"APPROXIMATION ALGORITHMS FOR SCHEDULING A SINGLE MACHINE TO MINIMIZE TOTAL LATE WORK"

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APPROXIMATION ALGORITHMS FOR SCHEDULING A SINGLE MACHINE TO MINIMIZE TOTAL LATE WORK

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In the problem of scheduling a single machine to minimize total late work, there are n jobs to be processed, each of which has an integer processing time and an integer due date. The objective is to find a sequence of jobs which minimizes 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. Three families of approximation algorithms $\{E_k\}$, $\{A_\epsilon\}$ and $\{B_\epsilon\}$ are presented. Contained in the first family is a $(1+1/k)$-approximation algorithm E_k, for any positive integer $k \leq n$, which uses truncated enumeration; E_k requires $O(n^{k+1})$ time and $O(n)$ space. The two other families $\{A_\epsilon\}$ and $\{B_\epsilon\}$ are fully polynomial approximation schemes which are based on the rounding of state variables in dynamic programming formulations. In the superior scheme, for $0 < \epsilon < 1$, B_ϵ is a $(1+\epsilon)$-approximation algorithm which has a time requirement of $O(n^2/\epsilon)$ and a space requirement of $O(n/\epsilon)$.

1. Introduction

The non-preemptive single machine total late work problem may be stated as follows. Each of n jobs (numbered $1, \ldots, n$) is to be processed without interruption 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 an integer *processing time* p_i and has an 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 any schedule, the *late work* V_i for job i is the amount of processing performed on i after its due date d_i. Thus, if job i is completed at time C_i, then $V_i = 0$ if job i is *early*, i.e., if $C_i \leq d_i$; $V_i = C_i - d_i$ if job i is *partially early*, i.e., if $d_i < C_i < d_i + p_i$; and $V_i = p_i$ if job i is *late*, i.e., if $C_i \geq d_i + p_i$. Expressed differently, if $T_i = \max\{C_i - d_i, 0\}$ is the *tardiness* of job i, then $V_i = \min\{T_i, p_i\}$. The objective is to find a processing order of jobs which minimizes the total late work $\sum_{i=1}^{n} V_i$.

This type of model is first studied by Blazewicz [1] who points out its relevance in the field of information processing. In a recent paper, Potts and Van Wassenhove [5] derive an algorithm for the preemptive version of this problem in which the processing of a job may be interrupted and resumed at a later time. This algorithm requires $O(n \log n)$ time and generates at most one preemption. They also show that the non-preemptive problem is (binary) NP-hard. A key result is that an optimal non-preemptive schedule may be obtained by specifying a set of early and partially early jobs; these are sequenced first in EDD order followed by the remaining late jobs in an arbitrary order. This result is used in a pseudopolynomial dynamic programming algorithm which requires $O(n\text{UB})$ time, where UB is any upper bound on the minimum total late work. Computational results indicate that this algorithm can solve problems with up to 3000 jobs if processing times are small ($p_i \leq 100$ for $i = 1, \ldots, n$).

In this paper, we study approximation algorithms for the non-preemptive single machine total late work problem. When processing times are large, these algorithms are especially useful since the dynamic programming algorithm of Potts and Van Wassenhove may require excessive core storage. Let V^* denote the minimum value of the total late work and let V^A be the total late work when jobs are scheduled using a certain approximation algorithm A. We describe A as a *ρ-approximation algorithm* if $V^A \leq \rho V^*$ for all problem instances.

In Section 2, we describe $(1 + 1/k)$-approximation algorithms E_k, for $k = 1, \ldots, n$, which are based on truncated enumeration. Algorithm E_k requires $O(n^{k+1})$ time and $O(n)$ space. Section 3 presents $(1 + \epsilon)$-approximation algorithms A_ϵ and B_ϵ for any $\epsilon > 0$, which are based on the rounding of state variables in dynamic programming formulations. For $0 < \epsilon < 1$, Algorithm A_ϵ requires $O(n^3/\epsilon)$ time and $O(n^2/\epsilon)$ space, whereas B_ϵ requires $O(n^2/\epsilon)$ time and $O(n/\epsilon)$ space. Since time requirements are polynomial in n and $1/\epsilon$, the families $\{A_\epsilon\}$ and $\{B_\epsilon\}$ are *fully polynomial approximation schemes.*

2. Truncated enumeration

2.1. A lower bounding scheme

Our truncated enumeration algorithms have at their core a branch and bound algorithm. Lower bounds are obtained from the solution to the problem in which jobs of a set E are constrained so that they cannot be preempted and they cannot be late, whereas other jobs can be preempted. An algorithm to solve this problem in $O(n)$ time (once an EDD sequence of jobs is known) is described below.

It is assumed that jobs are renumbered so that $E = \{1, \ldots, e\}$, where $d_1 \leq \ldots \leq d_e$. Firstly, suppose that $\sum_{i=1}^{a} p_i \leq d_a$ for $a = 1, \ldots, e$. Thus, it is possible to construct a schedule in which all jobs of E are early. A lower bound is obtained by applying the following variant of a preemptive algorithm for the total late work problem [5]. Firstly, the maximum tardiness $T_{\max}$ for an EDD sequence is computed. If $T_{\max} = 0$, then the EDD sequence is optimal with total late work equal to zero. Alternatively, if $T_{\max} > 0$, then a preemptive schedule is constructed from the EDD sequence by selecting $T_{\max}$ units of processing to be repositioned as late work at the end of the schedule. The $T_{\max}$ units of processing are chosen as close to the start of the EDD schedule as possible, although processing corresponding to jobs of E is not eligible for repositioning. It is easily verified that this procedure generates an optimal preemptive schedule with total late work equal to $T_{\max}$. Furthermore, at most one job is preempted. Once an EDD sequence of jobs is known, this variant of the preemptive scheduling algorithm requires $O(n)$ time.

The alternative case that $\sum_{i=1}^{a} p_i > d_a$ for some $a \in E$, where a is chosen as large as possible, remains to be discussed. We claim that there exists an optimal solution of our constrained problem in which jobs $1, \ldots, a$ are sequenced first. To justify this, we observe that any processing on job j, where $j \notin E$, which is executed before job a, can be removed as late work to produce a corresponding decrease in the late work for job a. After computing their contribution to the total late work, jobs $1, \ldots, a$ are removed from the problem by subtracting $\sum_{i=1}^{a} p_i$ from the due dates of other jobs. Jobs are also removed as late work if their due dates become negative. For the remaining jobs, the procedure described above is applied to generate a lower bound.

2.2. Description of the algorithms

We now present details of our family of truncated enumeration algorithms. Consider the following branch and bound algorithm. Lower bounds are computed by allowing preemption. If no job is preempted in the solution of the preemptive problem, then an optimal solution of the non-preemptive problem is obtained. Otherwise, a single job j is preempted. A binary branching rule fixes job j either to be late or non-late. In the former case, job j is discarded from the problem by including it in a set L of late jobs. In the latter case, job j is included in a set E of non-late jobs. As pointed out in Section 2.1, it is straightforward to allow for the jobs of E in the computation of lower bounds through preemptive scheduling. For each lower bound that is computed, a corresponding upper bound, obtained by setting any preempted job to be late, is evaluated. A node is fathomed if its lower bound is at least as large as the smallest upper bound that is currently available or if the EDD sequence of the jobs of E yields a late job, i.e., if the set E is infeasible. This algorithm delivers an optimal solution after a maximum of $2^{n+1}-1$ search tree nodes are generated.

Our truncated enumeration algorithms E_k, for $k = 1, \ldots, n$, artificially fathom nodes to reduce computational requirements. More precisely, a node of the search tree is discarded if exactly k jobs are constrained to be late, i.e., if $|L| = k$. In algorithm E_n, no nodes are artificially fathomed, so it reduces to the branch and bound algorithm which generates an optimal solution. More generally, algorithms E_k only deliver approximate solutions because, on full exploration of the search tree, each optimal solution is found at a successor of an artificially fathomed node.

2.3. Analysis of the algorithms

Our main result of this section shows that E_k is a $(1 + 1/k)$-approximation algorithm.

Theorem 1. *For $k = 1, \ldots, n$, E_k is a $(1 + 1/k)$-approximation algorithm with time and space requirements of $O(n^{k+1})$ and $O(n)$ respectively.*

Proof. Unless all optimal schedules correspond to the decisions taken at artificially fathomed nodes, algorithm E_k generates an optimal solution. Thus, we consider the case that an optimal solution is consistent with an artificially fathomed node in which the jobs of $L = \{j_1, \ldots, j_k\}$ are constrained to be late. Let $j \in L$ be chosen such that $p_j = \min\{p_{j_1}, \ldots, p_{j_k}\}$. Since jobs $j_1, \ldots, j_k$ are late in an optimal schedule, we have

$$V^* \geq \sum_{i=1}^{k} p_{j_i} \geq kp_j. \tag{1}$$

At some predecessor node in the search tree, job j is the preempted job in the lower bounding computation. Since this is a predecessor node, an optimal schedule is consistent with the sets of jobs constrained to be late and non-late. Let v be the lower bound at this node. Setting job j to be late gives an upper bound which algorithm E_k may select. Thus,

$$V^{E_k} < v + p_j.$$

Using the information that v is a lower bound on the value V^* of an optimal schedule and applying (1) yields

$$V^{E_k} < (1 + 1/k)V^*,$$

which is the required inequality.

The time and space bounds are now established. Since at each node of the search tree for algorithm E_k we have $|L| \leq k$, the tree contains a maximum of $O(n^k)$ nodes, each of which requires $O(n)$ time for the computation of a lower bound. Thus, the time complexity of E_k is $O(n^{k+1})$. Clearly, it requires $O(n)$ space if a newest active node search strategy is employed. □

Algorithm E_k appears to be mainly of theoretical interest unless k is small. However, E_1 is of special interest. A simplified statement of algorithm E_1 is as follows. First solve the preemptive problem to find any preempted job j; if there is no preempted job, then an optimal solution is obtained. Setting job j to be late gives one non-preemptive schedule which is evaluated. Job j is included in a set E of jobs which are constrained to be non-late in all subsequent computations. The procedure continues until either E becomes infeasible or until there is no preempted job in the solution of the preemptive problem. Algorithm E_1 selects the best of the non-preemptive schedules generated.

Theorem 1 shows that E_1 is a 2-approximation algorithm. The following instance shows that no stronger bound on the performance of E_1 can be derived. There are n jobs, where $n \geq 3$, with processing times and due dates defined by $p_1 = n - 2$, $d_1 = n - 2$, and $p_i = n - 1$ and $d_i = (i - 1)n - i$ for $i = 2, \ldots, n$. In a solution of the preemptive scheduling problem, job 1 is late and job 2 is preempted with one unit of its processing scheduled after its due date. By setting job 2 to be late, the total late work is $2n-3$. When job 2 is constrained to be non-late, it is removed from the problem by setting $d_i = (i-2)n - i + 1$ for $i = 3, \ldots, n$. In subsequent iterations where $E = \{2, \ldots, i-1\}$, sequences $(2, \ldots, i-1, i+1, \ldots, n, 1, i)$ with job 1 and job i late are generated for $i = 3, \ldots, n$, which have total late work equal to $2n + i - 5$. Finally, when $E = \{2, \ldots, n\}$, the sequence $(2, \ldots, n, 1)$ is generated, for which the total late work is again equal to $2n-3$. An optimal sequence is $(1, 3, \ldots, n, 2)$ in which job 2 is late and all other jobs are early. Thus, we have $V^{E_1} = 2n-3$ and $V^* = n-1$, giving $V^{E_1}/V^* = 2 - 1/(n-1)$. Therefore, the ratio V^{E_1}/V^* can be arbitrarily close to 2, which demonstrates that E_1 is no better than a 2-approximation algorithm.

3. Dynamic programming and rounding

The families of approximation algorithms $\{A_\epsilon\}$ and $\{B_\epsilon\}$, which we describe and analyze in this section, are based on the rounding of state variables in dynamic programming formulations. This methodology is proposed by Sahni [6] for various single and parallel machine scheduling problems and has subsequently been used for a variety of scheduling problems by Gens and Levner [2], Hall and Shmoys [3] and Lawler [4].

The $(1+\epsilon)$-algorithms A_ϵ and B_ϵ each have two phases. In both algorithms, the first phase applies algorithm E_1 to generate an upper bound in $O(n^2)$ time and $O(n)$ space. If $V^{E_1} = 0$ or $\epsilon \geq 1$, the second phase is not executed since $V^{E_1} \leq (1+\epsilon)V^*$: this inequality is apparent when $V^{E_1} = 0$ and is deduced from Theorem 1 when $\epsilon \geq 1$. However, if $V^{E_1} > 0$ and $\epsilon < 1$, the second phase uses dynamic programming with rounded state variables to generate an approximate solution. The subsequent analysis concentrates only on those cases in which the second phase is required.

Our first approximation scheme $\{A_\epsilon\}$ has at its core the dynamic programming algorithm DP_t of Potts and Van Wassenhove. The subscript t in DP_t is used to denote that time is a state variable: later we use a dynamic programming algorithm having a different state variable. The algorithm uses a recursion defined on values $f_j(t)$ for $j = 1, \ldots, n$; at most $\mathrm{UB} + 1$ values of t are considered, where $\mathrm{UB} = V^{E_1}$ is the upper bound found in the first phase of A_ϵ. The function $f_j(t)$ represents the total late work on jobs $1, \ldots, j$ when all early and partially early jobs are completed at time t. The time complexity of this algorithm is $O(nV^{E_1})$ and its space requirement is $O(V^{E_1})$. In the second phase of A_ϵ, a *rounded* problem $\tilde{P}$ is created by, if necessary, rounding down each processing time to the nearest integer multiple of K, where $K = \epsilon V^{E_1}/(n(n+1))$. Thus, job i ($i = 1, \ldots, n$) has processing time $\tilde{p}_i = K\lfloor p_i/K \rfloor$ and due date $\tilde{d}_i = d_i$ in $\tilde{P}$. Algorithm A_ϵ takes as its schedule an optimal sequence σ_ϵ for $\tilde{P}$, which is obtained by applying DP_t. In this application of DP_t, only state variables t which are integer multiples of K are considered. Thus, when $K > 1$, the number of recursion equations to be solved reduces from $O(nV^{E_1})$ in the original problem P to $O(nV^{E_1}/K)$ in problem $\tilde{P}$. Clearly, if $K \leq 1$, there is no advantage in considering problem $\tilde{P}$.

The following result establishes bounds on the performance of the family $\{A_\epsilon\}$.

Theorem 2. *For any ϵ such that $0 < \epsilon < 1$, A_ϵ is a $(1+\epsilon)$-approximation algorithm with time and space requirements of $O(n^3/\epsilon)$ and $O(n^2/\epsilon)$ respectively.*

Proof. Let $\tilde{V}^*$ denote the minimum value of the total late work for problem $\tilde{P}$. Since $\tilde{P}$ is obtained from the original problem P by reducing processing times, its minimum total late work provides a lower bound on the total late work for problem P. Thus,

$$\tilde{V}^* \leq V^*. \tag{2}$$

Consider now the increase in the total late work for the sequence σ_ϵ that arises through increasing the processing time of job i ($i = 1, \dots, n$) from its value $K\lfloor p_i/K \rfloor$ in $\tilde{P}$ to p_i in P. The maximum increase in any processing time is less than K. Thus the late work of the first job of σ_ϵ increases by less than K, the late work of the second job of σ_ϵ increases by less than $2K$, etc., to give a total increase in late work of less than $n(n+1)K/2$. Thus,

$$V^{A_\epsilon} < \tilde{V}^* + n(n+1)K/2. \tag{3}$$

Combining (2) and (3) and substituting for K, we obtain

$$V^{A_\epsilon} < V^* + \epsilon V^{E_1}/2. \tag{4}$$

Since E_1 is a 2-approximation algorithm, $V^{E_1} \leq 2V^*$. Substituting this inequality into (4) shows that A_ϵ is a $(1+\epsilon)$-approximation algorithm.

We now establish the time and space bounds for the solution of problem $\tilde{P}$ by algorithm DP_t. The number of recursion equations which are solved is $O(nV^{E_1}/K)$. Substituting for K yields the time bound of $O(n^3/\epsilon)$. Similarly, the minimum storage required to solve the recursion equations is $O(V^{E_1}/K)$, which produces the space bound of $O(n^2/\epsilon)$. □

The analysis in the proof of Theorem 2 shows that the conversion of an optimal solution of problem $\tilde{P}$ into an approximate solution of problem P increases each processing time by close to K in the worst case. This has a cumulative effect on completion times and, consequently, late work contributions are increased by up to $K, 2K, \ldots, nK$. Thus, the increase in total late work is $O(n^2K)$ in the worst case. If this cumulative effect was not present, the value of K could be increased to $O(\epsilon V^{E_1}/n)$, thereby reducing the time and space complexity. We now describe an alternative approximation scheme which achieves this desired aim.

As observed previously, algorithm DP_t is based on the determination of values $f_j(t)$, representing the total late work for jobs $1, \ldots, j$ when early and partially early jobs are completed at time t. We now propose an essentially equivalent dynamic programming algorithm DP_v in which the state variable t and the function definition are interchanged. More precisely, let $g_j(v)$ denote the minimum completion time of early and partially early jobs when jobs $1, \ldots, j$ are scheduled so that their total late work is v. For each job j, the values $v = 0, \ldots, \mathrm{UB}$ are considered, where we use the upper bound $\mathrm{UB} = V^{E_1}$. Having determined $g_{j-1}(0), \ldots, g_{j-1}(V^{E_1})$, the values of $g_j(v)$ are computed as follows. We start by setting values $g_j(v) = g_{j-1}(v-p_j)$ for $v = p_j, \ldots, V^{E_1}$, based on the assumption that job j is late. Under the assumption that job j is early or partially early, each entry $g_{j-1}(v)$, where $g_{j-1}(v) < d_j$, generates a schedule for jobs $1, \ldots, j$ with a total late work of $v' = v + \max\{g_{j-1}(v) + p_j - d_j, 0\}$ and a total processing time for early and partially early jobs of $p' = g_{j-1}(v) + p_j$. If $p' < g_j(v')$, then we reset $g_j(v') = p'$; otherwise $g_j(v')$ remains unchanged. Initialization sets $g_0(0) = 0$ and $g_j(v) = \infty$ for $j \neq 0$ or $v \neq 0$. The minimum total late work is the smallest value of v for which $g_n(v)$ is finite. As is the case for DP_t, algorithm DP_v requires $O(nV^{E_1})$ time and $O(V^{E_1})$ space.

We now give details of our second family of approximation algorithms $\{B_\epsilon\}$, which are based on algorithm DP_v. In the second phase of B_ϵ, a *rounded* problem $\bar{P}$ is created by, if necessary, rounding down the late work contribution for each each job to the nearest integer multiple of L, where $L = \epsilon V^{E_1}/(2n)$. Thus, the late work for job i ($i = 1, \ldots, n$) in $\bar{P}$ when it is completed at time t is $L \min\{\max\{\lfloor (t - d_i)/L \rfloor, 0\}, \lfloor p_i/L \rfloor\}$. Algorithm B_ϵ takes as its schedule an optimal sequence π_ϵ for problem $\bar{P}$, which is obtained by applying DP_v. Since in this application of DP_v only state variables v which are integer multiples of L are considered, the number of recursion equations to be solved is $O(nV^{E_1}/L)$.

We proceed to establish bounds on the performance of the family $\{B_\epsilon\}$.

Theorem 3. *For any ϵ such that $0 < \epsilon < 1$, B_ϵ is a $(1+\epsilon)$-approximation algorithm with time and space requirements of $O(n^2/\epsilon)$ and $O(n/\epsilon)$ respectively.*

Proof. Let $\bar{V}^*$ denote the minimum value of the total late work for problem $\bar{P}$. Clearly,

$$\bar{V}^* \leq V^* \tag{5}$$

since $\bar{P}$ is obtained from the original problem P by reducing late work contributions. Consider now the increase in the total late work for the sequence π_ϵ that is incurred when the late work of each job increases from its rounded to its true value. The late work of each job increases by less than L to give a total increase of less than nL. Therefore,

$$V^{B_\epsilon} < \bar{V}^* + nL. \tag{6}$$

Combining (5) and (6) and substituting for L yields

$$V^{B_\epsilon} < V^* + \epsilon V^{E_1}/2. \tag{7}$$

Substituting into (7) the inequality $V^{E_1} \leq 2V^*$, which is valid because E_1 is a 2-approximation algorithm, shows that B_ϵ is a $(1+\epsilon)$-approximation algorithm.

We now establish the time and space bounds for the solution of problem $\bar{P}$ by DP_v. Recalling that the number of recursion equations solved is $O(nV^{E_1}/L)$, we use $L = \epsilon V^{E_1}/(2n)$ to obtain the time bound of $O(n^2/\epsilon)$. Similarly, the minimum storage of $O(V^{E_1}/L)$ values yields a space bound of $O(n/\epsilon)$. □

Theorems 2 and 3 show $\{B_\epsilon\}$ to be a more efficient approximation scheme than $\{A_\epsilon\}$. However, $\{A_\epsilon\}$ can be regarded as a more natural family, since A_ϵ is derived from the easily implemented dynamic programming algorithm DP_t.

Lastly, it is appropriate to comment on the relative merits of the algorithms of this section and algorithms E_k, for $k = 1, \ldots, n$, of Section 2. Suppose $\epsilon = 1/k$. Although A_ϵ and B_ϵ are clearly superior in terms of time requirements, algorithm E_k has much smaller space requirements. Thus, no definitive conclusion can be drawn as to whether the truncated enumeration algorithms or the schemes based on dynamic programming and rounding are preferred.

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88/45	Robert KORAJCZYK and Claude VIALLET	**"An empirical investigation of international asset pricing"**, November 1986, revised August 1988.
88/46	Yves DOZ and Amy SHUEN	**"From intent to outcome: a process framework for partnerships"**, August 1988.
88/47	Alain BULTEZ, Els GIJSBRECHTS,	**"Asymmetric cannibalism between substitute items listed by retailers"**, September 1988.

	Philippe NAERT and Piet VANDEN ABEELE	
88/48	Michael BURDA	**"Reflections on 'Wait unemployment' in Europe, II"**, April 1988 revised September 1988.
88/49	Nathalie DIERKENS	**"Information asymmetry and equity issues"**, September 1988.
88/50	Rob WEITZ and Arnoud DE MEYER	**"Managing expert systems: from inception through updating"**, October 1987.
88/51	Rob WEITZ	**"Technology, work, and the organization: the impact of expert systems"**, July 1988.
88/52	Susan SCHNEIDER and Reinhard ANGELMAR	**"Cognition and organizational analysis: who's minding the store?"**, September 1988.
88/53	Manfred KETS DE VRIES	**"Whatever happened to the philosopher-king: the leader's addiction to power,** September 1988.
88/54	Lars-Hendrik RÖLLER and Mihkel M. TOMBAK	**"Strategic choice of flexible production technologies and welfare implications"**, October 1988
88/55	Peter BOSSAERTS and Pierre HILLION	**"Method of moments tests of contingent claims asset pricing models"**, October 1988.
88/56	Pierre HILLION	**"Size-sorted portfolios and the violation of the random walk hypothesis: Additional empirical evidence and implication for tests of asset pricing models"**, June 1988.
88/57	Wilfried VANHONACKER and Lydia PRICE	**"Data transferability: estimating the response effect of future events based on historical analogy"**, October 1988.
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88/60	Michael BURDA	**"Is mismatch really the problem? Some estimates of the Chelwood Gate II model with US data"**, September 1988.
88/61	Lars-Hendrik RÖLLER	**"Modelling cost structure: the Bell System revisited"**, November 1988.
88/62	Cynthia VAN HULLE, Theo VERMAELEN and Paul DE WOUTERS	**"Regulation, taxes and the market for corporate control in Belgium"**, September 1988.
88/63	Fernando NASCIMENTO and Wilfried R. VANHONACKER	**"Strategic pricing of differentiated consumer durables in a dynamic duopoly: a numerical analysis"**, October 1988.
88/64	Kasra FERDOWS	**"Charting strategic roles for international factories"**, December 1988.
88/65	Arnoud DE MEYER and Kasra FERDOWS	**"Quality up, technology down"**, October 1988
88/66	Nathalie DIERKENS	**"A discussion of exact measures of information assymetry: the example of Myers and Majluf model or the importance of the asset structure of the firm"**, December 1988.
88/67	Paul S. ADLER and Kasra FERDOWS	**"The chief technology officer"**, December 1988.

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89/01	Joyce K. BYRER and Tawfik JELASSI	**"The impact of language theories on DSS dialog"**, January 1989.
89/02	Louis A. LE BLANC and Tawfik JELASSI	**"DSS software selection: a multiple criteria decision methodology"**, January 1989.

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89/04	Kasra FERDOWS and Arnoud DE MEYER	**"Lasting improvement in manufacturing performance: In search of a new theory"**, January 1989.
89/05	Martin KILDUFF and Reinhard ANGELMAR	**"Shared history or shared culture? The effects of time, culture, and performance on institutionalization in simulated organizations"**, January 1989.
89/06	Mihkel M. TOMBAK and B. SINCLAIR-DESGAGNÉ	**"Coordinating manufacturing and business strategies: I"**, February 1989.
89/07	Damien J. NEVEN	**"Structural adjustment in European retail banking. Some view from industrial organisation"**, January 1989.
89/08	Arnoud DE MEYER and Hellmut SCHÜTTE	**"Trends in the development of technology and their effects on the production structure in the European Community"**, January 1989.
89/09	Damien NEVEN, Carmen MATUTES and Marcel CORSTJENS	**"Brand proliferation and entry deterrence"**, February 1989.
89/10	Nathalie DIERKENS, Bruno GERARD and Pierre HILLION	**"A market based approach to the valuation of the assets in place and the growth opportunities of the firm"**, December 1988.
89/11	Manfred KETS DE VRIES and Alain NOEL	**"Understanding the leader-strategy interface: application of the strategic relationship interview method"**, February 1989.
89/12	Wilfried VANHONACKER	**"Estimating dynamic response models when the data are subject to different temporal aggregation"**, January 1989.
89/13	Manfred KETS DE VRIES	**"The impostor syndrome: a disquieting phenomenon in organizational life"**, February 1989.
89/14	Reinhard ANGELMAR	**"Product innovation: a tool for competitive advantage"**, March 1989.
89/15	Reinhard ANGELMAR	**"Evaluating a firm's product innovation performance"**, March 1989.
89/16	Wilfried VANHONACKER, Donald LEHMANN and Fareena SULTAN	**"Combining related and sparse data in linear regression models"**, February 1989.
89/17	Gilles AMADO, Claude FAUCHEUX and André LAURENT	**"Changement organisationnel et réalités culturelles: contrastes franco-américains"**, March 1989.
89/18	Srinivasan BALAK-RISHNAN and Mitchell KOZA	**"Information asymmetry, market failure and joint-ventures: theory and evidence"**, March 1989.
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.
89/27	David KRACKHARDT and Martin KILDUFF	"Friendship patterns and cultural attributions: the control of organizational diversity", April 1989.
89/28	Martin KILDUFF	"The interpersonal structure of decision making: a social comparison approach to organizational choice", Revised April 1989.
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.
89/31	Michael C. BURDA and Stefan GERLACH	"Intertemporal prices and the US trade balance in durable goods", July 1989.
89/32	Peter HAUG and Tawfik JELASSI	"Application and evaluation of a multi-criteria decision support system for the dynamic selection of U.S. manufacturing locations", May 1989.
89/33	Bernard SINCLAIR-DESGAGNÉ	"Design flexibility in monopsonistic industries", May 1989.
89/34	Sumantra GHOSHAL and Nittin NOHRIA	"Requisite variety versus shared values: managing corporate-division relationships in the M-Form organisation", May 1989.
89/35	Jean DERMINE and Pierre HILLION	"Deposit rate ceilings and the market value of banks: The case of France 1971-1981", May 1989.
89/36	Martin KILDUFF	"A dispositional approach to social networks: the case of organizational choice", May 1989.
89/37	Manfred KETS DE VRIES	"The organisational fool: balancing a leader's hubris", May 1989.
89/38	Manfred KETS DE VRIES	"The CEO blues", June 1989.
89/39	Robert KORAJCZYK and Claude VIALLET	"An empirical investigation of international asset pricing", (Revised June 1989).
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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89/46	Marcel CORSTJENS, Carmen MATUTES and Damien NEVEN	"Entry Encouragement", July 1989.
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89/48	Damien NEVEN and Lars-Hendrik RÖLLER	"European integration and trade flows", August 1989.

89/49	Jean DERMINE	**"Home country control and mutual recognition"**, July 1989.
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89/54	S. BALAKRISHNAN and Mitchell KOZA	**"Organisation costs and a theory of joint ventures"**, September 1989.
89/55	H. SCHUTTE	**"Euro-Japanese cooperation in information technology"**, September 1989.
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.
89/59 (OB)	Manfred KETS DE VRIES, Daphna ZEVADI, Alain NOEL and Mihkel TOMBAK	**"Locus of control and entrepreneurship: a three-country comparative study"**, October 1989.
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89/61 (All)	Susan SCHNEIDER and Arnoud DE MEYER	**"Interpreting and responding to strategic issues: The impact of national culture"**, October 1989.
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89/63 (TM)	Enver YUCESAN and Lee SCHRUBEN	**"Equivalence of simulations: A graph approach"**, November 1989.
89/64 (TM)	Enver YUCESAN and Lee SCHRUBEN	**"Complexity of simulation models: A graph theoretic approach"**, November 1989.
89/65 (TM, AC, FIN)	Soumitra DUTTA and Piero BONISSONE	**"MARS: A mergers and acquisitions reasoning system"**, November 1989.
89/66 (TM,EP)	B. SINCLAIR-DESGAGNÉ	**"On the regulation of procurement bids"**, November 1989.
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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90/05 FIN/EP	Gabriel HAWAWINI and Bertrand JACQUILLAT	**"European Equity Markets: Toward 1992 and Beyond"**, January 1990.

90/06 FIN/EP	Gabriel HAWAWINI and Eric RAJENDRA	**"Integration of European Equity Markets: Implications of Structural Change for Key Market Participants to and Beyond 1992"**, January 1990.
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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90/09 EP/FIN	Alberto GIOVANNINI and Jae WON PARK	**"Capital Controls and International Trade Finance"**, January 1990.
90/10 TM	Joyce BRYER and Tawfik JELASSI	**"The Impact of Language Theories on DSS Dialog"**, January 1990.
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90/13 TM	Soumitra DUTTA and Shashi SHEKHAR	**"Approximate Reasoning about Temporal Constraints in Real Time Planning and Search"**, January 1990.
90/14 TM	Albert ANGEHRN and Hans-Jakob LÜTHI	**"Visual Interactive Modelling and Intelligent DSS: Putting Theory Into Practice"**, January 1990.
90/15 TM	Arnoud DE MEYER, Dirk DESCHOOLMEESTER, Rudy MOENAERT and Jan BARBE	**"The Internal Technological Renewal of a Business Unit with a Mature Technology"**, January 1990.
90/16 FIN	Richard LEVICH and Ingo WALTER	**"Tax-Driven Regulatory Drag: European Financial Centers in the 1990's"**, January 1990.
90/17 FIN	Nathalie DIERKENS	**"Information Asymmetry and Equity Issues"**, Revised January 1990.
90/18 MKT	Wilfried VANHONACKER	**"Managerial Decision Rules and the Estimation of Dynamic Sales Response Models"**, Revised January 1990.
90/19 TM	Beth JONES and Tawfik JELASSI	**"The Effect of Computer Intervention and Task Structure on Bargaining Outcome"**, February 1990.
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90/22 FIN	Ingo WALTER	**"European Financial Integration and Its Implications for the United States"**, February 1990.
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.
90/25 FIN/EP	Lars Tyge NIELSEN	**"Existence of Equilibrium in CAPM"**, January 1990.
90/26 OB/BP	Charles KADUSHIN and Michael BRIMM	**"Why networking Fails: Double Binds and the Limitations of Shadow Networks"**, February 1990.
90/27 TM	Abbas FOROUGHI and Tawfik JELASSI	**"NSS Solutions to Major Negotiation Stumbling Blocks"**, February 1990.
90/28 TM	Arnoud DE MEYER	**"The Manufacturing Contribution to Innovation"**, February 1990.

90/29 FIN/AC	Nathalie DIERKENS	**"A Discussion of Correct Measures of Information Asymmetry"**, January 1990.
90/30 FIN/EP	Lars Tyge NIELSEN	**"The Expected Utility of Portfolios of Assets"**, March 1990.
90/31 MKT/EP	David GAUTSCHI and Roger BETANCOURT	**"What Determines U.S. Retail Margins?"**, February 1990.
90/32 SM	Srinivasan BALAK-RISHNAN and Mitchell KOZA	**"Information Asymmetry, Adverse Selection and Joint-Ventures: Theory and Evidence"**, Revised, January 1990.
90/33 OB	Caren SIEHL, David BOWEN and Christine PEARSON	**"The Role of Rites of Integration in Service Delivery"**, March 1990.
90/34 FIN/EP	Jean DERMINE	**"The Gains from European Banking Integration, a Call for a Pro-Active Competition Policy"**, April 1990.
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).
90/39 TM	Louis LE BLANC and Tawfik JELASSI	**"An Evaluation and Selection Methodology for Expert System Shells"**, May 1990.
90/40 OB	Manfred KETS DE VRIES	**"Leaders on the Couch: The case of Roberto Calvi"**, April 1990.
90/41 FIN/EP	Gabriel HAWAWINI, Itzhak SWARY and Ik HWAN JANG	**"Capital Market Reaction to the Announcement of Interstate Banking Legislation"**, March 1990.
90/42 MKT	Joel STECKEL and Wilfried VANHONACKER	**"Cross-Validating Regression Models in Marketing Research"**, (Revised April 1990).
90/43 FIN	Robert KORAJCZYK and Claude VIALLET	**"Equity Risk Premia and the Pricing of Foreign Exchange Risk"**, May 1990.
90/44 OB	Gilles AMADO, Claude FAUCHEUX and André LAURENT	**"Organisational Change and Cultural Realities: Franco-American Contrasts"**, April 1990.
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90/46 TM	Spyros MAKRIDAKIS and Michèle HIBON	**"Exponential Smoothing: The Effect of Initial Values and Loss Functions on Post-Sample Forecasting Accuracy"**.
90/47 MKT	Lydia PRICE and Wilfried VANHONACKER	**"Improper Sampling in Natural Experiments: Limitations on the Use of Meta-Analysis Results in Bayesian Updating"**, Revised May 1990.
90/48 EP	Jae WON PARK	**"The Information in the Term Structure of Interest Rates: Out-of-Sample Forecasting Performance"**, June 1990.
90/49 TM	Soumitra DUTTA	**"Approximate Reasoning by Analogy to Answer Null Queries"**, June 1990.
90/50 EP	Daniel COHEN and Charles WYPLOSZ	**"Price and Trade Effects of Exchange Rates Fluctuations and the Design of Policy Coordination"**, April 1990.

90/51 EP	Michael BURDA and Charles WYPLOSZ	"Gross Labour Market Flows in Europe: Some Stylized Facts", June 1990.
90/52 FIN	Lars Tyge NIELSEN	"The Utility of Infinite Menus", June 1990.
90/53 EP	Michael Burda	"The Consequences of German Economic and Monetary Union", June 1990.
90/54 EP	Damien NEVEN and Colin MEYER	"European Financial Regulation: A Framework for Policy Analysis", (Revised May 1990).
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
90/60 TM	Peri IZ and Tawfik JELASSI	"An Interactive Group Decision Aid for Multiobjective Problems: An Empirical Assessment", September 1990
90/61 TM	Pankaj CHANDRA and Mihkel TOMBAK	"Models for the Evlauation of Manufacturing Flexibility", August 1990
90/62 EP	Damien NEVEN and Menno VAN DIJK	"Public Policy Towards TV Broadcasting in the Netherlands", August 1990
90/63 SM	Sumantra GHOSHAL and Eleanor WESTNEY	"Organising Competitor Analysis Systems", August 1990
90/64 SM	Sumantra GHOSHAL	"Internal Differentiation and Corporate Performance: Case of the Multinational Corporation", August 1990
90/65 EP	Charles WYPLOSZ	"A Note on the Real Exchange Rate Effect of German Unification", August 1990
90/66 TM/SE/FIN	Soumitra DUTTA and Piero BONISSONE	"Computer Support for Strategic and Tactical Planning in Mergers and Acquisitions", September 1990
90/67 TM/SE/FIN	Soumitra DUTTA and Piero BONISSONE	"Integrating Prior Cases and Expert Knowledge In a Mergers and Acquisitions Reasoning System", September 1990
90/68 TM/SE	Soumitra DUTTA	"A Framework and Methodology for Enhancing the Business Impact of Artificial Intelligence Applications", September 1990
90/69 TM	Soumitra DUTTA	"A Model for Temporal Reasoning in Medical Expert Systems", September 1990
90/70 TM	Albert ANGEHRN	"'Triple C': A Visual Interactive MCDSS", September 1990
90/71 MKT	Philip PARKER and Hubert GATIGNON	"Competitive Effects in Diffusion Models: An Empirical Analysis", September 1990
90/72 TM	Enver YÜCESAN	"Analysis of Markov Chains Using Simulation Graph Models", October 1990
90/73 TM	Arnoud DE MEYER and Kasra FERDOWS	"Removing the Barriers in Manufacturing", October 1990
90/74 SM	Sumantra GHOSHAL and Nitin NOHRIA	"Requisite Complexity: Organising Headquarters-Subsidiary Relations in MNCs", October 1990

90/75 MKT — Roger BETANCOURT and David GAUTSCHI — **"The Outputs of Retail Activities: Concepts, Measurement and Evidence"**, October 1990

90/76 MKT — Wilfried VANHONACKER — **"Managerial Decision Behaviour and the Estimation of Dynamic Sales Response Models"**, Revised October 1990

90/77 MKT — Wilfried VANHONACKER — **"Testing the Koyck Scheme of Sales Response to Advertising: An Aggregation-Independent Autocorrelation Test"**, October 1990

90/78 EP — Michael BURDA and Stefan GERLACH — **"Exchange Rate Dynamics and Currency Unification: The Ostmark - DM Rate"**, October 1990

90/79 TM — Anil GABA — **"Inferences with an Unknown Noise Level in a Bernoulli Process"**, October 1990

90/80 TM — Anil GABA and Robert WINKLER — **"Using Survey Data in Inferences about Purchase Behaviour"**, October 1990

90/81 TM — Tawfik JELASSI — **"Du Présent au Futur: Bilan et Orientations des Systèmes Interactifs d'Aide à la Décision,"** October 1990

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90/85 MKT — Avijit GHOSH and Vikas TIBREWALA — **"Optimal Timing and Location in Competitive Markets,"** November 1990

90/86 EP/TM — Olivier CADOT and Bernard SINCLAIR-DESGAGNE — **"Prudence and Success in Politics,"** November 1990

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

91/05 OB — Susan SCHNEIDER — **"Managing Boundaries in Organisations,"** January 1991

91/06 OB — Manfred KETS DE VRIES, Danny MILLER and Alain NOEL — **"Understanding the Leader-Strategy Interface: Application of the Strategic Relationship Interview Method,"** January 1990 (89/11, revised April 1990)

91/07 EP	Olivier CADOT	**"Lending to Insolvent Countries: A Paradoxical Story,"** January 1991
91/08 EP	Charles WYPLOSZ	**"Post-Reform East and West: Capital Accumulation and the Labour Mobility Constraint,"** January 1991
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91/10 TM	Luc Van WASSENHOVE and C. N. POTTS	**"Integrating Scheduling with Batching and Lot-Sizing: A Review of Algorithms and Complexity"**, February 1991
91/11 TM	Luc VAN WASSENHOVE et al.	**"Multi-Item Lotsizing in Capacitated Multi-Stage Serial Systems"**, February 1991
91/12 TM	Albert ANGEHRN	**"Interpretative Computer Intelligence: A Link between Users, Models and Methods in DSS"**, February 1991
91/13 EP	Michael BURDA	**"Labor and Product Markets in Czechoslovakia and the Ex-GDR: A Twin Study"**, February 1991
91/14 MKT	Roger BETANCOURT and David GAUTSCHI	**"The Output of Retail Activities: French Evidence"**, February 1991
91/15 OB	Manfred F.R. KETS DE VRIES	**"Exploding the Myth about Rational Organisations and Executives"**, March 1991
91/16 TM	Arnoud DE MEYER and Kasra FERDOWS et.al.	**"Factories of the Future: Executive Summary of the 1990 International Manufacturing Futures Survey"**, March 1991
91/17 TM	Dirk CATTRYSSE, Roelof KUIK, Marc SALOMON and Luk VAN WASSENHOVE	**"Heuristics for the Discrete Lotsizing and Scheduling Problem with Setup Times"**, March 1991