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Hybrid method integrating agent-based modeling and heuristic tree search for scheduling of complex batch processes

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ABSTRACT

We propose a hybrid method integrating agent-based modeling and heuristic tree search to solve complex batch scheduling problems. Agent-based modeling describes the batch process and constructs a feasible schedule under various constraints. To overcome myopic decisions of agents, the agent-based simulation is embedded into a heuristic search algorithm. The heuristic algorithm partially explores the solution space generated by the agent-based simulation. Because global information of the objective function value is used in the search algorithm, the schedule performance is improved. The proposed method shares the advantages from both agent-based modeling and mixed integer programing, achieving a better balance between the solution efficiency and the schedule performance. As a polynomial-time algorithm, the hybrid method is applicable to large-scale complex industrial scheduling problems. Its performance is demonstrated by comparing with agent-based modeling and mixed integer programing in two case studies, including a complex one from The Dow Chemical Company.

1. Introduction

Scheduling is a critical layer of decision hierarchy in process manufacturing, having a significant impact on process productivity (Floudas & Lin, 2004; Mendez, Cerda, Grossmann, Harjunkoski, & Fahl, 2006; Yue & You, 2013a, 2013b). In process industry, scheduling problems can be broadly cast into continuous process scheduling problems and batch process scheduling problems (Kallrath, 2002). Batch processes are preferable to manufacture a large number of products with high profit margins and low volume requirements. Though a wide spectrum of batch scheduling methods have been presented, solving an industrial scheduling problem still encounters some challenges due to the complexity of a real-world batch process (Mendez et al., 2006; Wassick et al., 2012). The goal of this work is to propose an efficient and effective scheduling method which combines advantages from conventional mixed-integer programing (MIP) methods and agent-based modeling (ABM) methods.

MIP methods are prevalent in solving batch scheduling problems, which include mixed-integer linear programing (MILP) methods and mixed-integer nonlinear programing (MINLP) methods. A great variety of discrete-time models (Kondili, Pantelides, & Sargent, 1993; Shah, Pantelides, & Sargent, 1993) and continuous-time models (Ierapetritou & Floudas, 1998; Maravelias & Grossmann, 2003; Sundaramoorthy & Karimi, 2005) have been developed. MIP methods can take advantage of the state-of-the-art mathematical programing solvers and guarantee the solution optimality in theory. However, these exact methods suffer from computational complexity. Apart from very simple instances, most scheduling problems, which are among the hardest combinatorial optimization problems, are strongly NP-hard (Ouelhadj & Petrovic, 2009; Pinedo, 2012; Ullman, 1975). The computational time required to find the optimal schedule can increase exponentially with the problem size, hindering the application to complex problems. Besides the combinatorial complexity, a scheduling problem can also include nonlinear terms (Chu & You, 2012; Yue & You, 2013a, 2013b). The nonlinearity can further complicate the scheduling problem. Though an MIP method can be applied heuristically by being terminated with a large gap, the returned suboptimal solution can be worse than that by a heuristic method within the same computational time (Blum, Puchinger, Raidl, & Roli, 2011). Given limited computational time a feasible solution may not be found with MIP methods.

To overcome the computational complexity, ABM methods have been developed (Cowling, Ouelhadj, & Petrovic, 2003; Kaihara, Fujii, Tsujibe, & Nonaka, 2010; Lou, Liu, Zhou, Wang, & Sun, 2012; Palombarini & Martinez, 2012; Verstraete et al., 2008; Wong, Leungy, Mak, & Fung, 2006). These methods use intelligent agents (Leitao, 2009; Macal & North, 2010) to model a manufacturing process, and then construct a schedule by simulating the agent-based model. Because decision-making is distributed among individual agents, ABM methods can easily cope with a large-scale complex

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problem (Shen, Wang, & Hao, 2006; Trentesaux, 2009). The main advantage of the ABM methods is the computational efficiency, even for a nonlinear scheduling problem (Chu, Wassick, & You, 2013). However, the ABM methods suffer from the poor schedule performance because the distributed agent decisions are myopic based on local information. Unlike the MIP methods, the ABM methods cannot directly use an objective function value like the makespan or the total tardiness to make scheduling decisions. This is because the objective function value is only available after the entire schedule is constructed, which is not accessible during the simulation procedure aiming to construct the schedule.

Both conventional MIP methods and ABM methods have difficulties in solving a complex industrial-size scheduling problem. To solve a complex problem as efficiently as the ABM methods while guaranteeing a high-quality solution comparable to that of the MIP methods, we propose a novel hybrid method integrating agent-based modeling and heuristic tree search. The hybrid method is outlined in Fig. 1. It consists of the following three phases:

- *Phase I (Process modeling)*. The complex batch process is modeled by agents. An industrial batch process could be complex not only due to the large scale but also due to various specifications on process structures, production conditions, storage policies, and practical requirements. Some important but nonstandard specifications are often encountered in practice. These specifications can be easily represented by agent-based modeling.
- *Phase II (Schedule generation)*. The process is simulated using the agent-based model to construct a feasible schedule satisfying the constraints specified in Phase I. The scheduling problem is transformed into a task assignment problem. During the agent-based simulation, a ready task is assigned to a processing unit when the unit is idle. This is a multi-stage decision problem, of which the possible solutions are characterized by a decision tree. The root of the tree is the empty schedule and a leaf node represents a feasible schedule. The intermediate nodes represent a partial schedule. The scheduling problem is solved by finding a path from the root to a leaf so that the objective function value can be as good as possible.
- Phase III *(Schedule search)*. The decision tree generated in Phase II is enumerated to search for a good schedule. Because the size of the entire decision tree is tremendous, a complete enumeration of the tree is time-consuming. Thus heuristic tree search techniques are preferred where the solution tree is partially explored. Various tree search algorithms can be applied. In this work, beam search (Ow & Morton, 1988; Sabuncuoglu & Bayiz, 1999) with its extensions are adopted. The beam search algorithms adopt the heuristic breadth-first search strategy. The computational complexity is controlled by restricting the number of nodes opened at each level. The opened nodes represent promising partial schedules, starting from which a complete schedule with a good objective function value can be obtained. Phase III iterates with Phase II, so that only the nodes required to be explored in Phase III are generated in Phase II.

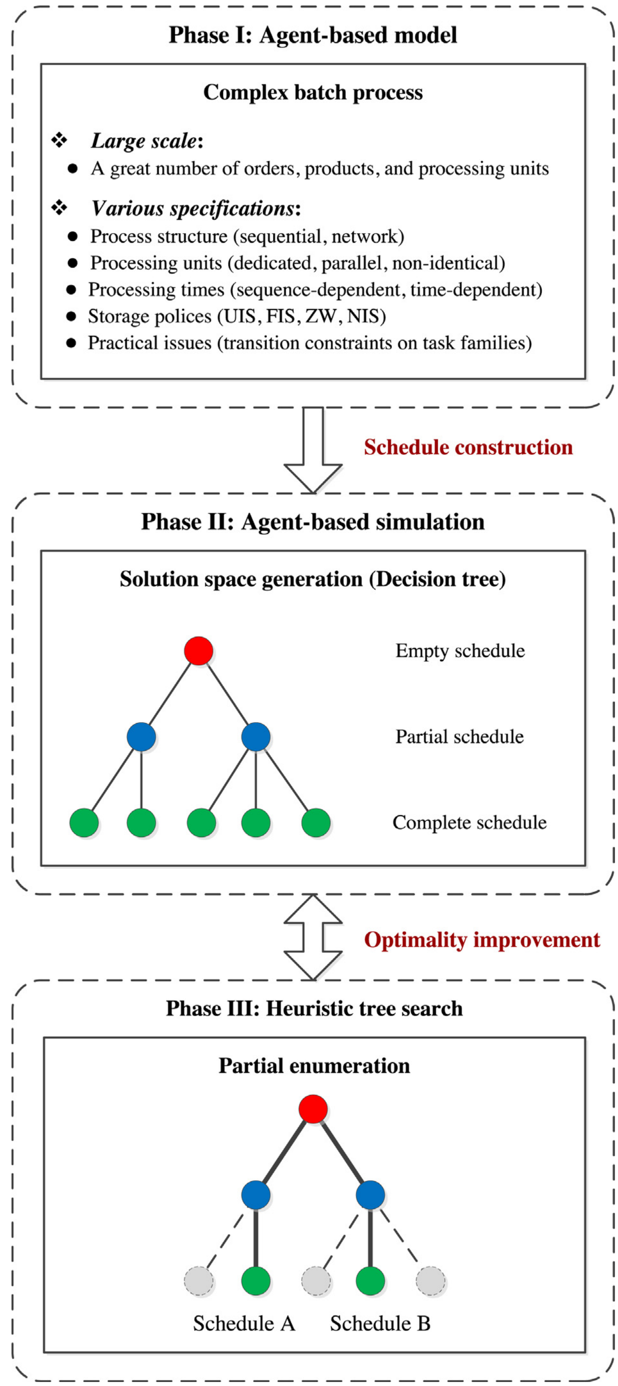

Fig. 1. Framework of the hybrid method integrating agent-based modeling and heuristic tree search. In this work, beam search is applied to partially explore the solution tree.

The novelty of the hybrid method is that the objective function is used directly to guide the agent-based simulation so that the myopic decisions of agents are overcome. The schedule performance is improved to a near-optimal one which can be validated by an MIP method. Meanwhile, the hybrid method preserves the computational efficiency of the ABM methods. The beam search algorithms are all polynomial-time (the number of computational steps in the algorithms can be bounded by a polynomial function of the problem size), ensuring the hybrid method applicable to large-scale scheduling problems.

The performance of the hybrid method is demonstrated in several case studies. For examples taken from the literature, the hybrid method outperforms the ABM method by returning a better objective function value. The solution quality is close to the optimal one returned by an MIP method. In the case of complex problems where the MIP method cannot return the optimal solution within the limited computational time, the hybrid method can even provide a better solution than that of the MIP method. Besides examples from the literature, the ability of the hybrid method for solving large-scale scheduling problems with complicated specifications is also demonstrated by solving a complex industrial scheduling problem from The Dow Chemical Company. The problem is large in scale and contains nonstandard constraints which are difficult to model and