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Single-machine scheduling against due dates with past-sequence dependent setup times

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Abstract

Recently Koulamas and Kyparisis (2006) introduced past-sequence-dependent setup times to scheduling problems. This means that the setup time of a job is proportionate to the sum of processing times of the jobs already scheduled. Koulamas and Kyparisis (2006) were able to show for a number of single-machine scheduling problems with completion time goals that they remain polynomially solvable. In this paper we extend the analysis to problems with due dates. We were able to show that some problems remain polynomially solvable. However, for some other problems well-known polynomially solution approaches do not guarantee optimality any longer, consequently we concentrated on finding polynomially solvable special cases.

Keywords: scheduling, setup times, due dates

1 Introduction

Recently Koulamas and Kyparisis (2006) introduced the concept of past-sequence-dependent setup times. Past-sequence-dependent (psd) setup times occur, for example, in high tech manufacturing environments, „in which a batch of jobs consists of a group of electronic components mounted together on an integrated circuit (IC) board“ (Koulamas and Kyparisis 2006). In addition to this „un-readiness“ of components, the wear-out of equipment (e.g. a drill) is an other example where the sum of processing times of the prior jobs adds to the processing time of the actual job. Koulamas and Kyparisis (2006) concentrated on single-machine scheduling problems with completion time goals, namely minimizing maximum completion time, total completion time, total absolute differences in completion times, and a bi-criterial objective function consisting of the two last mentioned goals. They were able to show that all these problems remain polynomially solvable when past-sequence-dependent setup times are included in the analysis. This note concentrates on single-machine scheduling problems with different due date based goals while past-sequence-dependent setup times are considered. After introducing the notation needed in the next sections we will analyze problems with individual due dates in section 3. In section 4 problems with common due dates are tackled. The paper concludes with some summarizing remarks in section 5.

2 Notation and model formulation

There are n jobs available at time zero which have to be processed on a single machine. Preemption is not allowed and the machine is only able to process one job at the time. Let p_i denote the processing time of the job i, $i = 1, ..., n$. The setup time of a job, s_i, depends on the total length of the jobs already scheduled:

$$s_{[i]} = \gamma \sum_{r=1}^{i-1} p_{[r]}$$

where $[i]$ denotes the i-th position in the sequence and γ is a non-negative constant. For all jobs a due date d_i is given. Furthermore C_i, $E_i = \max\{0, d_i - C_i\}$, $T_i = \max\{0, C_i - d_i\}$ and $L_i = C_i - d_i$ are the completion time, earliness, tardiness and lateness of job i, $i = 1, ..., n$, respectively. π will denote a schedule; a schedule contains all information that are necessary to schedule the jobs. These are the sequence of the jobs, their start times, and eventually the common due date if it is a decision variable. Throughout the paper we will make use of the well-known three-field notation for scheduling problems introduced by Graham et al. (1979); past-sequence-dependent setup times will be abbreviated by psd.

3 Problems with individual due dates

In this section we will analyze different single-machine problems with individual due dates and past-sequence-dependent setup times. An excellent introduction to single-machine problems with individual due dates problems is given by Baker (1997).

Total lateness

The total lateness L can be calculated by

$$\begin{aligned} L &= \sum_{r=1}^{n} \left[C_{[r]} - d_{[r]}\right] \\ &= \sum_{r=1}^{n} \left[\sum_{i=1}^{r}(\gamma(r-i)+1)p_{[i]} - d_{[r]}\right] \end{aligned}$$

Property 1. *The shortest processing time (SPT) sequence leads to an optimal solution for* $1/psd/\Sigma L_i$.

Proof: Total lateness L is minimized if $F = \sum_{r=1}^{n}\left[\sum_{i=1}^{r}(\gamma(r-i)+1)p_{[i]}\right]$ is minimized as $\sum_{r=1}^{n} d_{[r]}$ is a constant. Rearranging F to $F = \sum_{r=1}^{n}((n-r+1)+\gamma/2((n-r)(n-r+1)))p_{[r]}$ makes it obvious that it is the scalar product of two vectors, the $w_r = (n-r+1)+\gamma/2((n-r)(n-r+1))$ and $p_{[r]}$ vectors respectively $(r = 1, ..., n)$, see Koulamas and Kyparisis (2006). As $w_r \geq w_{r+1}$, the SPT sequence leads to an optimal solution (Hardy et al. (1967), p. 261).

Total tardiness

The single-machine total tardiness problem, $1//\Sigma T_i$, is NP-hard (Du and Leung (1990)). Hence $1/psd/\Sigma T_i$ must be NP-hard, too. The total tardiness T can be calculated by

$$T = \sum_{r=1}^{n} \max\left\{\left[C_{[r]} - d_{[r]}\right], 0\right\} = \sum_{r=1}^{n} \max\left\{\left[\sum_{i=1}^{r}(\gamma(r-i)+1)p_{[i]} - d_{[r]}\right], 0\right\}$$

Property 2. *For any pair of jobs, suppose that processing times and due dates are agreeable, i.e.* $p_i \leq p_k$ *implies* $d_i \leq d_k$*. Then* $1/psd/\Sigma T_i$ *is minimized by the SPT or, equivalently, by the earliest due date (EDD) sequence.*

Proof: The proof follows directly from the pairwise interchange analysis. Consider a schedule π, in which jobs i and k are adjacent in sequence at the positions x and $x+1$, and the schedule π' that is identical to π expect that jobs i and k are interchanged. Let further $p_i \geq p_k$ and thus $d_i \geq d_k$. For the comparison of π and π' it will suffice to compare the total tardiness that stems from the jobs i and k. The tardiness of the first $x-1$ jobs is obviously not affected by the interchange of job i and k. And as makespan is minimized by the SPT sequence (see Koulamas and Kyparisis 2006), the maximum tardiness among the last $(n-x+1)$ jobs in schedule π' cannot be higher than that of schedule π.

The tardiness of the jobs i and k in schedule π, $T_{i,k}(\pi)$, is calculated as the tardiness of job i, $T_i(\pi)$ plus the tardiness of job k, $T_k(\pi)$:

$$\begin{aligned} T_{i,k}(\pi) &= T_i(\pi) + T_k(\pi) \\ &= \max\left\{t + \sum_{r=1}^{x-1} \gamma p_{[r]} + p_i - d_i, 0\right\} + \max\left\{t + 2\sum_{r=1}^{x-1} \gamma p_{[r]} + (1+\gamma)p_i + p_k - d_k, 0\right\} \end{aligned}$$

The calculation of the tardiness of the jobs k and i in schedule π', $T_{i,k}(\pi')$, is very similar:

$$\begin{aligned} T_{k,i}(\pi') &= T_k(\pi') + T_i(\pi') \\ &= \max\left\{t + \sum_{r=1}^{x-1} \gamma p_{[r]} + p_k - d_k, 0\right\} + \max\left\{t + 2\sum_{r=1}^{x-1} \gamma p_{[r]} + (1+\gamma)p_k + p_i - d_i, 0\right\} \end{aligned}$$

To compare π and π' we consider two cases. The first case is $t + \sum_{r=1}^{x-1} \gamma p_{[r]} + p_i \leq d_i$.

Thus,

$$\begin{aligned}
T_{i,k}(\pi) &= \max\left\{t + 2\sum_{r=1}^{x-1}\gamma p_{[r]} + (1+\gamma)p_i + p_k - d_k, 0\right\} \\
T_{k,i}(\pi') &= \max\left\{t + \sum_{r=1}^{x-1}\gamma p_{[r]} + p_k - d_k, 0\right\} + \max\left\{t + 2\sum_{r=1}^{x-1}\gamma p_{[r]} + (1+\gamma)p_k + p_i - d_i, 0\right\}.
\end{aligned}$$

Notice that $T_{i,k}(\pi)$ is at least as large as the first maximum in $T_{k,i}(\pi')$ (since $\sum_{r=1}^{x-1}\gamma p_{[r]} + (1+\gamma)p_i \geq 0$) and at least as large as the second (since $\gamma(p_i - p_k) \geq d_k - d_i$). Therefore, if one or both of the maxima in $T_{k,i}(\pi')$ are zero, we will have $T_{i,k}(\pi) \geq T_{k,i}(\pi')$. Now suppose that neither term in $T_{k,i}(\pi')$ is zero. Then

$$\begin{aligned}
T_{i,k}(\pi) - T_{k,i}(\pi') &= t + 2\sum_{r=1}^{x-1}\gamma p_{[r]} + (1+\gamma)p_i + p_k - d_k \\
&\quad - \left(t + \sum_{r=1}^{x-1}\gamma p_{[r]} + p_k - d_k\right) - \left(t + 2\sum_{r=1}^{x-1}\gamma p_{[r]} + (1+\gamma)p_k + p_i - d_i\right) \\
&= \gamma p_i - \sum_{r=1}^{x-1}\gamma p_{[r]} - t - (1+\gamma)p_k + d_i \geq 0 \\
\gamma(p_i - p_k) \geq 0 \geq t + \sum_{r=1}^{x-1}\gamma p_{[r]} &+ p_i - d_i \geq t + \sum_{r=1}^{x-1}\gamma p_{[r]} + p_k - d_i.
\end{aligned}$$

Therefore, the first case yields $T_{i,k}(\pi) \geq T_{k,i}(\pi')$. The second case consequently is $d_i < t + \sum_{r=1}^{x-1}\gamma p_{[r]} + p_i$. Thus,

$$\begin{aligned}
T_{i,k}(\pi) &= 2t + 3\sum_{r=1}^{x-1}\gamma p_{[r]} + (2+\gamma)p_i - d_i + p_k - d_k \\
T_{k,i}(\pi') &= \max\left\{t + \sum_{r=1}^{x-1}\gamma p_{[r]} + p_k - d_k, 0\right\} + t + 2\sum_{r=1}^{x-1}\gamma p_{[r]} + (1+\gamma)p_k + p_i - d_i \\
T_{i,k}(\pi) - T_{k,i}(\pi') &= t + \sum_{r=1}^{x-1}\gamma p_{[r]} + (1+\gamma)p_i - \gamma p_k - d_k - \max\left\{t + \sum_{r=1}^{x-1}\gamma p_{[r]} + p_k - d_k, 0\right\}.
\end{aligned}$$

If the maximum in the last term is zero, then

$$\begin{aligned} T_{i,k}(\pi) - T_{k,i}(\pi') = t + \sum_{r=1}^{x-1} \gamma p_{[r]} + (1+\gamma)p_i - \gamma p_k - d_k \geq 0 \\ \gamma(p_i - p_k) \geq -\left(t + \sum_{r=1}^{x-1} \gamma p_{[r]} + p_i - d_k\right). \end{aligned}$$

If the maximum in the last term is positive, then

$$\begin{aligned} T_{i,k}(\pi) - T_{k,i}(\pi') &= t + \sum_{r=1}^{x-1} \gamma p_{[r]} + (1+\gamma)p_i - \gamma p_k - d_k - t - \sum_{r=1}^{x-1} \gamma p_{[r]} - p_k + d_k \\ &= (1+\gamma)(p_i - p_k) \geq 0. \end{aligned}$$

Therefore, the second case yields $T_{i,k}(\pi) \geq T_{k,i}(\pi')$, too. This completes the proof.

Maximum lateness and maximum tardiness

Both, the single-machine maximum lateness problem, $1//L_{max}$ and the single-machine maximum tardiness problem, $1//T_{max}$ are minimized by the EDD sequence, see Smith (1956) or Baker (1997). The following example shows that the EDD rule does not necessarily lead to an optimal solution for the single-machine maximum lateness problem with past-sequence-dependent setup times:

Example 1.
Let p_1=*100*, p_2=*1*, d_1=*101*, d_2=*102*, *and* λ=*1 than the EDD sequence* ($S = (1,2)$) *leads to* L_{max}=*99 and the sequence* $S = (2,1)$ *leads to* L_{max}=*1.*

Note that the example holds for $1/psd/L_{max}$ as well as $1/psd/T_{max}$. However, the following property can be established:

Property 3. *The EDD sequence leads to an optimal schedule for* $1/psd/L_{max}$ *if the due dates and the processing times are agreeable, i.e. if* $p_i \leq p_k$ *implies* $d_i \leq d_k$.

Proof: Let π be a schedule in which the jobs i and k are sequenced on the positions x and $x+1$, respectively, and let $d_i > d_k$. We will create a new schedule π' by interchanging the jobs i and k.

The completion time of the job on the $(x-1)$-st position is t. Now the lateness of jobs i and k in schedule π can be calculated as:

$$L_i(\pi) = t + s_i + p_i - d_i = t + \sum_{r=1}^{x-1} \gamma p_{[r]} + p_i - d_i$$
$$L_k(\pi) = t + s_i + p_i + s_k + p_k - d_k = t + 2\sum_{r=1}^{x-1} \gamma p_{[r]} + (1+\gamma)p_i + p_k - d_k,$$

Similarily, the lateness of jobs k and i in schedule π' can be calculated as:

$$L_k(\pi') = t + \sum_{r=1}^{x-1} \gamma p_{[r]} + p_k - d_k$$
$$L_k(\pi') = t + 2\sum_{r=1}^{x-1} \gamma p_{[r]} + (1+\gamma)p_k + p_i - d_i,$$

Interchanging the jobs i and k has no impact on the maximum lateness among the first $(x-1)$ jobs. As makespan is minimized by the SPT sequence (see Koulamas and Kyparisis 2006), the maximum lateness among the last $(n-x+1)$ jobs in schedule π' cannot be higher than that of schedule π. To proof the property it is thus sufficient to show that $L_k(\pi) \geq \max\{L_k(\pi'), L_i(\pi')\}$.

$$L_k(\pi) \geq L_k(\pi') \Leftrightarrow \sum_{r=1}^{x-1} \gamma p_{[r]} + (1+\gamma)p_i \geq 0$$
$$L_k(\pi) \geq L_k(\pi') \Leftrightarrow \gamma(p_i - p_k) \geq d_k - d_i$$

As $d_i > d_k$ implies $p_i \geq p_k$, schedule π' is not inferior to schedule π. This completes the proof.

Maximum tardiness T_{max} is defined as $T_{max} = \max\{0, L_{max}\}$. The results of property 3 can be transferred directly to the case of minimizing maximum tardiness on a single machine with past- sequence-dependent setup times. Thus, $1/\text{psd}/T_{max}$ is minimized by the EDD sequence, too, if the due dates and the processing times are agreeable, i.e. if $p_i \leq p_k$ implies $d_i \leq d_k$.

Number of tardy jobs

The number of tardy jobs on a single machine, $1//\Sigma U_i$, can be minimized by the polynomially bounded algorithm presented by Moore (1968). If past-sequence-dependent setup times are included into the analysis, Moore's algorithm does not necessarily deliver optimal results anymore, see the following example:

Example 2.
Let p_1=1, p_2=2, p_3=3,with d_1=12, d_2=11, d_2=10 and λ=1. Moore's algorithm starts with the EDD sequence $(3, 2, 1)$ *and, because job 1 is late, moves job 3 to the set of tardy jobs. As within* $(2, 1, 3)$ *the jobs 2 and 1 are not late, this is the final sequence with job 3 being tardy. However, the SPT sequence* $(1, 2, 3)$ *leads to an optimal schedule without tardy jobs.*

4 Common due date problems

In this section we tackle common due date problems with past-sequence-dependent setup times. An excellent introduction to common due date problems is given by Baker and Scudder (1990), for a literature review see Gordon et al. (2002). For all problems discussed in this section a non-restrictive common due date d is given. A common due date is non-restrictive if it is either a decision variable or if it is sufficiently large; with sufficiently large we mean that $d \geq C_{[n]}$ holds.

We first consider the famous problem of Kanet (1981): $1/\text{psd}, d_i = d/\sum(E_i + T_i)$. Let b denote the number of jobs that are completed before or in the due date and let a denote the number of jobs that are finished after the due date, $a + b = n$. Obviously for the objective function the following holds:

$$f(\pi) = \sum_{i=1}^{n}(E_i + T_i) = \sum_{r=1}^{b} w_r^e p_{[r]} + \sum_{r=b+1}^{n} w_r^t p_{[r]}$$

with $w_r^e = (r - 1 + (n - r)\gamma)$ and $w_r^t = (n - r + 1 + (n - r)\gamma)$.

Property 4. *If $\gamma \leq 1$, for $1/psd, d_i = d/\sum(E_i + T_i)$ an optimal schedule exists that is V-shaped. V-shaped means that the first b jobs are scheduled in non-increasing order of* *their processing times and that the last a jobs are scheduled in non-decreasing order of their processing times.*

Proof: For any $b \in \{1, ..., n\}$ the following holds: $w_r^e \leq w_{r+1}^e, r = 1, ..., b-1$ and $w_r^t \geq w_{r+1}^t, r = b+1, ..., n-1$ if $\gamma \leq 1$. An optimal schedule can be constructed by assigning the longest job to the position with the smallest weight, the second longest job to the position with the second smallest weight (see Hardy et al. 1967, p.261). This leads to a V-shaped schedule as defined above.

Property 5. *If $\gamma \leq 1$, for $1/psd, d_i = d/\sum(E_i + T_i)$ an optimal schedule exists where the b-th job is completed in the due date with $b = \max\{1 \leq r \leq n | r - 1 + (n-r)\gamma \leq n - r + 1 + (n-r)\gamma\}$.*

Proof: Obvious from the objective function and Property 4.

With Property 4 and 5 an optimal solution to $1/\text{psd}, d_i = d/\sum(E_i + T_i)$ with $\gamma \leq 1$ can be constructed as follows: The number of non-tardy jobs b is determined and the weights for the positions are calculated. Then the longest job is assigned to the position with the smallest weight, the second longest job is assigned to the position with the second smallest weight etc. Ties can be broken arbitrarily. This matching procedure requires $O(n \log n)$ time. After constructing the solution as described, either $d = C_{[b]}$ (if d is a decision variable) or the start time of the first job is adjusted to $s_{[1]} = d - \sum_{i=1}^{b}(s_{[i]} + p_{[i]})$ (if a sufficiently large d is given).

With $\gamma > 1$ the analysis becomes slightly more complicated as the problem is no longer V-shaped. Now $w_r^e > w_{r+1}^e$ and $w_r^t > w_{r+1}^t$ holds for non-tardy as well as for tardy jobs. This means that b cannot be determined analytically by Property 5 but depends on the actual value of γ. However, for a given b all weights can be easily calculated and the jobs can be assigned to positions as described above. Therefore a polynomially bounded solution procedure for this case is given by the following Algorithm 1:

Algorithm 1.

```
Step 1: Set $b = 1$.
Step 2: Calculate the positional weights and assign the longest job to the position with the smallest weight, the second longest job to the position with the second smallest weight etc. Ties can be broken arbitrarily. Store the solution.
Step 3: If $b \leq n$ calculate $b := b + 1$ and return to Step 1.
Step 4: The best solution of the $n$ stored solutions is an optimal solution.
```

The Algorithm 1 requires $O(n^2 \log n)$ time. The above analysis can easily be extended to all common due date problems that consist of positional weights. These are:

- Different but not job-individual earliness and tardiness penalties α and β.

  $$f(\pi_I) = \sum_{i=1}^{n}(\alpha E_i + \beta T_i) = \sum_{r=1}^{b} w_{I,r}^{e} p_{[r]} + \sum_{r=b+1}^{n} w_{I,r}^{t} p_{[r]}$$

  with $w_{I,r}^{e} = (r-1)\alpha + (n-r)\gamma$ and $w_{I,r}^{t} = (n-r+1)\beta + (n-r)\gamma$.

- A penalty for assigning a late due date χ.

  $$f(\pi_{II}) = \sum_{i=1}^{n}(\alpha E_i + \beta T_i + \chi d) = \sum_{r=1}^{b} w_{II,r}^{e} p_{[r]} + \sum_{r=b+1}^{n} w_{II,r}^{t} p_{[r]}$$

  with $w_{II,r}^{e} = (r-1)\alpha + n\chi + (n-r)\gamma$ and $w_{II,r}^{t} = (n-r+1)\beta + n\chi + (n-r)\gamma$.

- A penalty on the completion time of the jobs θ.

  $$f(\pi_{III}) = \sum_{i=1}^{n}(\alpha E_i + \beta T_i + \theta C_i) = \sum_{r=1}^{b} w_{III,r}^{e} p_{[r]} + \sum_{r=b+1}^{n} w_{III,r}^{t} p_{[r]}$$

  with $w_{III,r}^{e} = (r-1)\alpha + (n-r-1)\theta + (n-r)\gamma$ and $w_{III,r}^{t} = (n-r+1)\beta + (n-r-1)\theta + (n-r)\gamma$.

These three extension remain polynomially solvable as Algorithm 1 delivers an optimal solution for each of them.

5 Conclusion

In this paper we considered single-machine scheduling problems with past-sequence-dependent setup times and due dates. We were able to show that some problems remain polynomially solvable while for other problems well-known solution procedures are no longer valid. .

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