Chun and Wong, 2003; Wang and Shen, 2003). In DPS, a scheduling activity is decomposed into a set of sub-problems; however, the problem-solving approach remains centrally designed, and its coordination strategy and information sharing are incorporated as an integral part of the system. Although the DPS approach provides the necessary encapsulation messages and can address the distributed aspect of the problem domain, it does not offer the sophisticated decision making required for proactive social interaction and cannot address the autonomous nature of the components.

Agent-based approaches, which are characterised by decentralised computation and information processing, are regarded as valid alternatives for manufacturing scheduling (Kaplanoğlu, 2014; Lai et al., 2008; Leitão and Restivo, 2008; Rajabinasab and Mansour, 2011; Xiang and Lee, 2008). A multiple-agent system is composed of a set of interrelated agents in a distributed and heterogeneous environment (Barbati et al., 2012), and such systems have recently been applied to solve various problems, including those involving supply chain planning and scheduling (Kim and Cho, 2010; Lin et al., 2008), cloud resource management (Gutierrez-Garcia and Sim, 2013; Sim, 2012, 2013), collaborative design (Lin et al., 2013), energy and smart grid (Hu et al., 2015; Kantamneni et al., 2015; Kilkki et al., 2014), health care monitoring (Su and Wu, 2011), transportation and logistics (Chen and Cheng, 2010; Khamis and

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Gomaa, 2014; Sprenger and Mönch, 2014), and virtual enterprise negotiations (Wang et al., 2014). Agent-based approaches to distributed scheduling rely on a loosely-coupled network of autonomous agents working together in the interests of their own welfare to solve a common problem. In an agent-based approach, manufacturing resources, such as machines, and job operators are each regarded as intelligent agents that can locally handle the resource scheduling. However, the participating intelligent agents can also improve the global performance through negotiation mechanisms and protocols (Shen, 2002). Therefore, the key to distributed scheduling is how to develop a negotiation mechanism that can provide a basis for conflict resolution among a set of cooperating and competing agents to obtain a globally beneficial schedule without consuming excess computation time.

Several negotiation models have been proposed for solving agent-based scheduling problems. Typically, a third-party agent is used for conflict resolution (Lau et al., 2006; Lee et al., 2003). A major problem with these approaches is that they are essentially centralized negotiation structures and require the sharing of sensitive strategic information that would not be revealed to opponents or even to a third-party mediator. The dedicated agent not only needs to have full knowledge of the information held among all the agents but could also act as a bottleneck, which hinders problem-solving. To address this problem, two popular and fully distributed negotiation protocols for message passing have been proposed for agent-based scheduling: (1) a contract net protocol (CNP) with various dispatching heuristics for decision-making and conflict resolution (Gu et al., 1997; Lin and Solberg, 1992; Macchiaroli and Riemma, 2002; Smith, 1980) and (2) an iterative market-based auction model (Adhau et al., 2012; Dewan and Joshi, 2001, 2002; Siwamogsatham and Saygin, 2004; Wellman et al., 2001). Problem-solving in these approaches involves activity announcement, bidding, and awarding to establish agreement among agents. Relying on this protocol, the agents demonstrate flexibility in resource selection and allocation. However, the resources selection in these methods is subjective and usually based on local evaluations with limited interaction and thus risks generating schedules of inferior quality.

This paper proposes an agent-based fuzzy constraint-directed negotiation (AFCN) mechanism for distributed job shop scheduling. Specifically, job shop scheduling is modelled as a set of fuzzy constraint satisfaction problems (FCSPs) interlinked by inter-agent constraints. Each FCSP represents the perspective of the participants and is governed by agents. Fuzzy constraints are used not only to represent the requirements that jobs being scheduled must satisfy but also to specify the possibilities prescribing the extent to which the solutions are suitable for scheduling to allow the solution quality to be ranked (Dubois et al., 1995, 2003; Lai, 1992; Li et al., 2002; Abdullah and Abdolrazzagh-Nezhad, 2014; Huang and Süer, 2015). However, most previous studies of the use of fuzzy constraints in JSSPs have used either centralized or DPS approaches and have encountered difficulties in addressing a distributed manufacturing environment. Several researchers have employed fuzzy constraints in agent-based approaches for bilateral and multi-issue negotiations in semi-competitive environments (Faratin et al., 2002; Kowalczyk and Bui, 2000; Luo et al., 2003; Lai and Lin, 2004; Lai et al., 2010). Nevertheless, little research has been conducted on the use of fuzzy constraints in agent-based approaches for solving JSSPs

The negotiation process is considered to have global consistency enforced via iterative constraint adjustment and relaxation. To facilitate convergence and improve the solution quality, scheduling information on the preferred task start time is shared during negotiation. Agents resolve conflicts in their local schedules and improve global performance by considering the opponents' intentions regarding the activities time allocation during the negotiation process. Therefore, the agents in the proposed AFCN mechanism not only exhibit autonomous cooperation and coordination but also make their decisions independently, allowing them to simultaneously optimise their local objectives without violating the constraints of other agents.

The novelty of the proposed AFCN is to bring the concept of a fuzzy membership function to represent the imprecise preferences of task start time for job and resource agents. This added information sharing is crucial for the effectiveness of distributed coordination. It not only can speed up the convergence, but also enforce a global consistency through iterative exchange of offers and counter-offers. To compare with other multi-agent systems, the negotiation mechanism can facilitate the exchange of messages without requiring the sharing of private information among agents while also providing the task allocation intentions of each participating agent to allow the construction of a global schedule. This mechanism is useful for distributed manufacturing scheduling involving a wide variety of processes, products, machines, and unforeseen disturbances. To consider the behaviour of different agent to resolve conflicts, the proposed AFCN mechanism can also adopt various negotiation strategies (collaborative, win-win, or competitive) during negotiation for increased flexibility. The experimental results demonstrate that the proposed AFCN mechanism not only achieves better makespan and average flow time but also increases the number of successful negotiations.

The remainder of this paper is organised as follows. Section 2 introduces the fundamentals of the JSSP modelling as a distributed fuzzy constraint satisfaction problem (DFCSP). Section 3 presents the AFCN mechanism, including the process for generating offers and counter-offers, a communication protocol, and agent behavioural models that support effective interactions between RAs and JAs. Section 4 examines the effectiveness and efficiency of the proposed AFCN through numerical experiments performed for various numbers of jobs. Section 5 presents the conclusion to this paper and includes a discussion on the findings and directions for future research.

2. Agent-based fuzzy constraint-directed negotiation for JSSP

In a JSSP, a set of jobs is assigned to be performed on a set of machines (resourcees). For flexible and decentralised operation, job shop scheduling is modelled as agent-based scheduling, which is the process of resolving conflicts among job agents (JAs) and resource agents (RAs) in a multi-agent system (MAS). As shown in Fig. 1, an MAS for job shop scheduling is represented by a triple ($\mathbf{E}$, $\mathbf{F}$, $\mathfrak{I}$), where $\mathbf{E}$ is a set of m job agents, $\mathbf{F}$ is a set of n resource agents, and $\mathfrak{I}$ is a set of inter-agent constraints between the two classes of agents. Each job consists of a set of m_i activities/tasks and is further specified by the enforcement of temporal and precedence constraints, including the processing time of each activity on a specific resource, the due dates, and the arrival (release) dates. Each resource agent is specified by a processing capacity constraint. Each interrelation $\mathfrak{I}_{i,j,k}$ specifies a corresponding RA, where $\mathbf{F}_j$ is a candidates for performing activity k governed by the JA $\mathbf{E}_i$. Job shop scheduling involves assigning a resource to activities such that the activities will be completed with a reasonable processing time.

Then, the JSSP can be represented as a distributed fuzzy constraint satisfaction problem (DFCSP) that leads to a mutually acceptable schedule by both JAs and RAs. The objectives of each agent are modelled in terms of fuzzy constraints, and the interrelations between agents are regarded as inter-constraints associated with each agent to determine whether a solution exists that satisfies all constraints in the DFCSP. A DFCSP can be represented by a distributed fuzzy constraint network (DFCN) in which fuzzy relations