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Single-machine scheduling problems with past-sequence-dependent setup times

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Abstract

This paper studies single-machine scheduling problems with setup times which are proportionate to the length of the already scheduled jobs, that is, with past-sequence-dependent or p-s-d setup times. The following objective functions are considered: the maximum completion time (makespan), the total completion time, the total absolute differences in completion times and a bicriteria combination of the last two objective functions. It is shown that the standard single-machine scheduling problem with p-s-d setup times and any of the above objective functions can be solved in $O(n\log n)$ time (where n is the number of jobs) by a sorting procedure. It is also shown that all of our results extend to a "learning" environment in which the p-s-d setup times are no longer linear functions of the already elapsed processing time due to learning effects.

Keywords: Scheduling; Single-machine; Setup times

1. Introduction

In single-machine scheduling problems, the setup times are considered either sequence-independent or sequence-dependent. In the former case, the setup times are usually added to the job processing times while in the latter case the setup times depend not only on the job currently being scheduled but also on the last scheduled job. In this paper, we consider a new form of setup times which depend on all already scheduled jobs from the current batch.

The motivation for this new form of setup times stems from certain situations in high-tech manufacturing in which a batch of jobs consists of a group of electronic components mounted together on an integrated circuit (IC) board. These jobs must be processed one-by-one by a machine while they are mounted together on the board. The machine's operation on any of these components has an adverse effect on the "readiness" of all the other components which have not yet been processed due to the flow of electrical current through the IC board while the machine is operating. Once a component is fully processed, its condition is not affected by the subsequent operation of the machine even if it remains mounted on the IC board. The degree of "un-readiness" of any component is

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proportional to the amount of time it has been exposed to the machine's operation on other components. Consequently, prior to a component's processing, a setup operation, proportional to the degree of "un-readiness" of the respective component, is needed to restore it to "full-readiness" status; this setup operation has no effect on the "readiness" of the remaining unprocessed components. The overall manufacturing process is completed when all components on the IC board have been processed by the machine.

The practical situation described above belongs to a more general manufacturing environment encountered in high-tech manufacturing in which either long setup times are common (e.g., the high-tech testing environment described in Uzsoy et al., 1992) and/or individual units cannot be processed in isolation resulting in their degree of "readiness" being affected by the nature of the preceding operations in a given batch. In earlier research, the degree of "un-readiness" of a job caused by the processing of other jobs in the batch has been modeled as a deteriorating job processing time (e.g. Browne and Yechiali, 1990). However, it is reasonable to model the degree of job "un-readiness" in the form of a required setup time followed by the actual constant job processing time. Using the terminology in Allahverdi et al. (1999), the effective setup times in the previously described situations can be classified as past-sequence-dependent (p-s-d for short) non-batch setup times. In order to formally define them, we consider a standard non-preemptive single-machine scheduling problem with a batch of n jobs available at time zero and with a continuously available machine. Let p_j denote the processing time of job J_j, $j = 1, \ldots, n$; also, let $J_{[j]}$, $p_{[j]}$ denote the job occupying the j position in the sequence and its processing time respectively. The processing of $J_{[j]}$ must be preceded by a p-s-d setup time $s_{[j]}$, which can be computed as

$$s_{[j]} = \gamma \sum_{i=1}^{j-1} p_{[i]}, \quad j = 2, \ldots, n, \quad s_{[1]} = 0, \tag{1}$$

where $\gamma \geqslant 0$ is a normalizing constant. The value of the normalizing constant γ determines the actual lengths of the required setups and when $\gamma = 0$ there is no need for any p-s-d setups; in that case our problem reduces to the standard single-machine scheduling problem with no setups.

It is clear from the above formulation that the setup times can theoretically grow substantially when the batch size n is large. This can be prevented by setting the normalizing constant γ equal to a very small value or by introducing some type of learning effect on the setup times. In the latter case, the setup times do not grow proportionally with the total length of the already processed jobs due to higher efficiencies in the setup process as time progresses stemming from the learning effect. This learning effect in the setup process is considered in detail in Section 4. In any case, it is clear that when the processing of all n jobs in the current batch is completed, the setup time for the first job in the next batch is reset to zero and this procedure is repeated with each new batch of jobs.

Using the standard three field notation, our scheduling problem can be denoted as $1/s_{psd}/f\,(C_j)$ where C_j is the completion time of job J_j and $f(C_j)$ is a function of C_j. In this paper we will consider the minimization of the following functions: the maximum completion time (makespan) $C_{\max} = \max_{j=1,\ldots,n}\{C_j\}$, the total completion time $\mathrm{TC} = \sum_{j=1}^{n} C_j$, the total absolute differences in completion times $\mathrm{TADC} = \sum_{i=1}^{n}\sum_{j=i}^{n}|C_j - C_i|$ and the bicriteria objective function $\mathrm{BC} = \delta\mathrm{TC} + (1-\delta)\mathrm{TADC}$ where $0 \leqslant \delta \leqslant 1$ is the weighting factor for the bicriteria problem. The corresponding scheduling problems are denoted as $1/s_{psd}/C_{\max}$, $1/s_{psd}/\mathrm{TC}$, $1/s_{psd}/\mathrm{TADC}$ and $1/s_{psd}/\mathrm{BC}$, respectively.

We close this section by mentioning that the comprehensive surveys on scheduling research with setup times by Allahverdi et al. (1999) and Potts and Kovalyov (2000) respectively did not mention any paper considering p-s-d setup times. Furthermore, to the best of our knowledge, no paper with p-s-d setup times has appeared in the literature up to now. For the latest developments on scheduling research with setup times, the reader is directed to the most recent comprehensive survey of Allahverdi et al. (submitted for publication).

The rest of the paper is organized as follows: the $1/s_{psd}/C_{\max}$ and $1/s_{psd}/\mathrm{TC}$ problems are studied in Section 2 and the $1/s_{psd}/\mathrm{TADC}$ and $1/s_{psd}/\mathrm{BC}$ problems are studied in Section 3. In Section 4, all of the above problems are studied in a learning environment with non-linear p-s-d setup times. The conclusions of this research are summarized in Section 5.

2. The $1/s_{psd}/C_{\max}$ and $1/s_{psd}/\mathrm{TC}$ scheduling problems

We first consider the $1/s_{psd}/C_{\max}$ problem. Clearly,