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Two-machine flow shop problem with effects of deterioration and learning ☆

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ABSTRACT

In this paper we consider a two-machine flow shop scheduling problem with effects of deterioration and learning. By the effects of deterioration and learning, we mean that the processing time of a job is a function of its execution starting time and its position in a sequence. The objective is to find a sequence that minimizes the total completion time. Optimal solutions are obtained for some special cases. For the general case, several dominance properties and some lower bounds are derived, which are used to speed up the elimination process of a branch-and-bound algorithm. A heuristic algorithm is also proposed, which is shown by computational experiments to perform effectively and efficiently in obtaining near-optimal solutions.

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1. Introduction

In the classical scheduling theory, the job processing times are considered to be constant. In practice, however, we often encounter settings in which the job processing times may be subject to change due to the phenomenon of learning and/or deterioration (Wang, 2007). For example, when the processing times arise from manual operations, the possibility of learning exists. Biskup (1999) indicated that the learning effect has been observed in numerous practical situations in different sectors of industry and for a variety of corporate activities. On the other hand, it has been noticed that jobs may deteriorate as they wait to be processed. Kunnathur and Gupta (1990) and Mosheiov (1991) presented several real-life situations where deteriorating jobs might occur. Lee (2004) first considered the effects of deterioration and learning simultaneous. The phenomena of learning effect and deteriorating jobs occurring simultaneously can be found in many real-life situations. For example, as the manufacturing environment becomes increasingly competitive, in order to provide customers with greater product variety, organizations are moving towards shorter production runs and frequent product changes. The learning and forgetting that workers undergo in this environment have thus become increasingly important as workers tend to spend more time in rotating among tasks and responsibilities prior to becoming fully proficient. These workers are often interrupted by product and process changes causing deterioration in performance, which we will refer to, for simplicity, as forgetting. Considering learning and forgetting effects in measuring productivity should be helpful in improving the accuracy of production planning and productivity estimation (Nembhard & Osothsilp, 2002). In this paper we investigate the implications of these phenomena occurring simultaneously for a two-machine flow shop scheduling problem.

Analysis of scheduling problems in which the processing time of a job is an increasing function of its starting time was introduced by Browne and Yechiali (1990). Mosheiov (1991) considered the flow time minimization problem under the assumption that basic processing times remain the same in the linear deterioration model. The motivation for analyzing identical basic processing times arises not only from its intrinsic interest, but it also serves as a good approximation to the general case. Later, Mosheiov (1994) further simplified the model to a simple linear deterioration model in which the jobs have a fixed job-dependent growth rate but no basic processing times. This follows from the fact that as the number of jobs increases, the starting times of many jobs are postponed and their basic processing times become irrelevant. Bachman and Janiak (2000) showed that the maximum lateness minimization problem under the linear deterioration assumption is NP-hard, and two heuristic algorithms are presented as a consequence. Bachman, Janiak, and Kovalyov (2002b) considered the problem of minimizing the total weighted completion time introduced by Browne and Yechiali (1990). They proved that the problem is NP-hard.

Chen (1996) and Mosheiov (1998) considered scheduling deteriorating jobs in a *multi-machine* setting. They assumed linear deterioration and parallel identical machines. Chen (1996) considered the minimum flow time and Mosheiov (1998) studied makespan

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minimization. Mosheiov (2002) considered the complexity of flow shop, open shop and job shop makespan minimization problems. Mosheiov (2002) introduced a polynomial-time algorithm for the two-machine flow shop and proved its NP-hardness when an arbitrary number of machines (three or more) are assumed. Wang and Xia (2006) considered no-wait or no-idle flow shop scheduling problems with job processing times dependent on their starting times. In these problems the job processing time is a simple linear function of a job's starting time and some dominating relationships between machines can be satisfied. They showed that for the problems to minimize makespan or weighted sum of completion times, polynomial algorithms still exist. When the objective is to minimize maximum lateness, the solutions of a classical version may not hold. Kang and Ng (2007) considered a parallel-machine scheduling with deteriorating jobs. They proposed a fully polynomial-time approximation scheme for this problem. Other types of deterioration have also been discussed. For instance, Kunnathur and Gupta (1990) and Mosheiov (1995) considered piecewise linear deteriorating functions.

Apart from the increasing linear model for the job processing times, there is also a decreasing linear model, which essentially presents the learning effect from modelling aspect. This model was introduced by Ho, Leung, and Wei (1993). Ho et al. (1993) considered the problem of solution feasibility with deadline restrictions. Ng, Cheng, Bachman, and Janiak (2002) considered three scheduling problems with a decreasing linear model of the job processing times, where the objective function was to minimize the total completion time, and two of the problems are solved optimally. A pseudopolynomial time algorithm was constructed to solve the third problem using dynamic programming. Some interesting relationships between the linear model with decreasing and increasing start time dependent parts have also been presented by Ng et al. (2002). Bachman, Cheng, Janiak, and Ng (2002a) considered the single-machine scheduling problem with start time dependent job processing times. They proved that the problem of minimizing the total weighted completion time is NP-hard. They also considered some special cases. Wang and Xia (2005b) considered the scheduling problems under a special type of linear decreasing deterioration. They presented optimal algorithms for single-machine scheduling of minimizing the makespan, maximum lateness, maximum cost and number of late jobs, respectively. For the two-machine flow shop scheduling problem to minimize the makespan, they proved that the optimal schedule can be obtained by Johnson's rule. If the processing times of the operations are equal for each job, they proved that the flow shop scheduling problems can be transformed into single-machine scheduling problems. Wang and Liu (2008) considered a two-machine flow shop scheduling problem with a proportional linear decreasing deterioration. They developed several dominance conditions and lower bounds for the total completion time of the problem and used in a proposed branch-and-bound algorithm to search for the optimal solutions. They also proposed a heuristic algorithm which was shown by computational experiments to be effective and efficient in obtaining near-optimal solutions. Extensive reviews of research on scheduling deteriorating jobs have been provided by Alidaee and Womer (1999) and Cheng et al. (2004).

Biskup (1999) and Cheng and Wang (2000) were among the pioneers that brought the concept of learning into the field of scheduling, although it has been widely employed in management science since its discovery by Wright (1936). Biskup (1999) proved that single-machine scheduling with a learning effect remains polynomial solvable if the objective is to minimize the deviation from a common due date or to minimize the sum of flow time. Cheng and Wang (2000) considered a single-machine scheduling problem in which the job processing times will decrease as a result of learning. A volume-dependent piecewise linear processing time function was used to model the learning effects. The objective was to minimize the maximum lateness. They showed that the problem is NP-hard in the strong sense and then identified two special cases which are polynomially solvable. They also proposed two heuristics and analysed their worst-case performance. Mosheiov (2001a, 2001b) investigated several other single-machine problems, and the problem of minimizing the total flow time on identical parallel machines. Mosheiov and Sidney (2003) considered the case of a job-dependent learning curve, where the learning in the production process of some jobs is faster than that of others. Wang and Xia (2005a) considered flow shop scheduling problems with a learning effect. The objective was to minimize one of two regular performance criteria, namely makespan and total flow time. They gave a heuristic algorithm with a worst-case error bound of m for each criterion, where m is the number of machines. They also found polynomial time solutions to two special cases of the problems, i.e., identical processing times on each machine and an increasing series of dominating machines. Wang (2008a) considered single-machine scheduling problems with a sum-of-processing-times-based learning effect. He proved that the SPT rule is optimal for the sum of completion times square minimization problem. He also showed by several examples that the total weighted completion time minimization problem, the maximum lateness minimization problem and the number of tardy jobs minimization problem cannot be optimally solved by the corresponding classical scheduling rules. Wang (2008b) considered single-machine scheduling problems with past-sequence-dependent (p-s-d) setup times and time-dependent learning effect. He proved that the makespan minimization problem, the total completion time minimization problem and the sum of the quadratic job completion times minimization problem can be solved by the SPT rule, respectively. He also proved that some special cases of the total weighted completion time minimization problem and the maximum lateness minimization problem can be solved in polynomial time. Wang (2009) considered single-machine scheduling with the effects of time-dependent learning and deterioration. He showed that the makespan minimization problem can be solved in polynomial time. Wang et al. (2009) considered single-machine scheduling problems with p-s-d setup times and exponential time-dependent learning effect. They proved that the makespan minimization problem, the total completion time minimization problem and the sum of the quadratic job completion times minimization problem can be solved by the SPT rule, respectively. Extensive reviews on this line of the scheduling research could be found in Bachman and Janiak (2004) and Biskup (2008).

In this paper we consider two-machine flow shop scheduling to minimize the sum of completion times with simple linear deterioration and a learning effect. This model was proposed by Lee (2004). It is well known that flow shop scheduling to minimize the total completion time is NP-hard even if there are no deteriorating jobs (Garey, Johnson, & Sethi, 1976). Therefore, the two-machine flow shop scheduling problem to minimize the sum of completion times with the effects of deterioration and learning is NP-hard.

The rest of this paper is organized as follows: In the next section we give the problem description. In Section 3 we consider some polynomially solvable special cases. In Section 4 we propose several elimination rules, which can be used to enhance the search for the optimal solution. In Section 5 we first develop a heuristic algorithm to find near-optimal solutions, then we establish some lower bounds to improve the branching procedures, and finally we propose a branch-and-bound algorithm for searching for the optimal solution. In Section 6 we present computational experiments to evaluate the performance of the branch-and-bound algorithm and the heuristic algorithm. Concluding remarks are given in the last section.

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