A taboo search approach for deadlock-free scheduling of automated manufacturing systems

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This paper addresses the scheduling problem of a class of automated manufacturing systems. A new manufacturing system model is proposed. In this model, a set of jobs is to be processed and each job requires a sequence of operations. Each operation may need more than one resource. Upon the completion of an operation, resources needed in the next operation of the same job cannot be released and the remaining resources cannot be released until the start of the next operation. The scheduling problem consists in sequencing the operations on the resources in order to avoid deadlocks and to minimize the makespan. The classical disjunctive graph representation is extended to model the scheduling problem. A taboo search algorithm is then proposed using an original neighborhood structure defined by two basic moves: the permutation of disjunctive arcs of critical paths and a deadlock recovery move if the former fails. Numerical results presented in the paper show the efficiency of the proposed algorithm.

Keywords: Scheduling, manufacturing systems, deadlock, taboo search

1. Introduction

Automated manufacturing systems such as flexible manufacturing systems are characterized by a high level of automation achieved through the use of NC machines, robots, modern transportation resources including AGVs and conveyors, and automated storage devices. Parallel processes, synchronization, resource sharing, and various technical constraints are typical characteristics of such systems. The traditional view of a manufacturing system as a set of products and a set of machines is no longer enough. In automated manufacturing system, the manufacturing of a product needs the co-operation of different resources ranging from machines, operators, transportation resources and machining tools. High costs of modern manufacturing resources results in their limited availability. Efficient coordination of resources engaged in a production is then needed.

This paper is part of our work for developing scheduling methods of automated manufacturing systems with complex product structures and complex resource behaviors. Here a manufacturing system composed of a set of resources and processing a set of jobs is considered. Each job requires a sequence of operations. Each operation may need more than one resource. Most importantly, upon the completion of an operation, resources needed in the next operation of the same job cannot be released, while the remaining resources cannot be released until the job proceeds to the next operation. This resource model corresponds to resources such as transportation resources, robots, production authorization carts in kanban controlled systems, machines with limited output buffers.

A comparison with the huge scheduling literature (Blazewicz et al., 1996; GOTHA, 1993) shows that existing scheduling methods are not readily applied to manage an automated manufacturing system. Most scheduling methods only take into account very simple product structures and very simple resource behaviors representing single machine systems, flow

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shops and job shops, etc. Exceptions include work on management of transportation resources, tools and robots (Blazewicz and Finke, 1994; Hall and Srikandarajah, 1996; Sethi et al., 1992).

It is well known that complex product structure and complex resource interactions easily lead to undesirable deadlock situations if not adequately managed. For example, loading a part using a robot on a machine being processed another part leads to a deadlock if the same robot is needed for unloading the machine and no extra buffer space is available. In such a situation, a set of products is engaged in a so-called circular wait relation, i.e., each product holds some resources and waits the availability of other resources held by other products of the set. When this happens, the product engaged in the deadlock cannot move forward while the related resources cannot be released. Existing work has mainly concentrated on the deadlock prevention, detection and avoidance (Banaszak and Krogh, 1990; Chu and Xie, 1997; Ezpeleta et al., 1995; Fanti et al., 1997). It is usually assumed that scheduling is determined without taking into account deadlock issues and a deadlock detection/avoidance mechanism is used to handle possible deadlock situations.

The separate consideration of scheduling and deadlock may lead to unsatisfactory performance. In this paper, we instead schedule the jobs by taking into account possible deadlocks. The joint consideration of scheduling and deadlock avoidance leads to highly combinatorial scheduling problems. As a matter of fact, many classical scheduling techniques do not apply and their extension to automated manufacturing systems is a challenging task. For example, the pairwise exchange of operations is recognized as one of the most efficient technique of scheduling job shops and does not directly apply here as it often leads to deadlock. Nevertheless, it is our belief that joint consideration may lead to more powerful heuristic solutions than separate handling of scheduling and deadlock issues.

The goal of this paper is to present an extension of the critical path method of classical job-shop scheduling problems. Critical path-based local search algorithms such as simulated annealing methods and taboo search methods have been proven extremely efficient in solving classical job-shop scheduling methods (see Osman and Laporte, 1996). In order to solve jointly the scheduling and deadlock avoidance problem, we first propose a new manufacturing system model called single resource job-shop with blocking (or SJSB for short) which includes a wide range of manufacturing systems models as special cases. The disjunctive graph representation is then extended to represent the SJSB scheduling problem. Based on this new representation, we propose a taboo search method based on an original neighborhood structure defined by two basic moves: the permutation of disjunctive arcs on the critical paths and a deadlock recovery move which allows to get out of deadlock situation following a deadlock-prone permutation. The numerical results presented in the paper prove the efficiency of the proposed taboo search method.

Most related to our work is the work of Ramaswamy and Joshi (1996) who provided a mathematical programming model for obtaining deadlock-free schedules for an automated manufacturing system with machines, transportation resources, limited buffers. Also related to this work are existing efforts to use Petri nets to generate schedules of manufacturing systems. Scheduling problems of cyclic manufacturing systems were formulated and solved using heuristic methods in (Camus, 1997; Hillion et al., 1987). Petri net models and heuristic solutions were proposed in Lee and DiCesare (1994) and Proth and Xie (1996) for manufacturing systems with complex product structures and simple resource behaviors in which each operation requires one resource and each operation is followed by an unlimited buffer. Jeng et al. (1996) considered the scheduling of manufacturing systems with complex product structures and relatively complex resource behaviors. They used a so-called A* search method, a branch and bound-like method, for exploring the reachability graph. However, it seems difficult to obtain reasonable bounds for partial solutions and it is unlike that the A* search method can solve large scheduling problems. Damasceno and Xie (1998, 1999) developed a heuristic approach based on dynamic programming and used the Petri net as a tool for deadlock detection. An efficient method was recently proposed by Mati et al. (2000a, 2000b). It is a greedy method that schedules jobs one by one using a new extension of the classical geometric method for 2-job scheduling problem of Brucker (1988). A taboo search is used to optimize the greedy method.

The paper is organized as follows. Section 2 introduces the manufacturing system under consideration and defines the scheduling problem. Section 3 formulates the scheduling problem using disjunctive