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A Graph-based Ant Colony Optimization Approach for Integrated Process Planning and Scheduling☆

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ABSTRACT

This paper considers an ant colony optimization algorithm based on AND/OR graph for integrated process planning and scheduling (IPPS). Generally, the process planning and scheduling are studied separately. Due to the complexity of manufacturing system, IPPS combining both process planning and scheduling can depict the real situation of a manufacturing system. The IPPS is represented on AND/OR graph consisting of nodes, and undirected and directed arcs. The nodes denote operations of jobs, and undirected/directed arcs denote possible visiting path among the nodes. Ant colony goes through the necessary nodes on the graph from the starting node to the end node to obtain the optimal solution with the objective of minimizing makespan. In order to avoid local convergence and low convergence, some improved strategy is incorporated in the standard ant colony optimization algorithm. Extensive computational experiments are carried out to study the influence of various parameters on the system performance.

1. Introduction

Process planning and scheduling are two important aspects in manufacturing systems, which determine how and when to produce with respect to manufacturing resources. Process planning is to establish technological requirements to satisfy the specified design. Scheduling is to arrange resources available to schedule the operations. Traditionally, these two activities are performed sequentially and separately. Scheduling is conducted after the process plan is generated. However, current manufacturing environment changes fast. Especially, with the development of manufacturing technology and personalized consumer demand, modern manufacturing systems operate with increasing complexity and flexibility. In such a system, order details, real-time status of production workshop and distribution of production facilities have an increasingly important effect on the performance of process planning and scheduling. If a process plan is carried out regardless of the scheduling objective, it may cause serious bottlenecks and obstacle to improve the productivity and responsiveness of the manufacturing systems [1].

Integrated process planning and scheduling (IPPS) is an important method to meet the need of modern manufacturing system, which optimizes the manufacturing system by combining process planning and scheduling. This paper presents the application of an improved ant colony optimization (ACO) algorithm in IPPS problem, which makes use of alternative process route as inputs of scheduling, and determines appropriate operations and process routes according to the actual status of manufacturing systems. The scheme of process planning and scheduling is achieved through choosing alternative process routes based on the ACO under the restriction of optimization targets.

2. Related Work

The preliminary idea of IPPS was introduced by Chryssolouris *et al.* [2,3]. Nasr and Essayed presented two heuristics based on mixed integer programming to determine an efficient schedule for n jobs m machines problem with alternative machine routings for each operation to minimize the mean flow time [4]. Bandeimarte and Calderini developed a two-phase hierarchical tabu search [5]. Kim *et al.* gave a scheduling system with flexible process plans and presented an auction-based task assignment method between multiple parts and multiple machines [6]. Kim and Egbelu proposed a mixed integer programming model for a problem with n-job, m-process plan, and k-operation IPPS to minimize the makespan of jobs [7]. Saygin and Kilic proposed a frame for IPPS to reduce the completion time. In order to solve the IPPS, a heuristic method was proposed [8]. Tan presented a review in the process planning and scheduling area and discussed the extent of applicability of various approaches [9].

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Lee and Kim proposed an approach to the integration of process planning and scheduling using simulation based genetic algorithms. A simulation module was used to compute performance measures based on process plan combinations and the results were fed into a genetic algorithm to improve the solution quality until the scheduling objectives were satisfied [10]. Kim *et al.* proposed the symbiotic evolutionary algorithm (SEA) [11], which is a modified evolutionary algorithm based on the idea that parallel searches for different pieces of solution are more efficient than a single search for the entire solution. Kumar *et al.* attempted to use ACO for the IPPS problem, which is represented by graph with nodes and arcs. Individual ants move from the initial node to the final node through all nodes desired to be visited. The solution of the algorithm is a collective outcome of the solution found by all the ants [12]. Tan and Khoshnevis presented a linearized polynomial mixed-integer programming model for IPPS [13]. Wong *et al.* developed a multi-agent negotiation (MAN) approach for IPPS and established an agent-based framework to simulate the IPPS approach [14]. Wang *et al.* presented a review in the distributed process planning and scheduling area [15].

Recently, some research results for the IPPS are presented. Li and McMahon used a unified model and a simulated annealing-based approach to facilitate the integration and optimization process. Three strategies, including processing flexibility, operation sequencing flexibility and scheduling flexibility, were used for exploring the search space to support the optimization process effectively [16]. Moon *et al.* dealt with IPPS in a supply chain, formulating a mixed integer programming model for integration, which considers alternative operation sequences and precedence constraints, and developing a new evolutionary search approach based on a topological sort [17]. Shao *et al.* developed a new integration model and a modified genetic algorithm-based approach to facilitate the integration and optimization of process planning and scheduling, and efficient genetic representation and operator schemes to improve the optimization performance of the modified genetic algorithm-based approach [18]. Li *et al.* developed a new hybrid algorithm based approach to solve the IPPS problem and efficient genetic representation, operator and local search strategy to improve the optimization performance [19]. Leung *et al.* presented an ACO algorithm in an agent-based system to IPPS and proposed a graph-based solution method to minimize makespan [20]. Wong *et al.* proposed a two-stage ACO algorithm by a multi-agent system to accomplish IPPS [21].

3. Representations for Process Planning and Scheduling

3.1. Statement of problem

The IPPS problem can be described as follows [22].

Given a set of n parts to be processed on machines with operations including alternative manufacturing resources, selecting suitable manufacturing resources and making sequence of operations so as to determine a schedule in which the precedence constraints among operations can be satisfied and corresponding objectives can be achieved.

3.2. Representations for process planning and scheduling

The IPPS is a typical combination optimization problem consisting of two sub-problems, process planning and job scheduling. This paper presents an approach to solve the IPPS problem through an AND/OR graph constructed on the ACO. For each part, all of the rational operations and feasible process routes are recorded in an AND/OR graph. The AND/OR graph structure can represent a set of possible alternative process routes [23]. The AND-subgraph means the priority constraints among the operations of the same parts. The OR-subgraph means the correlations among the operations of the part, which indicates that one of the alternative process routes is accessed to be visited. To apply the ACO algorithm to construct schedules for IPPS, the AND/OR graphs is represented. Given a disjunctive graph $D = (O, U, V)$, where O is a set of nodes representing all processing operations $O_{i,j}$, U is a set of directed arcs, which corresponds to the precedence relationships among the operations of the same parts, and V is a set of undirected arcs, which connects all possible combination of the nodes and represents the visited relations of the same or different parts [24]. Both U and V represent possible paths for ants to travel from one node to another. The ants are free to travel along the paths constructed on the AND/OR graph. To facilitate the implementation of ACO algorithm, two dummy nodes S and E are added as the starting and ending of the node [11,19]. Fig. 1 is the AND/OR graph with parts A and B, in which every note indicates certain operation. O_{11}, the first node on the left belonging to part A, stands for the first operation of part A. The corresponding processing time is 7 s on machine W_1 and 6 s on machine W_4. Fig. 1 indicates that part A includes three alternative process routes consisting of 11 operations and part B includes six alternative process routes consisting of 13 operations. All process route available consisting of the operations from the two parts can be described in detail on the AND/OR graph.

4. An Improved ACO Algorithm for IPPS

4.1. Standard ACO algorithm

Because AND/OR graph represents every available process route of all parts, ant colony can traverse all notes on the AND/OR to achieve the solution of IPPS. Every node on the AND/OR graph signifies an operation of the job, which can be processed by different machines. The ant colony is placed on the starting node. An artificial ant visits some nodes by emulating the behavior of real ants. At the end of the continuous traversal process, a scheduling solution for the IPPS is constructed. The ants deposit a mount of pheromone on the visited path consisting of nodes and arcs including directed and undirected arcs. Generally, in order to complete the traversal process, all nodes on the AND/OR have to be visited. In IPPS, due to the alternative process route of the same part represented by OR-subgraphs on the AND/OR graph, not all the nodes have to be visited [20]. For example, if node O_{12} of part A is selected, the branch including nodes O_{14}, O_{15}, O_{17}, and O_{111} will be neglected because they belong to another alternative process route.

k ants are deployed at the starting node S initially. They are allowed to go through the whole AND/OR graph along the nodes and arcs in accordance with the precedence relationship constraints of different nodes, until a scheduling solution is generated for all parts. Due to the machine flexibility, once a node is visited by an ant, all the other nodes of the same operation but of other alternative machines will be ignored, as the nodes and arcs of the AND/OR graph are pheromone carriers. When an ant chooses the next node v among all the possible nodes connecting to current node u, the pheromone amount τ_{uv} and the heuristic desirability η_{uv} will construct an important factor to guide the ant to search the optimal path.

The heuristic desirability η_{uv} shall reflect the attraction of selecting the next node. It will be calculated according to the process time of current operation on the selected machine [14]. The heuristic desirability η_{uv} can be given as

$$\eta_{uv} = \frac{E}{t_{ijk}} \tag{1}$$

where E is a positive constant. Eq. (1) shows that the nodes with smaller processing time have higher desirability value, which have more attraction to the ants.

The pheromone amount τ_{uv} indicates the attraction of arcs for the following ants, which specifies how good the previous scheduling solution obtained from those ants arrived at the end node are. It will