\\ 141 \\

Flow and open shop scheduling on two machines with transportation times and machine-independent processing times in NP-hard

di

Mauro Dell'Amico
R.J.M. Vaessens

Maggio 1996

Università degli Studi di Modena
Dipartimento di Economia Politica
Viale Berengario, 51
41100 Modena (Italia)
e-mail: dellamico@unimo.it

Flow and open shop scheduling on two machines with transportation times and machine-independent processing times is NP-hard

MAURO DELL'AMICO / *Dipartimento di Economia Politica,*
Università di Modena, Via Berengario 51, 41100 Modena, Italy;
Email: dellamic@elet.polimi.it

R.J.M. VAESSENS / *Department of Mathematics and Computing Science,*
Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven
Email: robv@win.tue.nl

Abstract

We consider non-preemptive flow-shop and open-shop with two machines and with an additional constraint requiring a minimum time lag between the processing of the two operation of a job. This time lag represent a transportation time needed to move a job from one machine to an other. The objective function is to minimize the maximum completion time of the operations. We show that both problems are strongly NP-hard even when both operations of a same job has identical processing time.

Key words: scheduling, flow-shop, open-shop, complexity.

1 Introduction

We consider the *flow-shop* and the *open-shop* scheduling problem. In the flow-shop m machines and n jobs are given. Each job consists of m operations each of which has a given processing time and has to be performed on a specific machine. The i-th operation of a job must start after the completion of operation $i-1$. Two operations on the same machine cannot be performed at the same time. In the open-shop the order in which the operations from a same job are performed is immaterial. It is only required that the two operations are not executed at the same time. The objective function, for both problems, is to minimize the *makespan* i.e. the maximum completion time of an operation. Following the standard notation introduced in Graham et al. [1979] the flow-shop is denoted by $F||C_{max}$ and the open-shop by $O||C_{max}$. When the number of machines is fixed the above notations become $Fm||C_{max}$ and $Om||C_{max}$.

In this paper we consider a generalization of shop problems with two machines, obtained by assuming that a job must be transported from one machine to the other. Thus a *transportation time* is defined, for each job, and the latter operation can start only when the given time is spent, after the completion of the first operation.

In the following section 2 we give the formal definition of the two problems and briefly review the existing literature. In section 4 we consider the flow-shop problem and we prove that it is strongly NP-hard even when the processing times of the two operations are identical. In the last section we show that the same time complexity holds for the open-shop problem with identical processing times.

2 Notations and Literature Review

We first consider the flow-shop problem. Given are 2 machines and a set J of n jobs each consisting of two operations. For each job $j \in J$ the first operation has to be processed by machine 1 and the second operation by machine 2; the processing time is identical for both operations and is denoted by p_j. Furthermore, for each job a minimum delay l_j (time lag) is given between the completion of the first operation of job j and the start of the second one. Our goal is to find a schedule that minimizes the maximum total completion time of any job. The problem can be denoted as $F2|p_{1j} = p_{2j}, l_j|C_{max}$.

More formally, let $S_j^i \in \mathbb{R} \cup \{0\}$ denote the start time of the unique operation of job j that needs to be processed by machine i. The following requirements have to be satisfied:

$$S_j^2 \geq S_j^1 + p_j + l_j, \qquad j \in J \tag{1}$$

$$S_{j1}^i \geq S_{j2}^i + p_{j2} \text{ or } S_{j2}^i \geq S_{j1}^i + p_{j1} \qquad i \in \{1,2\}, j1 \in J, j2 \in J, j1 \neq j2 \tag{2}$$

Constraint (1) ensures that the second operation of each job j starts at least l_j time units after the completion of the first operation, whereas (2) is a "disjunctive" constraint which ensures that the processing of two different jobs on the same machine do not overlap.

The *length* C of a schedule S is $\max_{j \in J}(S_j^2 + p_j)$, i.e., the earliest time at which all operations are completed. The problem is to find an *optimal* schedule which satisfies (1) and (2) and has minimum length.

A schedule can be completely characterized by the order $j_1^1, \ldots, j_n^1$ of the jobs on machine 1 and the order $j_1^2, \ldots, j_n^2$ of the jobs on machine 2. However, if the order on the first machine is given, the optimal complete solution can be obtained in polynomial time by scheduling the jobs on machine 1 as early as possible (i.e. by setting $S_1^1 = 0$; $S_j^1 = S_j^1 - 1 + p_j$ for $j = 2, \ldots, n$), and by scheduling the jobs on machine 2 as in the optimal solution of a single machine problem with release times given by $r_j = S_j^1 + p_j + l_j \forall j$.

In the case of the open-shop we use the same notation introduced for the flow-shop. The problem is defined by

$$S_j^1 \geq S_j^2 + p_j + l_j \text{ or } S_j^2 \geq S_j^1 + p_j + l_j, \qquad j \in J, \tag{3}$$

and by (2). Constraint (3) is the equivalent of (1) for the flow-shop. The objective function is: minimize $\max_{j \in J}(S_j^1 + p_j, S_j^2 + p_j)$. To characterize a schedule it is necessary to give both the order of the jobs on machine 1 and 2. The problem can be denoted by $O2|p_{1j} = p_{2j}, l_j|C_{max}$.

It is well known that problems $F2||C_{max}$ and $O2||C_{max}$ are solvable in polynomial time (Johnson [1954], Gonzalez and Shani [1976]). Both the open-shop and the flow shop become NP-hard when three machines are considered: $O3||C_{max}$ is NP-hard in ordinary sense (Gonzalez and Shani [1976]) whereas $F3||C_{max}$ is strongly NP-hard (Garey,Johnson and Sethi [1976]).

The flow-shop with two machines and transportation times has been proved to be strongly NP-hard by Lenstra [-]. The detail of the proof are reported in Dell'Amico [1993] where it is also proved that the preemptive version of the problem remains strongly NP-hard.

The open-shop with two machines and identical transportation times has been proved to be NP-hard in Rayward-Smith and Rebaine [1992]. This problem remains NP-hard even if the processing times on one machine are all zero (Strusevich [1994]). The problem with different transportation times, but restricted in such a way that the maximum transportation time do not exceedes the length of the minimum processing time is solvable in $O(n)$ (Rebaine and Strusevich [1995]).

3 Flow shop

In this section we consider the two machine flow shop problem introduced in section 2. We first give a lower bound on the optimal solution value and than we use it to proof the strongly NP-hardness of the problem.

3.1 Lower bound

Suppose a schedule S with length C is given: we will derive a minimum value for C depending on the processing times and the delays. Let $j_1^1, \ldots, j_n^1$ denote the order of the jobs on machine 1 and $j_1^2, \ldots, j_n^2$ denote the order of the jobs on machine 2. Our goal is to prove that

$$C\sum_{j=1}^{n} p_j \geq (\sum_{j=1}^{n} p_j)^2 + \sum_{j=1}^{n} p_j(l_j + p_j) \tag{4}$$

which immediately gives the lower bound

$$LBF = \sum_{j=1}^{n} p_j + \sum_{j=1}^{n} p_j(l_j + p_j)/\sum_{j=1}^{n} p_j. \tag{5}$$

Let us start by considering the difference between the starting time of the second and the first operation of a job $j \in J$, i.e. $S_j^2 - S_j^1$. Using constraint (1) and an algebraic manipulation we obtain:

$$\sum_{j=1}^{n} p_j(p_j+l_j) \le \sum_{j=1}^{n} p_j(S_j^2 - S_j^1) = \sum_{j=1}^{n} p_j S_j^2 - \sum_{j=1}^{n} p_j S_j^1 = \sum_{l=1}^{n} p_{j_l^2} S^2_{j_l^2} - \sum_{l=1}^{n} p_{j_l^1} S^1_{j_l^1}. \tag{6}$$

Reminding that any operation is completed at time C we can observe that the maximum starting time for the second operation of a job j_l^2 is

$$S^2_{j_l^2} \le C - \sum_{k=l}^{n} p_{j_k^2}. \tag{7}$$

Since no job can be scheduled before time zero we also have job j_l^1 is

$$S^1_{j_l^1} \ge \sum_{k=1}^{l-1} p_{j_k^1}. \tag{8}$$

Using inequalities (6), (7) and (8) we obtain

$$\begin{aligned}
\sum_{j=1}^{n} p_j(p_j+l_j) &\le \sum_{l=1}^{n} p_{j_l^2}\Big(C - \sum_{k=l}^{n} p_{j_k^2}\Big) - \sum_{l=1}^{n} p_{j_l^1} \sum_{k=1}^{l-1} p_{j_k^1} \\
&= C\sum_{l=1}^{n} p_{j_l^2} - \sum_{l=1}^{n} p_{j_l^2} \sum_{k=l}^{n} p_{j_k^2} - \sum_{l=1}^{n} p_{j_l^1} \sum_{k=1}^{l-1} p_{j_k^1} \\
&= C\sum_{j=1}^{n} p_j - \sum_{j=1}^{n} (p_{j_l^2})^2 - \sum_{l=1}^{n} \sum_{k=l+1}^{n} p_{j_l^2} p_{j_k^2} - \sum_{l=1}^{n} \sum_{k=1}^{l-1} p_{j_l^1} p_{j_k^1} \qquad (9)
\end{aligned}$$

Note that the last two terms in (9) are independent of the sequence of jobs, indeed any product $p_r p_s$ with $r \in J, s \in J$ and$r \neq s$ is added exactly once in each of the two sums. Therefore we have

$$\begin{aligned}
&\sum_{j=1}^{n} (p_{j_l^2})^2 + \sum_{l=1}^{n} \sum_{k=l+1}^{n} p_{j_l^2} p_{j_k^2} + \sum_{l=1}^{n} \sum_{k=1}^{l-1} p_{j_l^1} p_{j_k^1} \\
= &\sum_{j=1}^{n} (p_j)^2 + \sum_{l=1}^{n} \sum_{k=l+1}^{n} p_l p_k + \sum_{l=1}^{n} \sum_{k=1}^{l-1} p_l p_k \\
= &\Big(\sum_{j=1}^{n} p_j\Big)^2 \qquad (10)
\end{aligned}$$

From (9) and (10) we immediately obtain inequality (6) and the required lower bound.

Note that when the lower bound LBF is equal to the optimum completion time C, all the inequalities used to obtain the bound must hold with the "=" sign, so we have that:

(i) for any job the second operation starts exactly at the completion time of the first operation plus the transportation time (inequality (6));

(ii) the last operation on the second machine is completed at C and no idle time exists between two consecutive operations on machine 2 (inequality (7));

(iii) the first machine must process all operations from time 0 and without any idle time between two operations (inequality (8)).

3.2 Proof of NP-hardness

In the following theorem we prove that the flow shop problem described above is NP-hard.

Theorem 3.1 *The flow shop problem $F2|p_{1j} = p_{2j}, l_j|C_{max}$ is NP-hard.*

Proof: We give a polynomial-time reduction from the 3-PARTITION problem to the decision variant of this scheduling problem.

The 3-PARTITION problem is defined as follows: given are $3N$ items of size $x_k \in \mathbb{R}$ with

- $\sum_{k=1}^{3N} x_k = NX$ for some $X \in \mathbb{R}$ and
- $\forall 1 \leq k \leq 3N : \frac{X}{4} < x_k < \frac{X}{2}$;

the question is whether there exists a partition $K_1, \ldots, K_N$ of $\{1, \ldots, 3N\}$ such that

$$\sum_{k \in K_l} x_i = X \text{ for all } 1 \leq l \leq N.$$

3-PARTITION is proved to be strongly NP-complete by Garey and Johnson [1975]. Note that each set K_l in such a 3-partition contains exactly 3 items.

Consider an instance of 3-PARTITION: we transform it into an instance of the decision variant of problem F such that there exists a feasible schedule of a certain length if and only if a 3-partition exists.

The transformation is as follows. We define $4N$ jobs:

$$p_j = x_j \quad l_j = (2N+1)X - x_j \quad \text{for } 1 \leq j \leq 3N, \tag{11}$$

$$p_j = X \qquad l_j = (2N-2)X \qquad \text{for } 3N+1 \leq j \leq 4N. \tag{12}$$

We call the jobs of the first group *partition jobs* and the jobs of the second group *forcing jobs.* Now we require a schedule of length at most $4NX$.

Let us compute lower bound LBF for the above instance of problem F. We have

$$\sum_{j=1}^{3N} p_j = \sum_{j=3N+1}^{4N} p_j = NX$$

and

$$\sum_{j=1}^{3N} p_j(l_j + p_j) = NX(2N+1)X, \quad \sum_{j=3N+1}^{4N} p_j(l_j + p_j) = NX(2N-1)X,$$

thus the bound is $LBF = 4NX$.

We first show that if a YES answer exists for a given instance of 3-PARTITION then the corresponding schedule of F has an optimal schedule of length $4NX$. We schedule each forcing job j with $S_j^1 = (2(j - 3N - 1) + 1)X$ and $S_j^2 = S_j^1 + (2N - 1)X$ thus leaving exactly N empty buckets of length X in $[0, 2NX)$, on machine 1, and N in $[2NX, 4NX)$, on machine 2 (see Figure 1).

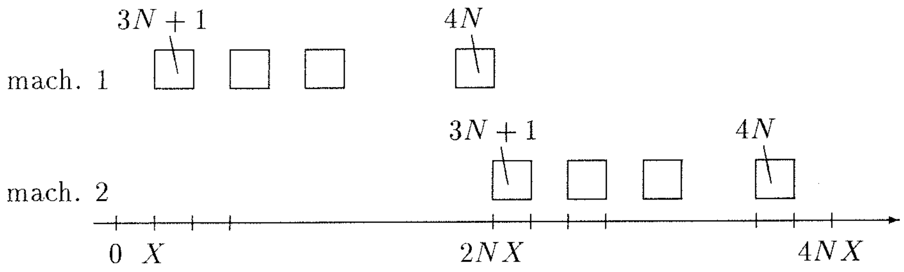

Figure 1: schedule of the forcing jobs.

Since a partition into N triples exists then the i-th empty bucket on machine 1 can be exactly filled with the first operation of the three jobs corresponding to the three items in K_i. It is not difficult to see that the second operation of these jobs can be scheduled in $[2NX + (2i - 1)X, 2NX + 2iX)$ so that the i-th bucket on machine 2 is completely filled. The resulting schedule occupies all the interval $[0, 2NX)$ on machine 1 and the interval $[2NX, 4NX)$ on machine 2 so giving an optimal schedule of length $4NX$.

Now suppose that a schedule S exists with length $C = 4NX$. From lower bound (5) we know that the schedule is optimal and that no schedule can have a smaller completion time. Moreover, since the bound is tight, we know that the three conditions (i)–(iii) in the previous section hold. Hence the time interval $[0, 2NX)$ on machine 1 and the time interval $[2NX, 4NX)$ on machine 2 must be completely occupied and the first operation on the second machine must start at time $2NX$. Since the delay for each partition job is larger than $2NX$, the second operation of such a job cannot start at time $2NX$. Hence, the operation starting at time $2NX$ must belong to a forcing job, say k. Since no difference must exists between S_j^2 and $S_j^1 + p_j + l_j$, for all j, then the first operation of the forcing job k starts at time X, leaving the time interval $[0, X)$ empty. The only operations that can occupy this interval must be operations belonging to partition jobs and the sum of their processing times must be exactly X. Reminding that $X/4 < p_j < X/2$ for each partition job j, we have that there must be exactly three operations in $[0, X)$. The corresponding second operations completely fill the interval $[2NX + X, 2NX + 2X)$.

So now the interval $[0, 2X)$ on the first machine and the interval $[2NX, 2NX + 2X)$ on the second machine is occupied. We can reason similarly for each next interval of length $2X$, thus, by induction, we have that on the first machine the interval $[0, 2NX)$ can be divided into N parts of length $2X$. Each such part starts with three operations of total length X that belong to partition jobs, and finishes with an operation of length X that belongs to a forcing job. Therefore, this schedule induces a 3-partition of the given instance of 3-PARTITION, which conclude the proof. □

4 Open Shop

The following theorem proves that the open shop problem introduced in section 2 is strongly NP-hard.

Theorem 4.1 *The open shop problem $O2|p_{1j} = p_{2j}, l_j|C_{max}$ is strongly NP-hard.*

Proof: We use a transformation from 3-PARTITION similar to that introduced in the previous section for the flow shop problem.

Given an instance of 3-PARTITION we define an instance of open-shop with $4N + 1$ jobs. As in the case of flow shop the first $4N$ jobs are partition and forcing jobs with processing times and delays defined by (11) and (12). The last job has processing time $p_{4N+1} = 2NX$ and zero delay. We look for a schedule of length $4NX$.

If a 3-partition exists a schedule of length $4NX$ can be obtained by scheduling the first $4N$ jobs as in the proof of theorem 3.1 and the remaining job with the operation on machine 2 starting at time zero, and the operation on machine 1 starting at time $2NX$. The solution has length $4NX$ and is optimal since it is equal to the trivial lower bound

$$LBO = \sum_{j=1}^{n} p_j/2.$$

We now show that if a schedule of length $4NX$ exists, then a solution to the corresponding instance of 3-PARTITION is defined. In any solution of length $4NX$ the job $4N + 1$ has to start at time 0 on one machine and to finish at time $4NX$ on the other machine. Let us suppose that job $4N + 1$ starts its operation on the second machine at time 0 (and its operation on the first machine at time $2NX$). It is easy to see that with this assumption we have no lack of generality, indeed the equality of the processing times and the absence of precedence between the operations of a same job, allows to renumber the machines without changing the solution structure. In this schedule the operations on machine 1 precedes the operations on machine 2, for jobs $1\ldots, 4N$. Therefore the relations used to obtain lower bound LBF are valid for jobs $1\ldots, 4N$. In particular one can see that conditions (i)–(iii) in section 3.1 hold. Applying the same reasoning used in the proof of theorem 3.1 one can see that this schedule induces a 3-partition and the proof is concluded. □

Acknowledgments

This research was partially supported by Human Capital and Mobility Project ERB-CHRX-CT93-0087.

References

M. DELL'AMICO (1993) Shop problems with two machines and time lags, *Operations Research*, to appear.

M.R. GAREY AND JOHNSON D.S. (1975), Complexity results for multiprocessor scheduling under resource constraints, *SIAM J. Comput. 4*, 397-411.

M.R. GAREY, D.S. JOHNSON AND R. SETHI(1979), The complexity of flowshopp and jobshop scheduling, *Mathematics of Operation Research*, 1, 117-129.

T. GONZALEZ AND S.SHANI (1976), Open shop scheduling to minimize finish time, J. ACM, 23, 665-679.

R.L. GRAHAM, E.L. LAWLER, J.K. LENSTRA AND RINNOOY KAN A.H.G. (1979), Optimization and Approximation in Deterministic Sequencing and Scheduling: a Survey. *Annals of Discrete Mathematics* 5, 287-326.

S.M. JOHNSON (1954). Optimal Two- and Three-Stage Production Schedules with Setup Times Included, *Naval Res. Logist. Quart.* 1, 61-68.

J.K. LENSTRA (-). Unpublished.

V.J. RAYWARD-SMITH AND D. REBAINE (1992), Open shop scheduling with delays, *Theoretical Informatics and Applications*, 26, 439-448.

D. REBAINE AND V.A. STRUSEVICH (1995), The two machine open shop scheduling problem with transportation times, (unpublished mänuscript).

V.A. STRUSEVICH (1994), The open shop scheduling problem with a non-bottleneck stage. CASSM R&D Paper 2, Center for Applied Statistics and System Modelling, University of Greenwich, London, U.K.

1. Maria Cristina Marcuzzo [1985] "Yoan Violet Robinson (1903-1983)", pp. 134
2. Sergio Lugaresi [1986] "Le imposte nelle teorie del sovrappiù", pp. 26
3. Massimo D'Angelillo e Leonardo Paggi [1986] "PCI e socialdemocrazie europee. Quale riformismo?", pp. 158
4. Gian Paolo Caselli e Gabriele Pastrello [1986] "Un suggerimento hobsoniano su terziario ed occupazione: il caso degli Stati Uniti 1960/1983", pp. 52
5. Paolo Bosi e Paolo Silvestri [1986] "La distribuzione per aree disciplinari dei fondi destinati ai Dipartimenti, Istituti e Centri dell'Università di Modena: una proposta di riforma", pp. 25
6. Marco Lippi [1986] "Aggregations and Dynamic in One-Equation Econometric Models", pp. 64
7. Paolo Silvestri [1986] "Le tasse scolastiche e universitarie nella Legge Finanziaria 1986", pp. 41
8. Mario Forni [1986] "Storie familiari e storie di proprietà. Itinerari sociali nell'agricoltura italiana del dopoguerra", pp. 165
9. Sergio Paba [1986] "Gruppi strategici e concentrazione nell'industria europea degli elettrodomestici bianchi", pp. 56
10. Nerio Naldi [1986] "L'efficienza marginale del capitale nel breve periodo", pp. 54
11. Fernando Vianello [1986] "Labour Theory of Value", pp. 31
12. Piero Ganugi [1986] "Risparmio forzato e politica monetaria negli economisti italiani tra le due guerre", pp. 40
13. Maria Cristina Marcuzzo e Annalisa Rosselli [1986] "The Theory of the Gold Standard and Ricardo's Standard Comodity", pp. 30
14. Giovanni Solinas [1986] "Mercati del lavoro locali e carriere di lavoro giovanili", pp. 66
15. Giovanni Bonifati [1986] "Saggio dell'interesse e domanda effettiva. Osservazioni sul cap. 17 della General Theory", pp. 42
16. Marina Murat [1986] "Betwin old and new classical macroeconomics: notes on Lejonhufvud's notion of full information equilibrium", pp. 20
17. Sebastiano Brusco e Giovanni Solinas [1986] "Mobilità occupazionale e disoccupazione in Emilia Romagna", pp. 48
18. Mario Forni [1986] "Aggregazione ed esogeneità", pp. 13
19. Sergio Lugaresi [1987] "Redistribuzione del reddito, consumi e occupazione", pp. 17
20. Fiorenzo Sperotto [1987] "L'immagine neopopulista di mercato debole nel primo dibattito sovietico sulla pianificazione", pp. 34
21. M. Cecilia Guerra [1987] "Benefici tributari nel regime misto per i dividendi proposto dalla commissione Sarcinelli: una nota critica", pp. 9
22. Leonardo Paggi [1987] "Contemporary Europe and Modern America: Theories of Modernity in Comparative Perspective", pp. 38
23. Fernando Vianello [1987] "A Critique of Professor Goodwin's 'Critique of Sraffa'", pp. 12
24. Fernando Vianello [1987] "Effective Demand and the Rate of Profits. Some Thoughts on Marx, Kalecki and Sraffa", pp. 41
25. Anna Maria Sala [1987] "Banche e territorio. Approccio ad un tema geografico-economico", pp. 40
26. Enzo Mingione e Giovanni Mottura [1987] "Fattori di trasformazione e nuovi profili sociali nell'agricoltura italiana: qualche elemento di discussione", pp. 36
27. Giovanna Procacci [1988] "The State and Social Control in Italy During the First World War", pp. 18
28. Massimo Matteuzzi e Annamaria Simonazzi [1988] "Il debito pubblico", pp. 62
29. Maria Cristina Marcuzzo (a cura di) [1988] "Richard F. Kahn. A discipline of Keynes", pp. 118
30. Paolo Bosi [1988] "MICROMOD. Un modello dell'economia italiana per la didattica della politica fiscale", pp. 34
31. Paolo Bosi [1988] "Indicatori della politica fiscale. Una rassegna e un confronto con l'aiuto di MICROMOD", pp. 25
32. Giovanna Procacci [1988] "Protesta popolare e agitazioni operaie in Italia 1915-1918", pp. 45
33. Margherita Russo [1988] "Distretto Industriale e servizi. Uno studio dei trasporti nella produzione e nella vendita delle piastrelle", pp. 157
34. Margherita Russo [1988] "The effect of technical change on skill requirements: an empirical analysis", pp. 28
35. Carlo Grillenzoni [1988] "Identification, estimations of multivariate transfer functions", pp. 33
36. Nerio Naldi [1988] "'Keynes' concept of capital", pp. 40
37. Andrea Ginzburg [1988] "locomotiva Italia?", pp. 30
38. Giovanni Mottura [1988] "La 'persistenza' secolare. Appunti su agricoltura contadina ed agricoltura familiare nelle società industriali", pp. 40
39. Giovanni Mottura [1988] "L'anticamera dell'esodo. I contadini italiani della 'restaurazione contrattuale' fascista alla riforma fondiaria", pp. 40
40. Leonardo Paggi [1988] "Americanismo e riformismo. La socialdemocrazia europea nell'economia mondiale aperta", pp. 120
41. Annamaria Simonazzi [1988] "Fenomeni di isteresi nella spiegazione degli alti tassi di interesse reale", pp. 44
42. Antonietta Bassetti [1989] "Analisi dell'andamento e della casualità della borsa valori", pp. 12
43. Giovanna Procacci [1989] "State coercion and worker solidarity in Italy (1915-1918): the moral and political content of social unrest", pp. 41
44. Carlo Alberto Magni [1989] "Reputazione e credibilità di una minaccia in un gioco bargaining", pp. 56
45. Giovanni Mottura [1989] "Agricoltura familiare e sistema agroalimentare in Italia", pp. 84
46. Mario Forni [1989] "Trend, Cycle and 'Fortuitous cancellation': a Note on a Paper by Nelson and Plosser", pp. 4
47. Paolo Bosi , Roberto Golinelli , Anna Stagni [1989] "Le origini del debito pubblico e il costo della stabilizzazione", pp. 26
48. Roberto Golinelli [1989] "Note sulla struttura e sull'impiego dei modelli macroeconometrici", pp. 21
49. Marco Lippi [1989] "A Shorte Note on Cointegration and Aggregation", pp. 11
50. Gian Paolo Caselli e Gabriele Pastrello [1989] "The Linkage between Tertiary and Industrial Sector in the Italian Economy: 1951-1988. From an External Dependence to an International One", pp. 40
51. Gabriele Pastrello [1989] "Francois quesnay: dal Tableau Zig-zag al Tableau Formule: una ricostruzione", pp. 48
52. Paolo Silvestri [1989] "Il bilancio dello stato", pp. 34
53. Tim Mason [1990] "Tre seminari di storia sociale contemporanea", pp. 26
54. Michele Lalla [1990] "The Aggregate Escape Rate Analysed throught the Queueing Model", pp. 23
55. Paolo Silvestri [1990] "Sull'autonomia finanziaria dell'università", pp. 11
56. Paola Bertolini, Enrico Giovannetti [1990] "Uno studio di 'filiera' nell'agroindustria. Il caso del Parmigiano Reggiano", pp. 164
57. Paolo Bosi, Roberto Golinelli, Anna Stagni [1990] "Effetti macroeconomici, settoriali e distributivi dell'armonizzazione dell'IVA", pp. 24
58. Michele Lalla [1990] "Modelling Employment Spells from Emilia Labour Force Data", pp. 18

59. Andrea Ginzburg [1990] "Politica Nazionale e commercio internazionale", pp. 22

60. Andrea Giommi [1990] "La probabilità individuale di risposta nel trattamento dei dati mancanti", pp. 13

61. Gian Paolo Caselli e Gabriele Pastrello [1990] "The service sector in planned economies. Past experiences and future prospectives", pp. 32

62. Giovanni Solinas [1990] "Competenze, grandi industrie e distretti industriali,. Il caso Magneti Marelli", pp. 23

63. Andrea Ginzburg [1990] "Debito pubblico, teorie monetarie e tradizione civica nell'Inghilterra del Settecento", pp. 30

64. Mario Forni [1990] "Incertezza, informazione e mercati assicurativi: una rassegna", pp. 37

65. Mario Forni [1990] "Misspecification in Dynamic Models", pp. 19

66. Gian Paolo Caselli e Gabriele Pastrello [1990] "Service Sector Growth in CPE's: An Unsolved Dilemma", pp. 28

67. Paola Bertolini [1990] "La situazione agro-alimentare nei paesi ad economia avanzata", pp. 20

68. Paola Bertolini [1990] "Sistema agro-alimentare in Emilia Romagna ed occupazione", pp. 65

69. Enrico Giovannetti [1990] "Efficienza ed innovazione: il modello "fondi e flussi" applicato ad una filiera agro-industriale", pp. 38

70. Margherita Russo [1990] "Cambiamento tecnico e distretto industriale: una verifica empirica", pp. 115

71. Margherita Russo [1990] "Distretti industriali in teoria e in pratica: una raccolta di saggi", pp. 119

72. Paolo Silvestri [1990] " La Legge Finanziaria. Voce dell'enciclopedia Europea Garzanti", pp. 8

73. Rita Paltrinieri [1990] "La popolazione italiana: problemi di oggi e di domani", pp. 57

74. Enrico Giovannetti [1990] "Illusioni ottiche negli andamenti delle Grandezze distributive: la scala mobile e l''appiattimento' delle retribuzioni in una ricerca", pp. 120

75. Enrico Giovannetti [1990] "Crisi e mercato del lavoro in un distretto industriale: il bacino delle ceramiche. Sez I", pp. 150

76. Enrico Giovannetti [1990] " Crisi e mercato del lavoro in un distretto industriale: il bacino delle ceramiche. Sez. II", pp. 145

78. Antonietta Bassetti e Costanza Torricelli [1990] "Una riqualificazione dell'approccio bargaining alla selezioni di portafoglio", pp. 4

77. Antonietta Bassetti e Costanza Torricelli [1990] "Il portafoglio ottimo come soluzione di un gioco bargaining", pp. 15

79. Mario Forni [1990] "Una nota sull'errore di aggregazione", pp. 6

80. Francesca Bergamini [1991] "Alcune considerazioni sulle soluzioni di un gioco bargaining", pp. 21

81. Michele Grillo e Michele Polo [1991] "Political Exchange and the allocation of surplus: a Model of Two-party competition", pp. 34

82. Gian Paolo Caselli e Gabriele Pastrello [1991] "The 1990 Polish Recession: a Case of Truncated Multiplier Process", pp. 26

83. Gian Paolo Caselli e Gabriele Pastrello [1991] "Polish firms: Pricate Vices Pubblis Virtues", pp. 20

84. Sebastiano Brusco e Sergio Paba [1991] "Connessioni, competenze e capacità concorrenziale nell'industria della Sardegna", pp. 25

85. Claudio Grimaldi, Rony Hamaui, Nicola Rossi [1991] "Non Marketable assets and hauseholds' Portfolio Choice: a Case of Study of Italy", pp. 38

86. Giulio Righi, Massimo Baldini, Alessandra Brambilla [1991] "Le misure degli effetti redistributivi delle imposte indirette: confronto tra modelli alternativi", pp. 47

87. Roberto Fanfani, Luca Lanini [1991] "Innovazione e servizi nello sviluppo della meccanizzazione agricola in Italia", pp. 35

88. Antonella Caiumi e Roberto Golinelli [1992] "Stima e applicazioni di un sistema di domanda Almost Ideal per l'economia italiana", pp. 34

89. Maria Cristina Marcuzzo [1992] "La relazione salari-occupazione tra rigidità reali e rigidità nominali", pp. 30

90. Mario Biagioli [1992] "Employee financial participation in enterprise results in Italy", pp. 50

91. Mario Biagioli [1992] "Wage structure, relative prices and international competitiveness", pp. 50

92. Paolo Silvestri e Giovanni Solinas [1993] "Abbandoni, esiti e carriera scolastica. Uno studio sugli studenti iscritti alla Facoltà di Economia e Commercio dell'Università di Modena nell'anno accademico 1990/1991", pp. 30

93. Gian Paolo Caselli e Luca Martinelli [1993] "Italian GPN growth 1890-1992: a unit root or segmented trend representatin?", pp. 30

94. Angela Politi [1993] "La rivoluzione fraintesa. I partigiani emiliani tra liberazione e guerra fredda, 1945-1955", pp. 55

95. Alberto Rinaldi [1993] "Lo sviluppo dell'industria metalmeccanica in provincia di Modena: 1945-1990", pp. 70

96. Paolo Emilio Mistrulli [1993] "Debito pubblico, intermediari finanziari e tassi d'interesse: il caso italiano", pp. 30

97. Barbara Pistoresi [1993] "Modelling disaggregate and aggregate labour demand equations. Cointegration analysis of a labour demand function for the Main Sectors of the Italian Economy: 1950-1990", pp. 45

98. Giovanni Bonifati [1993] "Progresso tecnico e accumulazione di conoscenza nella teoria neoclassica della crescita endogena. Una analisi critica del modello di Romer", pp. 50

99. Marcello D'Amato e Barbara Pistoresi [1994] "The relationship(s) among Wages, Prices, Unemployment and Productivity in Italy", pp. 30

100. Mario Forni [1994] "Consumption Volatility and Income Persistence in the Permanent Income Model", pp. 30

101. Barbara Pistoresi [1994] "Using a VECM to characterise the relative importance of permanent and transitority components", pp. 28

102. Gian Paolo Caselli and Gabriele Pastrello [1994] "Polish recovery form the slump to an old dilemma", pp. 20

103. Sergio Paba [1994] "Imprese visibili, accesso al mercato e organizzazione della produzione", pp. 20

104. Giovanni Bonifati [1994] "Progresso tecnico, investimenti e capacità produttiva", pp. 30

105. Giuseppe Marotta [1994] "Credit view and trade credit: evidence from Italy", pp. 20

106. Margherita Russo [1994] "Unit of investigation for local economic development policies", pp. 25

107. Luigi Brighi [1995] "Monotonicity and the demand theory of the weak axioms", pp. 20

108. Mario Forni e Lucrezia Reichlin [1995] "Modelling the impact of technological change across sectors and over time in manufactoring", pp. 25

109. Marcello D'Amato and Barbara Pistoresi [1995] "Modelling wage growth dynamics in Italy: 1960-1990", pp. 38

110. Massimo Baldini [1995] "INDIMOD. Un modello di microsimulazione per lo studio delle imposte indirette", pp. 37

111. Paolo Bosi [1995] "Regionalismo fiscale e autonomia tributaria: l'emersione di un modello di consenso", pp. 38

112. Massimo Baldini [1995] "Aggregation Factors and Aggregation Bias in Consumer Demand", pp. 33

113. Costanza Torricelli [1995] "The information in the term structure of interest rates. Can stocastic models help in resolving the puzzle?" pp. 25

114. Margherita Russo [1995] "Industrial complex, pôle de développement, distretto industriale. Alcune questioni sulle unità di indagine nell'analisi dello sviluppo." pp. 45

115. Angelika Moryson [1995] “50 Jahre Deutschland. 1945 - 1995” pp. 21

116. Paolo Bosi [1995] “Un punto di vista macroeconomico sulle caratteristiche di lungo periodo del nuovo sistema pensionistico italiano.” pp. 32

117. Gian Paolo Caselli e Salvatore Curatolo [1995] “Esistono relazioni stimabili fra dimensione ed efficienza delle istituzioni e crescita produttiva? Un esercizio nello spirito di D.C. North.” pp. 11

118. Mario Forni e Marco Lippi [1995] “Permanent income, heterogeneity and the error correction mechanism.” pp. 21

119. Barbara Pistoresi [1995] “Co-movements and convergence in international output. A Dynamic Principal Components Analysis” pp. 14

120. Mario Forni e Lucrezia Reichlin [1995] “Dynamic common factors in large cross-section” pp. 17

121. Giuseppe Marotta [1995] “Il credito commerciale in Italia: una nota su alcuni aspetti strutturali e sulle implicazioni di politica monetaria” pp. 20

122. Giovanni Bonifati [1995] “Progresso tecnico, concorrenza e decisioni di investimento: una analisi delle determinanti di lungo periodo degli investimenti” pp. 25

123. Giovanni Bonifati [1995] “Cambiamento tecnico e crescita endogena: una valutazione critica delle ipotesi del modello di Romer” pp. 21

124. Barbara Pistoresi e Marcello D’Amato [1995] “La riservatezza del banchiere centrale è un bene o un male? ,Effetti dell’informazione incompleta sul benessere in un modello di politica monetaria.” pp. 32

125. Barbara Pistoresi [1995] “Radici unitarie e persistenza: l’analisi univariata delle fluttuazioni economiche.” pp. 33

126. Barbara Pistoresi e Marcello D’Amato [1995] “Co-movements in European real outputs” pp. 20

127. Antonio Ribba [1996] “Ciclo economico, modello lineare-stocastico, forma dello spettro delle variabili macroeconomiche” pp. 31

128. Carlo Alberto Magni [1996] “Repeatable and una tantum real options a dynamic programming approach” pp. 23

129. Carlo Alberto Magni [1996] “Opzioni reali d’investimento e interazione competitiva: programmazione dinamica stocastica in optimal stopping” pp. 26

130. Carlo Alberto Magni [1996] “Vaghezza e logica fuzzy nella valutazione di un’opzione reale” pp. 20

131. Giuseppe Marotta [1996] “Does trade credit redistribution thwart monetary policy? Evidence from Italy” pp. 20

132. Mauro Dell’Amico e Marco Trubian [1996] “Almost-optimal solution of large weighted equicut problems” pp. 30

133. Carlo Alberto Magni [1996] “Un esempio di investimento industriale con interazione competitiva e avversione al rischio” pp. 20

134. Margherita Russo, Peter Börkey, Emilio Cubel, François Lévêque, Francisco Mas [1996] “Local sustainability and competitiveness: the case of the ceramic tile industry” pp. 66

135. Margherita Russo [1996] “Camionetto tecnico e relazioni tra imprese” pp. 190

136. David Avra Lane, Irene Poli, Michele Lalla, Alberto Roverato [1996] “Lezioni di probabilità e inferenza statistica” pp. 288

137. David Avra Lane, Irene Poli, Michele Lalla, Alberto Roverato [1996] “Lezioni di probabilità e inferenza statistica - Esercizi svolti - “ pp. 302

138. Barbara Pistoresi [1996] “Is an Aggregate Error Correction Model Representative of Disaggregate Behaviours? An example” pp. 24

139. Luisa Malaguti e Costanza Torricelli [1996] “Monetary policy and the term structure of interest rates”, pp. 30

140. Mauro Dell’Amico, Martine Labbé, Francesco Maffioli [1996] “Exact solution of the SONET Ring Loading Problem”, pp. 20