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An agent-based fuzzy constraint-directed negotiation model for solving supply chain planning and scheduling problems

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ABSTRACT

Supply chain planning and scheduling problems require manufacturers (project managers) to determine product configurations, select suppliers (contractors) for task allocation, and schedule project tasks while considering various production constraints among manufacturers and suppliers. Most relevant studies have focused on finding an optimal solution based on complete information provided by each enterprise in a supply chain. However, the practical implementation of complete information sharing is difficult, if not impossible, because of the fully distributed nature of the supply chain process. This work proposes an agent-based fuzzy constraint-directed negotiation (AFCN) model to solve problems associated with supply chain planning and scheduling, which are modeled as a set of fuzzy constraint satisfaction problems (FCSPs) that are interlinked *via* inter-agent constraints. To accommodate the perspectives and interests of each enterprise in a supply chain, conflicts among FCSPs are resolved using the AFCN protocol through the iterative exchange of offers/counter-offers with limited information sharing and without privacy breaches. A proposed offer/counter-offer represents not only a set of acceptable solutions and preferences for an operational task but also the possibility of conflict in this area. For each FCSP, the incremental process of offer/counter-offer evaluation eliminates redundant and infeasible solutions. The sharing of limited non-strategic sensitive information among agents enables them to elucidate their opponents' intentions through iterative negotiations, such that the agents can reach an agreement while ensuring that the solution to a project planning and scheduling problem is satisfactory. The AFCN model is also sufficiently flexible to incorporate different negotiation strategies such as competitive, win-win, and collaborative strategies, for various production environments. Herein, a numerical study was conducted to examine the practical viability and effectiveness of the proposed AFCN model. The experimental results show that the proposed AFCN model not only can generate a schedule that is comparable to a near-optimal solution but also is time-efficient. This indicates that the proposed AFCN is a practical and effective method for solving supply chain planning and scheduling problems in fully distributed environments.

1. Introduction

Faced with global economic volatility and intense competition, modern enterprises must respond rapidly to market fluctuations. In a supply chain, the various business entities, involved including suppliers, manufacturers, distributors and retailers, are partners, whose integrated actions produce products and services for customers [1]. In a customer-driven supply chain, an enterprise responds to rapidly customer demand, and diverse products are produced to satisfy that demand. In addition, most supply chains include various manufacturers that concurrently produce multiple products. To ensure good customer service and low production costs, enterprises must select partners and coordinate with them during process planning and scheduling in a cost-effective manner, given various constraints such as those related to processing time and due date [2–5].

The manufacturing process that is required to meet customer demand comprises various processes for the production of raw materials or the assembly of parts into finished products [3]. Planning involves supplier selection and product configuration decisions regarding the sequence of manufacturing operations

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based on the precedence relations among those operations. Scheduling involves the allocation of various jobs to different facilities to fill a customer's order in a timely manner.

This work aims to solve a supply chain planning and scheduling problem (SCPSP) involving multiple projects undertaken by various project managers and contractors who are distributed and autonomous agents in a supply chain network. A project comprises a set of tasks or operations for a particular product under precedence constraints. Project managers in make-to-order enterprises coordinate the production sequences of these tasks. Each task is selected and performed by a firm or contractor from among a set of candidate partners. Each contractor has its own processing time, resources, and operating costs. The enterprises involved in a supply chain have diverse intentions. The objective of the project manager is to minimize the operating costs associated with a project by defining an optimal sequence of tasks given the precedence of the task operations. The goal of the contractors is to maximize their profits from the projects in which they participate, given their limited capacity to complete contracted tasks [6]. Furthermore, each enterprise in the supply chain must make decisions based on limited information about production operations obtained from either project managers or contractors, such as the processing costs and resource capacities of the contractors.

The two main classes of methods used to solve the SCPSP are centralized and distributed methods. In a centralized method, a single coordinator performs process planning and scheduling in a manner that integrates all operational information from all of the enterprises in the supply chain. Various centralized methods have been used to find an optimal or near-optimal solution to the SCPSP under conditions of full information sharing, including linear programming [4,7,8], fuzzy linear programming [9], fuzzy mixed integer-linear programming [10], genetic algorithm-based methods [11–14], and other meta-heuristic methods [15–20]. However, centralized approaches are difficult to apply to real industry problems because they typically require sensitive strategic information from business partners. Moreover, the centralized method lacks flexibility and is unable to adapt when the strategic information from each enterprise in the supply chain is updated.

Agent-based methods, which are characterized by distributed computation and information processing, are regarded as valid alternatives for SCPSP modeling [21–26]. A multiple-agent system comprises a set of inter-related agents in a distributed and heterogeneous environment [27], and such systems have recently been applied to solve various problems such as those involving cloud resource management [28–30], collaborative design [31], health care monitoring [32], manufacturing scheduling [33–35], transportation and logistics [36,37], and virtual enterprise negotiations [38,39]. However, the lack of global information for the coordination of production operations is a challenge in the agent-based approach. In this approach, agents make their decisions independently of each other and optimize their local objectives without considering the constraints of other agents or the global performance [6].

To ensure global performance with limited interaction among agents, a mediator or a third-party agent between the project manager and contractor can be introduced to coordinate task allocation [40]. This mediator facilitates the negotiation processes by assisting the negotiating parties in understanding their own needs, suggesting possible agreements, and supporting the parties in reaching a final agreement. However, in such situations, agents may be required to share sensitive strategic information that would otherwise not be revealed to opponents or even to a third-party mediator.

As alternatives to involving a third-party mediator, the contract net protocol (CNP) and the market-based iterative auction (MIA) protocol are used to support information privacy and enhance coordination in a fully distributed environment [6,15,41]. The CNP is used to facilitate negotiation for the distribution of subtasks among various agents [42–45]. In the CNP, a project manager agent (PA) sends a request to all qualified contractor agents (CAs) for bids to complete a task. After receiving bids from the contractors, the PA assigns the task to the best contractor based on his/her objective. However, negotiations using the CNP allow a contract with a CA to be established for only one project at a time. With limited interaction and limited information sharing, agents must make their decisions independently of each other, leading to the local optimization of the entire supply chain network. Lau et al. [6] proposed the modified contract net protocol (MCNP) to enable multiple project managers to simultaneously select contractors to undertake their operations. The MCNP also allows project managers to share the start-time window information for an operation with contractors to improve global performance. However, the CNP and MCNP support only limited interactions with single-shot negotiations and thus yield less-than-satisfactory results.

The MIA protocol provides a more sophisticated negotiation mechanism [46–50] by adopting a market-based approach for auctioning resources to contractors and enabling the contractor to receive maximum revenue. The MIA protocol also supports iterative bargaining between PAs and CAs to yield a task-performing price that reflects the global competition for resources. During the iterative bidding process, the project managers adjust their bids according to the prices quoted by the contractors, but they lack sufficient information regarding where any contention should be resolved. Hence, the bidding process may oscillate and not converge efficiently.

Accordingly, facilitating convergence is necessary to guarantee global performance in supply chain scheduling; moreover, both convergence and global performance are strongly affected by the degree of information sharing and remain critical challenges [51–53]. Therefore, this work investigates how to improve global performance in solving the SCPSP by increasing the interaction among enterprises without sacrificing convergence and by allowing more information to be shared among enterprises while still addressing the information privacy concerns of the enterprises involved.

This work proposes an agent-based fuzzy-constraint-directed negotiation (AFCN) method for solving the SCPSP in a fully distributed environment. In this AFCN, the SCPSP is modeled as a set of fuzzy constraint satisfaction problems (FCSPs) that are interlinked *via* inter-agent constraints. Each FCSP represents the interests and perspectives of one enterprise in the supply chain. These constraints are characterized by non-directional, declarative, and intuitive properties related to descriptions of real-world problems, such as the allocation capacity of a contractor or the production sequence of a product. Subjective, imprecise, and qualitative knowledge, including that associated with human cognition, preferences, or even opponents' perspectives, is frequently encountered in the business decision-making component of a supply chain and can easily be captured using fuzzy constraints at various consistency levels. In particular, fuzzy constraints are used to conveniently rank the candidate solutions by specifying the possibilities and prescribing to what extent the solutions are suitable. Furthermore, similarity measurements between offers and counter-offers are used to provide a basis for selecting a solution from among a set of feasible alternatives when making a multi-objective decision.

To accommodate the perspectives and interests of each enterprise in a supply chain, conflicts among FCSPs are resolved using an AFCN protocol through the iterative exchange of offers/counter-offers with limited information sharing and without privacy