"SINGLE MACHINE SCHEDULING TO MINIMIZE TOTAL LATE WORK"

by

Luk N. VAN WASSENHOVE*
and
C. N. POTTS**

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* Professor of Operations Management and Operations Research, INSEAD, Boulevard de Constance, Fontainebleau 77305, Cedex, France.

** Faculty of Mathematical Studies, University of Southampton, Southampton, England.

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SINGLE MACHINE SCHEDULING TO MINIMIZE TOTAL LATE WORK

C.N. POTTS
Faculty of Mathematical Studies, University of Southampton, U.K.

L.N. VAN WASSENHOVE
INSEAD, Fontainebleau, France

Abstract

In the problem of scheduling a single machine to minimize total late work, there are n jobs to be processed for which each has an integer processing time and a due date. The objective is to minimize the total late work, where the late work for a job is the amount of processing of this job that is performed after its due date. For the preemptive total late work problem, an $O(n \log n)$ algorithm is derived. The non-preemptive total late work problem is shown to be NP-hard, although efficient algorithms are derived for the special cases in which all processing times are equal and in which all due dates are equal. A pseudopolynomial dynamic programming algorithm is presented for the general non-preemptive total late work problem; it requires $O(n\text{UB})$ time, where UB is any upper bound on the total late work. Computational results for problems with up to 10000 jobs are given.

The problem of scheduling a single machine to minimize total late work may be stated as follows. Each of n jobs (numbered $1,\ldots,n$) is to be processed on a single machine which can handle only one job at a time. Job i ($i=1,\ldots,n$) becomes available for processing at time zero, requires a positive integer *processing time* p_i and has a positive integer *due date* d_i. We assume that jobs are numbered in non-decreasing order of their due dates (EDD order) so that $d_1 \leq \ldots \leq d_n$. In the preemptive version of this problem processing may be interrupted and resumed at a later time, but in the non-preemptive problem no interruption in the processing of a job is allowed. Given a schedule σ, the *late work* $V_i(\sigma)$ for job i ($i=1,\ldots,n$), which is the amount of processing performed on i after its due date d_i, is easily computed. When no ambiguity results, we abbreviate $V_i(\sigma)$ to V_i. If $V_i=0$, then job i is *early*; if $0<V_i<p_i$, then job i is *partially early*; alternatively if $V_i=p_i$, then job i is *late*. We refer to p_i-V_i as *early work* for job i. The objective is to schedule the jobs so that the total late work $\sum_{i=1}^{n} V_i$ is minimized.

Problems which involve the scheduling of jobs with due dates on a single machine to minimize total cost have been widely studied in the literature. Two of these are related to the non-preemptive total late work problem. In the *total tardiness problem*, the cost of scheduling job i ($i=1,\ldots,n$) to be completed at time C_i is given by its tardiness $T_i=\max\{C_i-d_i,0\}$. Clearly, $V_i=\min\{T_i,p_i\}$ for non-preemptive scheduling. An effective decomposition algorithm that solves total tardiness problems with up to 100 jobs is given by Potts and Van Wassenhove (1982). It is based on some earlier results of Lawler (1977) which were used to derive a pseudopolynomial dynamic programming algorithm. In the *weighted number of late jobs problem*, the cost associated with job i is w_iU_i, where $U_i=1$ if $C_i>d_i$ and $U_i=0$ otherwise; w_i is a non-negative weight for job i. A pseudopolynomial dynamic programming algorithm for this (binary) NP-hard problem is given by Lawler and Moore (1969). Potts and Van Wassenhove (1988) present dynamic programming and branch and bound algorithms that solve weighted number of late jobs problems with up to 1000 jobs.

An application of the total late work problem occurs in information processing. In this context, a job is a message carrying an amount of information proportional to its length. All information received after a given due date is useless and is referred to as information loss. The total late work problem is originally presented in this setting by Blazewicz (1984) who considers parallel processors in a computing environment. He shows that the problem of preemptively scheduling jobs with release dates on identical parallel machines to minimize total weighted late work can be solved in polynomial time using linear programming. Because of this application, Blazewicz coined the problem as that of information loss.

A second example of the problem occurs when samples are to be taken or data are to be collected for processing by some data logging system in a computer controlled manufacturing system environment (CIM, FMS). The adaptive control system can only use data or samples collected before computations are started. Exceeding this due date causes the loss of all information which is not yet available and this reduces the precision of the estimate (which entails a cost).

We suggest the use of the term *total late work* problem rather than *information loss* problem as suggested by Blazewicz, in order to emphasize that applications can arise in any situation where a perishable commodity is involved. Clearly, information is one obvious example. Another is to be found in agriculture. For instance, consider different stretches of land to be harvested by a single harvester. Any part of the crop not gathered by a given date (which differs according to the site) can no longer be used. Minimizing total late work in this case corresponds to minimizing the quantity of wasted crop.

This paper is organized as follows. Section 1 deals with the preemptive problem, while the remainder of the paper assumes that preemption is not allowed. Section 2 establishes NP-hardness of the non-preemptive problem. In Section 3, we derive some important structural properties of the problem which are useful for restricting the search in enumerative algorithms. Section 4 describes some special cases for which polynomial time algorithms are available. In Section 5, we derive a pseudopolynomial dynamic programming algorithm and describe how it can be successfully implemented. A heuristic method which can usefully be applied prior to the dynamic programming algorithm is described in Section 6. Section 7 reports on computational experience with problems which have up to 10000 jobs. Finally, some concluding remarks are contained in Section 8.

1. The Preemptive Problem

In this section, we consider the problem of preemptively scheduling the jobs to minimize the total late work. Recall that jobs are renumbered in EDD order. Our *preemptive scheduling algorithm* first applies results of Jackson (1955) to obtain the minimum value of the maximum tardiness from the EDD sequence $(1,\ldots,n)$ using

$$T_{max} = \max\{\max_{i=1,\ldots,n}\{\sum_{h=1}^{i} p_h - d_i\},0\}. \tag{1}$$

If $T_{max}=0$, then $(1,\ldots,n)$ is an optimal sequence for which the total late work is zero.

Alternatively, if $T_{max}>0$, a preemptive schedule is constructed by repositioning after job n the first T_{max} units of processing from the sequence $(1,\ldots,n)$. More precisely, if job i is chosen so that $\sum_{h=1}^{i-1} p_h < T_{max} \leq \sum_{h=1}^{i} p_h$, then in the preemptive schedule, $\sum_{h=1}^{i} p_h - T_{max}$ units of processing of job i are scheduled first, followed by all processing on jobs $i+1,\ldots,n,1,\ldots,i-1$ respectively and finally the remaining $T_{max} - \sum_{h=1}^{i-1} p_h$ units of processing of job i. In this schedule, all processing not repositioned is scheduled T_{max} units earlier than in the sequence $(1,\ldots,n)$ and will therefore be early work, while the repositioned processing defines T_{max} units of late work. The total late work for this preemptive schedule is T_{max}.

It is apparent that the preemptive scheduling algorithm generates at most one preemption. The schedule is constructed in $O(n)$ time once an EDD sequence is known. However, the time requirement of the algorithm is $O(n \log n)$ because an EDD sequence has to be found.

We show next that the preemptive scheduling algorithm generates an optimal schedule.

Theorem 1. The preemptive scheduling algorithm generates an optimal schedule for which the total late work is T_{max}.

Proof. If $T_{max}=0$, it is clear that the result holds. Thus, we consider the case $T_{max}>0$, for which we deduce from (1) that

$$T_{max} = \sum_{i=1}^{j} p_i - d_j$$

for some job j. A lower bound on the minimum total late work is obtained by increasing due dates, where necessary, so that jobs $1,\ldots,j$ each have due date d_j. Considering only jobs $1,\ldots,j$, we obtain $\sum_{i=1}^{j} p_i - d_j = T_{max}$ as our lower bound. It is clear that the preemptive scheduling algorithm generates a schedule with total late work equal to T_{max}. Since this value of the total late work is equal to the lower bound, the schedule is optimal. □

We note that the preemptive scheduling algorithm is valid if processing times and due dates are arbitrary positive real numbers.

2. Complexity of the Non-Preemptive Problem

In this section, we establish that the non-preemptive total late work problem is NP-hard.

Theorem 2. The non-preemptive total late work problem is NP-hard.

Proof. The decision version of the scheduling problem is: Given a set of n jobs and an integer K, does there exist a schedule for which the total late work does not exceed K? It is apparent that this problem is in NP. We show that it is NP-complete by transformation from the known NP-complete problem KNAPSACK (Karp 1972), also known as SUBSET SUM): Given positive integers a_i $(i=1,\ldots,n)$ and b, is there a subset of the a_i's whose sum exactly equals b? Given any instance of KNAPSACK, construct the following instance of the non-preemptive total late work problem. There are $n+1$ jobs with $p_i=a_i$ and $d_i=b$ for $i=1,\ldots,n$, $p_{n+1}=1$ and $d_{n+1}=b+1$. Let $K=\sum_{i=1}^{n} a_i - b$. We show that there exists a subset of the a_i's summing exactly to b if and only if there is a schedule with total late work not exceeding K. If there is a subset of the a_i's summing to exactly b, then place the corresponding jobs in the first part of the sequence, followed by job $n+1$. This yields a sequence for which the total late work is exactly K. If there is a sequence for which the total late work does not exceed K, then job $n+1$ must have start time b in such a schedule. The jobs preceding job $n+1$ correspond to a subset of the a_i's that sums to exactly b. □

3. Properties of the Non-Preemptive Problem

Henceforth, we restrict our attention to the non-preemptive total late work problem. For this problem, an optimal solution is specified by a sequence of early and partially early jobs; any late jobs can be appended to this sequence in an arbitrary order.

In this section, we first derive lower and upper bounds on the minimum non-preemptive total late work V^* expressed in terms of T_{max}, defined by (1), and the maximum processing time

$$p_{max} = \max_{i=1,\ldots,n}\{p_i\}.$$

Theorem 3. $T_{max} \le V^* \le \min\{nT_{max}, T_{max}+p_{max}-1\}$.

Proof. A lower bound on V^*, obtained by allowing preemption and using Theorem 1, is $V^* \ge T_{max}$. Also, for the EDD sequence $(1,\ldots,n)$, we have $V_i \le T_i \le T_{max}$ for $i=1,\ldots,n$, which yields the upper bound $V^* \le \sum_{i=1}^{n} V_i \le nT_{max}$.

It remains to establish the upper bound $V^* \le T_{max}+p_{max}-1$. Consider the solution of the preemptive problem given by our preemptive scheduling algorithm. If this schedule contains no preempted job, then we have a non-preemptive schedule with total late work equal to T_{max}. In this case, $V^* \le T_{max}$ which implies $V^* \le T_{max}+p_{max}-1$. Alternatively, suppose that the schedule contains a preempted job j. Consider the sequence $(j+1,\ldots,n,1,\ldots,j)$ obtained from the preemptive schedule by repositioning the non-late units of processing for job j so that they become late. Since at most p_j-1 units are repositioned, the total late work for this sequence is at most $T_{max}+p_j-1$. This implies the upper bound $V^* \le T_{max}+p_{max}-1$. □

It is possible to strengthen the upper bound of Theorem 3. Let V_{max} be the minimum value of the maximum late work, obtained by applying the algorithm of Lawler (1973). For the sequence obtained from Lawler's algorithm, we have $\sum_{i=1}^{n} V_i \le nV_{max}$. Incorporating the upper bound $V^* \le nV_{max}$ into Theorem 3, yields the inequality

$$T_{max} \le V^* \le \min\{nV_{max},\ T_{max}+p_{max}-1\},$$

which is a stronger result than Theorem 3 because $V_{max} \le T_{max}$.

We note that the lower bound of Theorem 3 is achieved when a non-preemptive schedule is generated by our preemptive scheduling algorithm. The following instance also verifies that the upper bounds are the best possible. The processing time and due date for job i $(i=1,\ldots,n)$ are $p_i=p$ and $d_i=ip-1$, where p is any positive integer satisfying $p \le n$. The EDD sequence $(1,\ldots,n)$ yields $T_{max}=1$. Also $(2,\ldots,n,1)$ is an optimal sequence with $\sum_{i=1}^{n} V_i^* = p$. Therefore, $\sum_{i=1}^{n} V_i^* = p = T_{max}+p_{max}-1$. Furthermore, when $p=n$ we have $\sum_{i=1}^{n} V_i^* = n = nT_{max}$. This shows that both upper bounds are achieved.

For the problem of scheduling jobs on a single machine to minimize the (weighted) number of late jobs, it is well-known that in an optimal schedule the early jobs are sequenced first in EDD order followed by the late jobs sequenced in an arbitrary order. An analogous result is proved below for our total late work problem.

Theorem 4. There exists an optimal solution of the non-preemptive total late work problem in which the set of early and partially early jobs are sequenced first in EDD order followed by the late jobs sequenced arbitrarily.

Proof. Let σ be an optimal sequence. We show that a finite sequence of transformations of σ, each of which does not increase the total late work, yields a sequence that satisfies the conditions of the theorem. We observe that any late job in σ which precedes an early or partially early job can be moved to the last position in the sequence without increasing the total late work. Thus, we may assume that $\sigma = \sigma_1 \sigma_2$, where σ_1 is an initial partial sequence of early and partially early jobs and σ_2 is an arbitrarily ordered final partial sequence of late jobs.

Suppose that the jobs of σ_1 are not in EDD order. Let k and j be jobs of σ_1 such that k immediately precedes j and $d_k > d_j$ and let σ' be the sequence obtained from σ by interchanging k and j. We now establish that $\sum_{i=1}^{n} V_i(\sigma') \leq \sum_{i=1}^{n} V_i(\sigma)$ by showing $V_j(\sigma') + V_k(\sigma') \leq V_j(\sigma) + V_k(\sigma)$. Let t denote the start time of the first of the jobs j and k. If j is early in σ', then $V_j(\sigma') = 0$ and $V_j(\sigma') + V_k(\sigma') \leq T_k(\sigma') = \max\{t + p_j + p_k - d_k, 0\}$. Also, since j is not late in σ, we have $V_j(\sigma) + V_k(\sigma) \geq V_j(\sigma) = \max\{t + p_k + p_j - d_j, 0\}$. Using $d_k > d_j$, we deduce that $V_j(\sigma') + V_k(\sigma') \leq V_j(\sigma) + V_k(\sigma)$ in this first case. Alternatively, if j is partially early in σ', then $V_j(\sigma') = t + p_j - d_j$. In this case, j is also partially early in σ and $V_j(\sigma) + V_k(\sigma) \geq V_j(\sigma) = t + p_k + p_j - d_j$. Thus, $V_j(\sigma) + V_k(\sigma) \geq V_j(\sigma') + p_k \geq V_j(\sigma') + V_k(\sigma')$, where the last inequality holds by the definition of late work. We have now established that $V_j(\sigma') + V_k(\sigma') \leq V_j(\sigma) + V_k(\sigma)$ in both cases, which shows that σ' is an optimal sequence. If job k is late in σ', then it is moved to the last position and the resulting sequence is optimal. By repeating this argument, an optimal schedule satisfying the conditions of the theorem is obtained after a finite sequence of transformations of σ. □

Theorem 4 is an extremely powerful result because the sequencing element of the problem can be eliminated. If a set of jobs which are to be early or partially early is specified, then a schedule can be constructed by sequencing these jobs in EDD order and then appending the remaining jobs. An optimal schedule could, in theory, be found by considering each of 2^n possible sets, sequencing the jobs within each set in EDD order and evaluating those sequences which contain only early and partially early jobs.

4. Special Cases

Since our problem is NP-hard, it is of interest to study special cases in an attempt to locate the exact boundary between "easy" and "hard" problems. Firstly, the case of equal due dates is considered for which $d_i = d$ for $i = 1,\ldots,n$, where d is a positive integer. For any ordering of the jobs the total late work is equal to $\max\{\sum_{i=1}^{n} p_i - d, 0\}$. Thus, any job sequence specifies an optimal schedule.

Our other special case is that of equal processing times for which $p_i = p$ for $i = 1,\ldots,n$, where p is a positive integer. The following result restricts the search for an optimal solution to at most two possible schedules. Recall that jobs are numbered in EDD order.

Theorem 5. For the case of equal processing times, either the sequence $(u+1,\ldots,n,1,\ldots,u)$ or the sequence $(u'+1,\ldots,n,1,\ldots,u')$ is optimal for $u = \lfloor T_{max}/p \rfloor$ and $u' = \lceil T_{max}/p \rceil$, where T_{max} is the maximum tardiness for the EDD sequence $(1,\ldots,n)$.

Proof. Consider any two jobs j and k with $j<k$ (implying $d_j \le d_k$). We claim first that schedules in which job j is early or partially early and job k is late need not be considered. This claim is justified by observing that jobs j and k in such a schedule may be interchanged without increasing the total late work. Using the result of our claim and Theorem 4, we deduce that at least one optimal schedule is of the form $(j,\ldots,n,1,\ldots j-1)$ for some j $(j=1,\ldots,n)$, where $j,\ldots,n$ are the early and partially early jobs sequenced in EDD order and jobs $1,\ldots,j-1$ are late. We need to show that $j = u+1$ or $j = u'+1$. When $T_{max} = 0$, then the result holds because $(1,\ldots,n)$ is an optimal sequence with zero total late work. It is sufficient to concentrate on the case $T_{max} > 0$, therefore. If $j = u'+1$, then clearly jobs $u'+1,\ldots,n$ will be early and all other jobs will be late giving $\sum_{i=1}^{n} V_i = pu'$, but if $j > u'+1$, then $\sum_{i=1}^{n} V_i > pu'$ which cannot correspond to an optimal schedule. To complete the proof we show that j values satisfying $j \le u$ cannot correspond to an optimal schedule. Using (1) we may assume that $T_{max} = pk - d_k$ for some job k. We observe that $u<k$ because $pu \le T_{max} = pk - d_k < pk$. When $j \le u$, we have a sequence of the form $(j,\ldots,k,\ldots,n,1,\ldots,j-1)$. In this sequence job k is late because its start time cannot be less than $p(k-u)$ which, in turn, cannot be less than d_k because $p(k-u) - d_k = T_{max} - pu \ge 0$. Thus, job k is late which invalidates $(j,\ldots,k,\ldots,n)$ as an initial partial sequence of early and partially early jobs when $j \le u$. Since the j values satisfying $j \le u$ and $j \ge u'+2$ can be eliminated in the search for an optimal schedule, the only possibilities that remain are $j = u+1$ and $j = u'+1$. □

We now discuss the computational complexity of the algorithm implied by Theorem 5 for the case of equal processing times. It requires $O(n \log n)$ time to renumber the jobs in EDD order. To evaluate the two sequences given in Theorem 5 and select the one which is better requires $O(n)$ time. Therefore, the non-preemptive total late work problem for the case of equal processing times can be solved in $O(n \log n)$ time.

Lastly, we note that the algorithms of this section remain valid if the processing times and due dates are positive real numbers.

5. A Dynamic Programming Algorithm

In this section, we derive a pseudopolynomial dynamic programming algorithm for the non-preemptive total late work problem. This algorithm relies on the result of Theorem 4 that early and partially early jobs are sequenced in EDD order. Our dynamic programming algorithm is very much in the same spirit as that of Lawler and Moore for the problem of minimizing the weighted number of late jobs on a single machine. In both algorithms, each job is considered in EDD order and two decisions are possible: either it is late and occupies no machine time (until all early and partially early jobs are completed), or it is early or partially early and requires machine time. The dynamic programming recursion is defined on variables $f_j(t)$ which represent the minimum total late work incurred when scheduling jobs $1,\ldots,j$ so that the last early or partially early job is completed at time t. Since all early and partially early jobs amongst $1,\ldots,j$ are completed by time $b_j = \min\{\sum_{i=1}^{j} p_i, \max_{i=1,\ldots,j}\{d_i+p_i-1\}\}$, $f_j(t)$ is defined for $j=1,\ldots,n$ and $t=0,\ldots,b_j$. The recursion is

$$
\begin{aligned}
f_j(t) &= \min\{f_{j-1}(t-p_j)+\max\{t-d_j,0\}, f_{j-1}(t)+p_j\} && \text{for } t < d_j+p_j \\
f_j(t) &= f_{j-1}(t)+p_j && \text{for } t \ge d_j+p_j
\end{aligned}
\tag{2}
$$

where $f_0(0)=0$ and all other initial values are set to infinity. The case that $f_j(t)=f_{j-1}(t-p_j)+\max\{t-d_j,0\}$ corresponds to the decision that job j is early or partially early, whereas the case that $f_j(t)=f_{j-1}(t)+p_j$ corresponds to the decision that job j is late.

Equation (2) is used to compute $f_j(t)$ for $j=1,\ldots,n$ and $t=0,\ldots,b_j$ after which the minimum total late work is given by $\min_{t=0,\ldots,b_n}\{f_n(t)\}$. Since the recursion is solved for n values of j and at most b_n+1 values of t, the time requirement of the dynamic programming algorithm is $O(n \min\{\sum_{i=1}^{n} p_i, \max_{i=1,\ldots,n}\{d_i+p_i\}\})$.

To improve the efficiency of the dynamic programming algorithm, we describe two devices by which computation time and storage space may be saved. The first device produces a saving through *redundant state elimination.* Let UB denote any upper bound on the minimum total late work. We assume that UB>0; otherwise, the EDD sequence provides an optimal solution with $V^*=T_{max}=0$. For jobs $1,\ldots,j$, if t denotes the completion time of the last early or partially early job, then the total late work is at least $\sum_{i=1}^{j} p_i-t$. To obtain a solution value of UB or less, the total late work for jobs $1,\ldots,j$ must be less than or equal to UB, so $\sum_{i=1}^{j} p_i-t\le \text{UB}$. The states corresponding to $t<\sum_{i=1}^{j} p_i-\text{UB}$, therefore, may be eliminated. We have shown that, to obtain an optimal solution, recursion equations (2) are solved for $j=1,\ldots,n$ and $t=a_j,\ldots,b_j$, where $a_j=\max\{\sum_{i=1}^{j} p_i-\text{UB},0\}$ and $b_j\le \sum_{i=1}^{j} p_i$. Alternative bounds on the time complexity can now be given. The maximum number of t values for which we compute $f_j(t)$ is UB$+1$. Therefore, at most $n(\text{UB}+1)$ recursion equations (2) are solved, to give a time complexity of $O(n\text{UB})$. Furthermore, using the upper bounds of Theorem 3, the time complexity can be expressed as $O(n^2T_{max})$ or $O(n(T_{max}+p_{max}))$.

Our second device for improving efficiency involves *termination tests.* The main idea of such a test is that if during the course of performing the recursion it becomes apparent how to generate a schedule having total late work equal to some lower bound, then such a schedule is necessarily optimal and no further recursion equations need to be solved. For each job i, let τ_i denote the latest start time of job i (which may be negative) such that jobs $i,\ldots,n$ are each completed by their due date. We compute $\tau_1,\ldots,\tau_n$ in

$O(n)$ time by applying the backward recursion

$$\tau_i = \min\{\tau_{i+1}, d_i\} - p_i,$$

where $\tau_n = d_n - p_n$. It is also convenient to compute recursively

$$u_i = \begin{cases} u_{i+1} & \text{if } \tau_{i+1} \leq d_i, \\ i & \text{if } \tau_{i+1} > d_i, \end{cases}$$

where $u_n = n$, so that $\tau_i = d_{u_i} - \sum_{h=i}^{u_i} p_h$. Similarly, let τ_i' denote the latest start time of job i such that at most one of the jobs $i,\ldots,n$ is completed after its due date. The values $\tau_i',\ldots,\tau_n'$ are also computed in $O(n)$ time from the backward recursion

$$\tau_i' = \max\{\tau_{i+1}, \min\{\tau_{i+1}', d_i\}\} - p_i,$$

where $\tau_n' = \infty$. From these definitions, if job i ($i = 1,\ldots,n-1$) starts at time t, where $\tau_i \leq t \leq \tau_i'$, then the total late work for jobs $i,\ldots,n$ is $t - \tau_i$.

Before providing details of our termination tests, it is convenient to define a non-decreasing sequence of lower bounds on the total late work which are computed during the course of solving the dynamic programming recursion. The initial lower bound $\mathrm{LB}_0 = T_{max}$ is obtained from Theorem 3. Thereafter, the lower bound LB_j, for $j = 1,\ldots,n-1$, is computed from the values $f_j(a_j),\ldots,f_j(b_j)$ as follows. Clearly, $f_j(t)$ is the value of an optimal partial schedule for some value of t ($t = a_j,\ldots,b_j$). By considering jobs $j+1,\ldots,u_{j+1}$, a lower bound on the total late work for jobs $j+1,\ldots,n$, when the first early or partially early job starts at time t, is given by the smaller of the maximum tardiness and the total processing time of these jobs: it is computed using

$$\mathrm{LB}(j,t) = \begin{cases} 0 & \text{if } t \leq \tau_{j+1}; \\ t - \tau_{j+1} & \text{if } \tau_{j+1} < t \leq d_{u_{j+1}}; \\ d_{u_{j+1}} - \tau_{j+1} & \text{if } t > d_{u_{j+1}}. \end{cases}$$

It is now apparent that a valid lower bound is given by

$$\mathrm{LB}_j = \min_{t=a_j,\ldots,b_j}\{f_j(t) + \mathrm{LB}(j,t)\}.$$

We note that the time complexity of the dynamic programming algorithm remains $O(n\mathrm{UB})$ after the addition of these bounding computations.

Our *first termination tests* $T_1(j,k,t)$ are defined for pairs of jobs j and k, where $j < k$, and $t = a_j,\ldots,\tau_k$. Corresponding to each such value (j,k,t) is a schedule with total late work equal to $f_j(t) + \sum_{i=j+1}^{k-1} p_i$. In this schedule, early and partially early jobs amongst $1,\ldots,j$, as defined by the dynamic programming algorithm, finish at time t, jobs $j+1,\ldots,k-1$ are late, and jobs $k,\ldots,n$ are scheduled to start at time t (by the definition of τ_k, jobs $k,\ldots,n$ are early). Thus if $f_j(t) + \sum_{i=j+1}^{k-1} p_i = \mathrm{LB}_j$ for some t $(t = a_j,\ldots,\tau_k)$, then a schedule is identified that has total late work which is equal to the lower bound LB_j, so $T_1(j,k,t)$ terminates the dynamic programming algorithm and outputs this optimal solution; otherwise, no conclusion is drawn from $T_1(j,k,t)$.

Our implementation of these first termination tests is as follows. Having computed $f_j(t)$ for $t = a_j,\ldots,b_j$ and LB_j, we apply test $T_1(j,j+1,t)$ for $t = a_j,\ldots,\min\{\tau_{j+1},b_j\}$. If this does not terminate the algorithm, $T_1(j,k,t)$ is applied for $k = j+2,\ldots,n$ and $t = \max\{\tau_{k-1}+1,a_j\},\ldots,\min\{\tau_k,b_j\}$. To justify that tests $T_1(j,k,t)$, where $k = j+2,\ldots,n$ and $t = a_j,\ldots,\tau_{k-1}$, cannot terminate the algorithm, we observe that if $f_j(t) + \sum_{i=j+1}^{k-1} p_i = \mathrm{LB}_j$, then $f_j(t) + \sum_{i=j+1}^{k-2} p_i < \mathrm{LB}_j$. This inequality indicates the existence of a schedule (where jobs $j+1,\ldots,k-2$ are late and jobs $k-1,\ldots,n$ are early) which has total late work of less than LB_j, thereby contradicting the lower bound. Since $\tau_1 < \tau_2 < \ldots < \tau_n$, for each j $(j = 1,\ldots,n)$, at most one test is applied for each value of t $(t = a_j,\ldots,b_j)$. Recalling that $b_j - a_j \le \mathrm{UB}$, we deduce that our first elimination test requires $O(n\mathrm{UB})$ time.

Our *second elimination tests* $T_2(j,k,t)$ are similar to the first. For each pair of jobs j and k, where $j < k$, and $t = \tau_k+1,\ldots,\tau'_k$, $T_2(j,k,t)$ evaluates the total late work for the schedule in which early and partially early jobs amongst $1,\ldots,j$ .finish at time t, jobs $j+1,\ldots,k-1$ are late and jobs $k,\ldots,n$ are scheduled to start at time t. In this schedule, by the definition of τ_k and τ'_k, the late work for one of the jobs $k,\ldots,n$ is $t-\tau_k$ and the late work for the others is zero. Thus, if $f_j(t)+\sum_{i=j+1}^{k-1} p_i+t-\tau_k=\mathrm{LB}_j$, then $T_2(j,k,t)$ terminates computations and outputs this optimal schedule; otherwise, $T_2(j,k,t)$ fails to terminate the algorithm.

We complete the specification of the algorithm by describing our implementation of the second termination tests. Firstly, $T_2(j,j+1,t)$ is applied for $t=\max\{\tau_{j+1}+1,a_j\},\ldots,\min\{\tau'_{j+1},b_j\}$. If these tests fail to terminate the algorithm, we apply $T_2(j,k,t)$ for $k=j+2,\ldots,n$ and $t=\max\{\tau'_{k-1}+1,\tau_k+1,a_j\},\ldots,\min\{\tau'_k,b_j\}$. We claim that $T_2(j,k,t)$ is redundant when $k=j+2,\ldots,n$ and $t=\max\{\tau_k+1,a_j\},\ldots,\min\{\tau'_{k-1},b_j\}$. Our claim applies only when $\tau_k\le d_{k-1}$, since for the case that $\tau_k>d_{k-1}$, we have $\tau'_{k-1}=\max\{\tau_k,\min\{\tau'_k,d_{k-1}\}\}-p_{k-1}=\tau_k-p_{k-1}<\tau_k$. Thus, in the justification of our claim, we assume that $\tau_k\le d_{k-1}$, or equivalently, $\tau_{k-1}=\tau_k-p_{k-1}$. If test $T_2(j,k,t)$, which we claim to be redundant, terminates the algorithm, then $f_j(t)+\sum_{i=j+1}^{k-1} p_i+t-\tau_k=\mathrm{LB}_j$. Substituting $\tau_{k-1}=\tau_k-p_{k-1}$ yields $f_j(t)+\sum_{i=j+1}^{k-2} p_i\ +t-\tau_{k-1}=\mathrm{LB}_j$, which demonstrates that test $T_2(j,k-1,t)$ is successful. If, according to our claim, $T_2(j,k-1,t)$ is also redundant, the entire argument is repeated until a successful non-redundant test $T_2(j,h,t)$ is found with $j+1<h<k$ and $\tau'_{h-1}<t\le\tau'_h$, or with $h=j+1$ and $t\le\tau'_{j+1}$. We have now established our claim. Since $\tau'_1<\tau'_2<\ldots<\tau'_n$, for each j $(j=1,\ldots,n)$, at most one test is applied for each value of t $(t=a_j,\ldots,b_j)$. Thus, our second elimination test also requires $O(n\mathrm{UB})$ time.

The above analysis shows that, after the addition of these termination tests, our algorithm still requires $O(n\mathrm{UB})$ time. Although further tests based on these ideas are possible, initial computational experiments indicate these two tests are usually strong enough to terminate computations at an early stage.

6. A Heuristic Method

Prior to applying the dynamic programming algorithm, it is advantageous to use a heuristic method to schedule the jobs. The possible benefits are that the heuristic may generate a solution with total late work equal to its initial lower bound T_{max}, in which case the problem is solved. Furthermore, even if the upper bound UB given by the heuristic exceeds T_{max}, from the arguments in Section 5, the value UB restricts the number of state variables t in the dynamic programming algorithm.

Our heuristic method firstly partitions the jobs into subsets E, E', L and L'. The initial choice of these subsets is described later. At each stage of the method, a sequence with the following characteristics is defined. The jobs of E are sequenced first in EDD order and each is early; the jobs of E' are sequenced next in EDD order and each is early except at most one which is partially early. The jobs of L and L' are late and are sequenced in an arbitrary order at the end of the schedule. Set E' remains fixed throughout, although the method transfers jobs from L to E and from L to L'.

Jobs are transferred from L in non-decreasing order of processing times. Subject to retaining the required characteristics of the schedule defined by the subsets, a job is transferred from L to E. If it cannot be added to E, it is transferred to L'. Transfer of jobs continues either until a schedule is generated with total late work equal to T_{max}, in which case the algorithm terminates with an optimal schedule, or until $L=\emptyset$.

Up to four iterations are performed, each with a different initial choice of subsets. The initial choice of subsets is based on the solution of the preemptive problem. If there is no preempted job, then we have an optimal non-preemptive schedule. Otherwise, some job j is preempted and the following choices of subsets are used:

$$E=\emptyset,\ E'=\{j+1,\dots,n\},\ L=\{1,\dots,j\},\ L'=\emptyset;$$
$$E=\emptyset,\ E'=\{j+2,\dots,n\},\ L=\{1,\dots,j\},\ L'=\{j+1\};$$
$$E=\emptyset,\ E'=\{j+3,\dots,n\},\ L=\{1,\dots,j+1\},\ L'=\{j+2\};$$
$$E=\emptyset,\ E'=\{j+4,\dots,n\},\ L=\{1,\dots,j+2\},\ L'=\{j+3\}.$$

(If $j>n-3$, fewer iterations are performed.) Although other choices of subsets are possible, initial computational results indicate that additional iterations are not worthwhile. If no schedule with value T_{max} is found, the best of the schedules obtained when $L=\emptyset$ is selected. This heuristic method requires $O(n^2)$ time.

Computational results when our heuristic method is first applied and then, if necessary, the dynamic programming algorithm is used, are shown in the next section.

7. Computational Experience

Our aim in this section is to assess the effectiveness of the dynamic programming algorithm in solving large problems. The algorithm was first tested on *standard* problems with numbers of jobs ranging from $n = 1000$ to $n = 10000$ in steps of 1000, which were generated as follows. For each job i an integer processing time p_i was generated from the uniform distribution [1,100]. The "hardness" of a problem is likely to depend on the values of the due dates relative to the processing times. Two parameters d^l and d^u were chosen to provide lower and upper bounds on the relative values of the due dates. Having selected d^l and d^u and having computed $P = \sum_{i=1}^{n} p_i$, an integer due date was generated from the uniform distribution $[Pd^l, Pd^u]$ for each job i. For each value of n, five problems were generated for each of the 15 pairs of values d^l and d^u, where $d^l \in \{0.0, 0.2, 0.4, 0.6, 0.8\}$, $d^u \in \{0.2, 0.4, 0.6, 0.8, 1.0\}$ and $d^l < d^u$. This yields 75 problems for each value of n.

Our algorithm, which first applies the heuristic method and then, if necessary, uses dynamic programming, was coded in FORTRAN 77 and run on a IBM 3090 computer. Computational results for the standard test problems are given in the left half of Table 1. Average computation times in seconds and numbers of problems solved by the heuristic method with total late work equal to T_{max} are listed. Also, considering only those problems which are not solved by the heuristic method, the average and maximum number of iterations performed by the dynamic programming recursion are listed, where an iteration refers to the computation, for some job j, of $f_j(t)$ for all necessary t values.

Our first observation from Table 1 is that all standard test problems are solved with fairly small computation times. These encouraging results are partly explained by the success of the heuristic method in solving problems

Table 1: Computational results

Standard problems					Adjusted problems				
n	ACT	NSH	ANI	MNI	n	ACT	NSH	ANI	MNI
1000	0.10	69	6	9	100	0.43	40	45	100
2000	0.21	72	5	6	200	1.92	40	101	190
3000	0.34	67	9	37	300	3.16	49	154	292
4000	0.46	69	7	13	400	3.57	52	170	369
5000	0.61	71	9	13	500	8.65	53	280	487
6000	0.75	63	8	21	600	11.56	52	319	586
7000	0.88	69	21	97	700	15.18	47	334	640
8000	1.00	70	8	17	800	26.32	46	439	789
9000	1.20	69	16	26	900	28.92	48	464	897
10000	1.32	69	10	17	1000	31.26	53	544	949

ACT: average computation time in seconds.

NSH: number of problems solved by the heuristic method (out of 75).

ANI: average number of iterations performed by the dynamic programming algorithm for problems not solved by the heuristic method.

MNI: maximum number of iterations performed by the dynamic programming algorithm.

by generating a solution with total late work equal to T_{max}, thereby avoiding the need to apply dynamic programming; over 90% of standard test problems are solved by the heuristic. When dynamic programming is applied, the number of recursion equations solved is small. One reason for this is that the elimination of redundant states successfully restricts the number of state variables t that need to be considered. The other reason is the effectiveness of the termination test. The average and maximum numbers of dynamic programming iterations listed in Table 1 show that, in each problem, only a small fraction of the maximum number of possible iterations n is needed.

Clearly, the standard test problems lie well within the scope of our algorithm, even if the number of jobs is large. With a view to providing a greater challenge, some *adjusted* test problems were generated from standard problems as follows. In each standard problem, a single job i was selected at random and its processing time reset using $p_i = p_i + d_i$, while all other data remain unaltered. Our algorithm is likely to experience much more difficulty is solving these adjusted problems for the following reasons. Firstly, lengthening the processing time of job i will cause T_{max} to increase, thereby yielding a corresponding increase in the time requirement $O(nT_{max})$ of the dynamic programming algorithm. Secondly, consider the case where the corresponding standard problems has a small value of the minimum total late work (for example, when $d^u = 1.0$). In the adjusted problem, it is likely that $p_i > T_{max}$, so the lower bound T_{max} cannot be achieved if job i is late. Furthermore, if job i is partially early (it cannot be early because $p_i > d_i$), then it may not be possible to achieve the preemptive minimum late work T_{max} without moving some of the $p_i - d_i$ units of late work for job i to the end of the schedule. Thus, for such problems, $\mathrm{UB} > T_{max}$, so it is necessary to apply dynamic programming. Also, the minimum total late work depends on whether job i is partially early or late in an optimal schedule, so a tight lower bound cannot be found before LB_i is computed.

Adjusted problems were generated with numbers of jobs ranging from $n = 100$ to $n = 1000$ in steps of 100. Computational results are given in the right half of Table 1. As anticipated, computation times are substantially larger than for the standard problems. One factor that leads to increased computation times is the inability of the heuristic to solve a significant number of the adjusted problems: it is necessary to apply dynamic programming to over 35% of these problems. Another factor is the relatively large number of dynamic programming iterations which are necessary. In over 20% of the adjusted test problems (mostly with $d^u = 1.0$), the minimum total late work exceeds T_{max} and the dynamic programming algorithm continues at least until $f_i(t)$ is computed for $t = a_i, \ldots, b_i$ (where i is the job with a reset processing time).

The reason why our algorithm is so successful on the standard test problems is that in all cases except one (a problem with $n = 9000$, $d^l = 0.0$ and $d^u = 1.0$) a solution with value equal to the lower bound T_{max} is found very quickly. This might be expected from computational findings for the knapsack problem given in Section 2 (or, more precisely, for the optimization version of this problem which is known as the zero-one value independent knapsack problem) which show that randomly generated problems with small data are easily solved (Ahrens and Finke 1975). The artificially created adjusted problems are much harder to solve because the minimum total late work frequently exceeds the lower bound T_{max}. Nevertheless, fairly large problems can still be solved using reasonable computer resources. If processing times in the total late work problem are large, then problems would become very much harder. However, for practical situations, our algorithm is likely to be extremely effective.

8. Concluding Remarks

This paper discusses the problem of scheduling jobs on a single machine to minimize total late work. This problem arises when work completed after a given due date is wasted, e.g., when the commodity considered is perishable. We derive an $O(n \log n)$ algorithm for the preemptive version, while the non-preemptive problem is shown to be NP-hard.

We also present a pseudopolynomial dynamic programming algorithm for the non-preemptive total late work problem that solves problems with up to 10000 jobs. Its effectiveness is achieved by eliminating the need to search a large amount of the state space. This reduction in search is largely based on structural properties of the optimal solution developed in Section 3 and on an effective heuristic method presented in Section 6. It appears that, not unlike many versions of the knapsack problem, the non-preemptive total late work problem, although NP-hard, is easily solvable for all practical purposes. Our algorithm could be demanding on computation time and storage when processing times are large. In this eventuality, it may be appropriate either to use the very effective heuristic we propose or to solve an suitably scaled version of the problem.

When comparing the total late work problem with related problems in terms of effectiveness of currently available solution algorithms, it is now possible to solve total tardiness problems with up to 100 jobs, total weighted number of late jobs problems with up to 1000 jobs and total late work problems with up to 10000 jobs. For all three problems, fairly effective pseudopolynomial dynamic programming algorithms are available. Of the three problems, the total late work problem considered in this paper has the most structure and therefore allows the most efficient curtailing of the search in the dynamic programming state space.

Unfortunately, when job weights are introduced many of the useful structural properties of the non-preemptive problem are destroyed. For instance, in an optimal sequence, early and partially early jobs are no longer guaranteed to appear in EDD order. Therefore, the non-preemptive total weighted late work problem is harder to solve. The preemptive version, however, can be solved in $O(n \log n)$ time. This total weighted late work problem is the subject of a follow-up paper.

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89/19	Wilfried VANHONACKER, Donald LEHMANN and Fareena SULTAN	**"Combining related and sparse data in linear regression models"**, Revised March 1989.
89/20	Wilfried VANHONACKER and Russell WINER	**"A rational random behavior model of choice"**, Revised March 1989.
89/21	Arnoud de MEYER and Kasra FERDOWS	**"Influence of manufacturing improvement programmes on performance"**, April 1989.
89/22	Manfred KETS DE VRIES and Sydney PERZOW	**"What is the role of character in psychoanalysis?"** April 1989.
89/23	Robert KORAJCZYK and Claude VIALLET	**"Equity risk premia and the pricing of foreign exchange risk"** April 1989.
89/24	Martin KILDUFF and Mitchel ABOLAFIA	**"The social destruction of reality: Organisational conflict as social drama"** zApril 1989.

89/25	Roger BETANCOURT and David GAUTSCHI	**"Two essential characteristics of retail markets and their economic consequences"** March 1989.
89/26	Charles BEAN, Edmond MALINVAUD, Peter BERNHOLZ, Francesco GIAVAZZI and Charles WYPLOSZ	**"Macroeconomic policies for 1992: the transition and after"**, April 1989.
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89/29	Robert GOGEL and Jean-Claude LARRECHE	**"The battlefield for 1992: product strength and geographic coverage"**, May 1989.
89/30	Lars-Hendrik ROLLER and Mihkel M. TOMBAK	**"Competition and Investment in Flexible Technologies"**, May 1989.
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89/40	Balaji CHAKRAVARTHY	**"Management systems for innovation and productivity"**, June 1989.
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89/42	Robert ANSON and Tawfik JELASSI	**"A development framework for computer-supported conflict resolution"**, July 1989.
89/43	Michael BURDA	**"A note on firing costs and severance benefits in equilibrium unemployment"**, June 1989.
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89/54	S. BALAKRISHNAN and Mitchell KOZA	**"Organisation costs and a theory of joint ventures"**, September 1989.
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89/56	Wilfried VANHONACKER and Lydia PRICE	**"On the practical usefulness of meta-analysis results"**, September 1989.
89/57	Taekwon KIM, Lars-Hendrik RÖLLER and Mihkel TOMBAK	**"Market growth and the diffusion of multiproduct technologies"**, September 1989.
89/58 (EP,TM)	Lars-Hendrik RÖLLER and Mihkel TOMBAK	**"Strategic aspects of flexible production technologies"**, October 1989.
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89/67 (FIN)	Peter BOSSAERTS and Pierre HILLION	**"Market microstructure effects of government intervention in the foreign exchange market"**, December 1989.

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90/01 TM/EP/AC	B. SINCLAIR-DESGAGNÉ	**"Unavoidable Mechanisms"**, January 1990.
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90/07 FIN/EP	Gabriel HAWAWINI	**"Stock Market Anomalies and the Pricing of Equity on the Tokyo Stock Exchange"**, January 1990.
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90/18 MKT	Wilfried VANHONACKER	**"Managerial Decision Rules and the Estimation of Dynamic Sales Response Models"**, Revised January 1990.
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90/23 EP/SM	Damien NEVEN	**"EEC Integration towards 1992: Some Distributional Aspects"**, Revised December 1989
90/24 FIN/EP	Lars Tyge NIELSEN	**"Positive Prices in CAPM"**, January 1990.
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90/33 OB	Caren SIEHL, David BOWEN and Christine PEARSON	**"The Role of Rites of Integration in Service Delivery"**, March 1990.
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90/35 EP	Jae Won PARK	**"Changing Uncertainty and the Time-Varying Risk Premia in the Term Structure of Nominal Interest Rates"**, December 1988, Revised March 1990.
90/36 TM	Arnoud DE MEYER	**"An Empirical Investigation of Manufacturing Strategies in European Industry"**, April 1990.
90/37 TM/OB/SM	William CATS-BARIL	**"Executive Information Systems: Developing an Approach to Open the Possibles"**, April 1990.
90/38 MKT	Wilfried VANHONACKER	**"Managerial Decision Behaviour and the Estimation of Dynamic Sales Response Models"**, (Revised February 1990).
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90/43 FIN	Robert KORAJCZYK and Claude VIALLET	**"Equity Risk Premia and the Pricing of Foreign Exchange Risk"**, May 1990.
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90/48 EP	Jae WON PARK	**"The Information in the Term Structure of Interest Rates: Out-of-Sample Forecasting Performance"**, June 1990.
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90/55 EP	Michael BURDA and Stefan GERLACH	"Intertemporal Prices and the US Trade Balance", (Revised July 1990).
90/56 EP	Damien NEVEN and Lars-Hendrik RÖLLER	"The Structure and Determinants of East-West Trade: A Preliminary Analysis of the Manufacturing Sector", July 1990
90/57 FIN/EP/ TM	Lars Tyge NIELSEN	Common Knowledge of a Multivariate Aggregate Statistic", July 1990
90/58 FIN/EP/TM	Lars Tyge NIELSEN	"Common Knowledge of Price and Expected Cost in an Oligopolistic Market", August 1990
90/59 FIN	Jean DERMINE and Lars-Hendrik RÖLLER	"Economies of Scale and Scope in the French Mutual Funds (SICAV) Industry", August 1990
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90/65 EP	Charles WYPLOSZ	"A Note on the Real Exchange Rate Effect of German Unification", August 1990
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90/87 FIN/EP	Lars Tyge NIELSEN	**"Existence of Equilibrium in CAPM: Further Results"**, December 1990
90/88 OB/MKT	Susan C. SCHNEIDER and Reinhard ANGELMAR	**"Cognition in Organisational Analysis: Who's Minding the Store?"** Revised, December 1990
90/89 OB	Manfred F.R. KETS DE VRIES	**"The CEO Who Couldn't Talk Straight and Other Tales from the Board Room,"** December 1990
90/90 MKT	Philip PARKER	**"Price Elasticity Dynamics over the Adoption Lifecycle: An Empirical Study,"** December 1990

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91/01 TM/SM	Luk VAN WASSENHOVE, Leonard FORTUIN and Paul VAN BEEK	**"Operational Research Can Do More for Managers Than They Think!,"** January 1991
91/02 TM/SM	Luk VAN WASSENHOVE, Leonard FORTUIN and Paul VAN BEEK	**"Operational Research and Environment,"** January 1991
91/03 FIN	Pekka HIETALA and Timo LÖYTTYNIEMI	**"An Implicit Dividend Increase in Rights Issues: Theory and Evidence,"** January 1991
91/04 FIN	Lars Tyge NIELSEN	**"Two-Fund Separation, Factor Structure and Robustness,"** January 1991
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91/23 TM — Spyros MAKRIDAKIS and Michèle HIBON — "Exponential Smoothing: The Effect of Initial Values and Loss Functions on Post-Sample Forecasting Accuracy", April 1991 (Revision of 90/46)

91/24 TM — Louis LE BLANC and Tawfik JELASSI — "An Empirical Assessment of Choice Models for Software Evaluation and Selection", May 1991

91/25 SM/TM — Luk N. VAN WASSENHOVE and Charles J. CORBETT — "Trade-Offs? What Trade-Offs?" April 1991