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A comparison of several optimization schemes for the integrated process planning and production scheduling problems

H. Ibrahim Demir
Lehigh University

Demir, H. Ibrahim

A Comparison of Several Optimization Schemes for the Integrated Process

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A Comparision of Several Optimization Schemes for the Integrated Process Planning and Production Scheduling Problems

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H.Ibrahim Demir

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Chairperson of Department

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Abstract

Traditionally process planning and scheduling functions are treated separately. Because of the pressure in reducing overall production lead times and the potential advantages of integration, research in integraing process planning and scheduling has regained its attention. Most proposed solutions to this problem are heuristic procedures due to the complex nature of the integrated problem. Analytical solutions are possible only for small sized problems. In this research we propose several off-line heuristic solutions by viewing the problem as a loading and a scheduling subproblem. Solutions for the loading subproblem assigns a route to each job by solving a mixed integer program. ATC (Apparent Tardiness Cost) scheduling heuristic is then used to schedule the jobs after the route assignment. Intensive simulation experiments are conducted which compares varous optimization schemes and a heuristic developed by Al-Refai and Wu (1996).

Chapter 1

Introduction

Process planning and scheduling are manufacturing system functions which are traditionally treated separately. Conflicting goals of these two functions and the lack of information feedback between them prompt the interest in integrating the two functions for improved overall performance. Process planning is an off-line manufacturing engineering function for generating manufacturing plan for a certain product given its design, market potential and the manufacturing resources at hand [3]. Process planning finds the best way to manufacture a part by finding the "optimal" processing sequence of the features and the ideal machines to process the part [6].

Production scheduling function is a resource allocator which considers timing information while allocating resources to the tasks [17]. Scheduling attempts to assign manufacturing resources to the operations indicated in the process plans in such a way that some criteria, such as meeting the due dates, are fulfilled. Unlike process planning, which works on one part at a time, scheduling takes into account all the parts specified in the production order and works on them simultaneously [6]. Since process planning and scheduling functions are often treated separately, independently developed process plans often produce poor input to its downstream scheduling problem.

The quality of process plans can directly influences the quality of scheduling in two aspects. Good processing time estimations, not only for machining but also for loading, unloading and machine set-ups, are necessary to build a reliable schedule. High quality operation routings should allow the scheduler to level the workshop loading and maximize workshop throughput at minimal cost, and yet gives respect to due dates. Process planning realizes a local cost minimization by generating a 'most pertinent' operation routing. However, if all process plans require the same 'high performant machine', scheduling ends up with severe bottleneck problems [11]. The advantages of integrated solution and the disadvantages of the separation of process planning and scheduling functions are discussed by [3], [7], [11], [1], [14] and [17].

Process planners typically assume unlimited resource and they typically don't consider operational aspects of the resources such as machine breakdowns or other unexpected occurrences. Since processes are made and selected independently they don't have any information feedback about shopfloor status or even the objectives at the shopfloor. Often process planning and scheduling have conflicting objectives and process planners' choice may very well be undesired input for the schedulers. As a result inherent structure of the process plans may cause unnecassary congestions in the shop, limits the achievable throughput rate of the system and hinders the overall efficiency. In practice, process plans are not completely followed at the shopfloor and plans are often altered arbitrarily to fit processing needs.

Chapter 2

Related Researches

The Job Shop Scheduling Problem by itself belongs to the class of NP-hard problems. Integrated process planning and scheduling problem is much harder to solve. Since exact solutions are only feasible for small size problems heuristic solutions are developed to find a reasonable solution to the problem .

from a modelling point of view we can define our problem as scheduling with flexible process plans or scheduling with alternative routing. There are alternative routes, flexible process plans, for each job and one route is to be selected for each job. In the literature exact solutions are tested for small problems. Most of the work are heuristics which decompose the problem into subproblems to get a feasible or efficient (in terms of computing time) solution. In the following related work to our research are briefly explained.

Wilhelm and Shin [16] developed three schemes for implementing alternate operations within the hierarchical structure of the FMS. They compared the results of these schemes with the performance achieved using no alternate operations and their result showed that alternate operations can reduce flow time (therefore in-process inventory) while increasing the machine utilization.

Sundaram and Fu [14] proposed a systematic method for integrating the two important planning functions in manufacturing. Their approach seemed to work pretty well on a number of problems that they solved. First they assign operations to the machines and then they find the key machine which has the highest load or minimum idle time. After determining the key machine they perform left shift operation to reduce the load on that machine.

Nasr and Elsayed [13] investigated the problem of minimizing the flow time in a general job shop type machining system with alternative machine tool routings. They develop a mixed integer programming. Two algorithms were developed one based on the mixed integer programming formulation that decompose the problem into subproblems to get tractable solution and the other is based on the SPT rule. Proposed algorithms presented efficient solutions to the problems and they are able to solve large scale problems in a very short time.

Jiang and Chen [9] investigated the influence of alternate process planning on the scheduling performance according to three criteria which are mean tardiness, mean work in process and mean machine utilization. They found that the choice of alternate process plans affects the three performance measures significantly and is highly interacted with the priority rules and the scheduling algorithm.

Khoshnevis and Chen [12] have developed a heuristic to show the potential impact of the integrated system of planning and scheduling . The performance of this simplified heuristic was found good.

Chen and Khoshnevis [6] investigated the problem of integrating the process planning and scheduling functions as a scheduling problem with flexible process plans. They developed a concurrent assignment algorithm based on the added flexibilities introduced by the integration and found several improvements over the traditional method. The improvements are as they stated :

". adding more flexibilities by building a process planning module into the system;
. considering several simultaneous assignments of parts to machines;
. making compromises among the assignments;
. introducing a time window so that the possible number of the assignments at each assignment stage is under control;
. compromising between the process planning related costs and the scheduling related costs through the selection of alternative machines and processes with

the aid of a process planning module. " (Chen and Khoshnevis , pp 342 [6])

Jiang and Hsiao [10] developed an analytic solution to the problem but their 0-1 integer programming is only applicable to small sized problems.

Huang *et al* [7] proposed a progressive approach that separates the planning and scheduling parts into preplanning, pairing planning and final planning phases. The activities within each phase take palace in different time periods. Since progressive approach reduces the computational complexity, it was able to be realized in a real manufacturing environment where time is critical.

H.C. Zhang and S.Mallur [17] introduced an integrated model that has three important modules: process planning module, production schedule and decision-making module. In the integrated model a hybrid dynamic and alternative process planning approach is used.

In their article J. Kempenaers *et al* [11] described the results of ESPRIT project COMPLAN , which aims at the implementation of an integrated automatic process planning and scheduling system based on the concept of non-linear process plans. In addition to the use of non-linear process plan for flexible load balancing and reactive scheduling , they presented a new collaborative approach based on production constraints as a means to realizing a feedback from scheduling to process planning.

Hutchison *et al* [8] developed two off-line and one real time scheduling scheme. The first of the off-line schemes gives an overall optimal solution to the problem but again it is only applicable to the small sized problems in terms of computational time requirements. The second off-line scheme decomposes the problem into loading and scheduling subproblem and finds optimal solution to both subproblems. In this research we adapted a part of off-line scheme for the purpose of comparison. It is desirable to find the overall optimal solution to the integrated process planning and scheduling problem but from the above research we can see that the complex nature of the problem makes hierarchical and sequential solution possible.

Al-Refai and Wu [1] developed an approach where they first formed route groups using a hierarchical clustering algorithm and later solving a generalized assignment problem which assigns a route to each job. The performance of route assignment is evaluated by a scheduling heuristic. This is conducted as iterative search which continues until the improvement is smaller than a prespecified value. The objective is to minimize total weighted tardiness.

Problem Set 20x5

Table 1 Avg. weighted tardiness for random route selection

		Avg. Tardiness				
Scheme	**Series**	**Prob1**	**Prob2**	**Prob3**	**Prob4**	**Prob5**
Random	Series1	5496.6	5160.9	2283.6	2590.3	2405.8

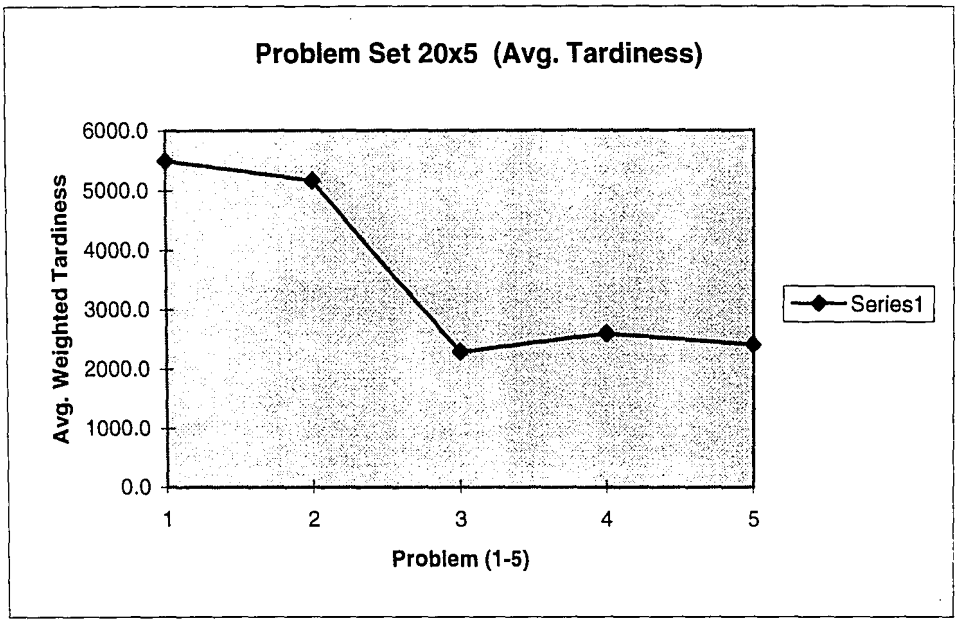

Figure 1 Avg. weighted tardiness for random route selection

Problem Set 20x5

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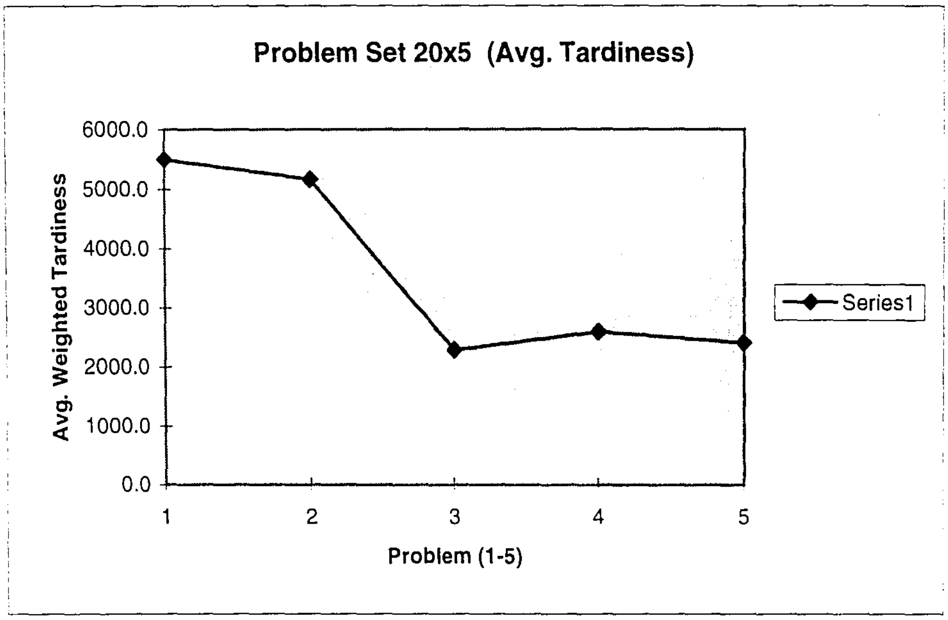

Figure 1 Avg. weighted tardiness for random route selection

Chapter 3

Problem Definition

We study the integrated process planning and production scheduling problem. A process planning decision corresponds to alternative routes that could be used for each job. One route must be selected for each job so that in the resulting scheduling problem total weighted tardiness could be minimized .

The purpose of this research is to compare various optimization schemes that consider both process planning and scheduling functions so as to increase the global performance. Since process planning and scheduling functions have conflicting goals even if we get optimal solutions for beach individual problem, we may not achieve the global optimum. We propose several schemes which integrate process planning and scheduling decisions. Traditional approaches consider process plan selection and scheduling independently so we compose a scheme which select the routes randomly and scheduled the jobs according to the independently selected routes. We use this scheme to represent the traditional approach which decouples completely process planning and scheduling. We then proposed five integrated schemes and compared their performance with the GAP approach developed by Al-Refai and Wu [1].

Chapter 4

Computational Experiments

The remainder of the research is an empirical study of different optimization schemes based on the following set up. Three groups of problem set are solved for static and dynamic cases. There are five test problems in each group 5×20, 20×5 and 30×10 (30 jobs and maximum10 operations). Five alternative routes are assumed for each job. Number of jobs and operations in each route are subject to variation. The number of operations are distributed randomly in the range of [10,15] for the set 5x20, [3,4] for the set 20x5 and [3,7] for the 30x10's. Processing times of the operations varies in the range of [10,50] and the weights of each job is found by uniform random numbers in the range [1,10]. Due dates are found by multiplying the total processing time for that specific route with a constant. This constant is chosen big enough to get 30-40% of the jobs tardy. This provided us some tardiness at the end of the scheduling so that we can compare the performance of different schemes. The loading part is coded in Lingo and the ATC heuristic is coded in C++ on an IBM RS-6000. The related cpu times for both set of programs are given in Tables 2,3 and 4 .

In Chapter 5, the computational results will be presented along with descriptions of each scheme. Six optimization schemes are compared for the problem sets 20x5 and 5x20. For the third problem set 30x10 only four schemes are compared.Each optimization scheme decomposed the problem as a loading and a scheduling subproblem . We used the same scheduling heuristic for all schemes while varying the loading subproblem. The different sets of schemes are summarized in Figure 2.

4.1 Robustness of the Problem

In the real world environment unexpected disruptions occur. If we assume the shop is deterministic and propose a solution based on that assumption, unexpected events such as machine breakdowns render our solution inefficient or even infeasible. In order to simulate the performance of the method under distruptions we perturbed the processing times by 5%, 15% and 25%. In this set of experoments p_i (processing time) are perturbed uniformly for each level and perturbed processing times (p_i') are calculated as :

$p_i' = \text{Max} \{ 0, p_i + p.U\}$ where $p=5, 15, 25$ and U changes uniformly in the range [-1,1]

We then solved five replica of each problem for the three level of perturbation then compare their results.

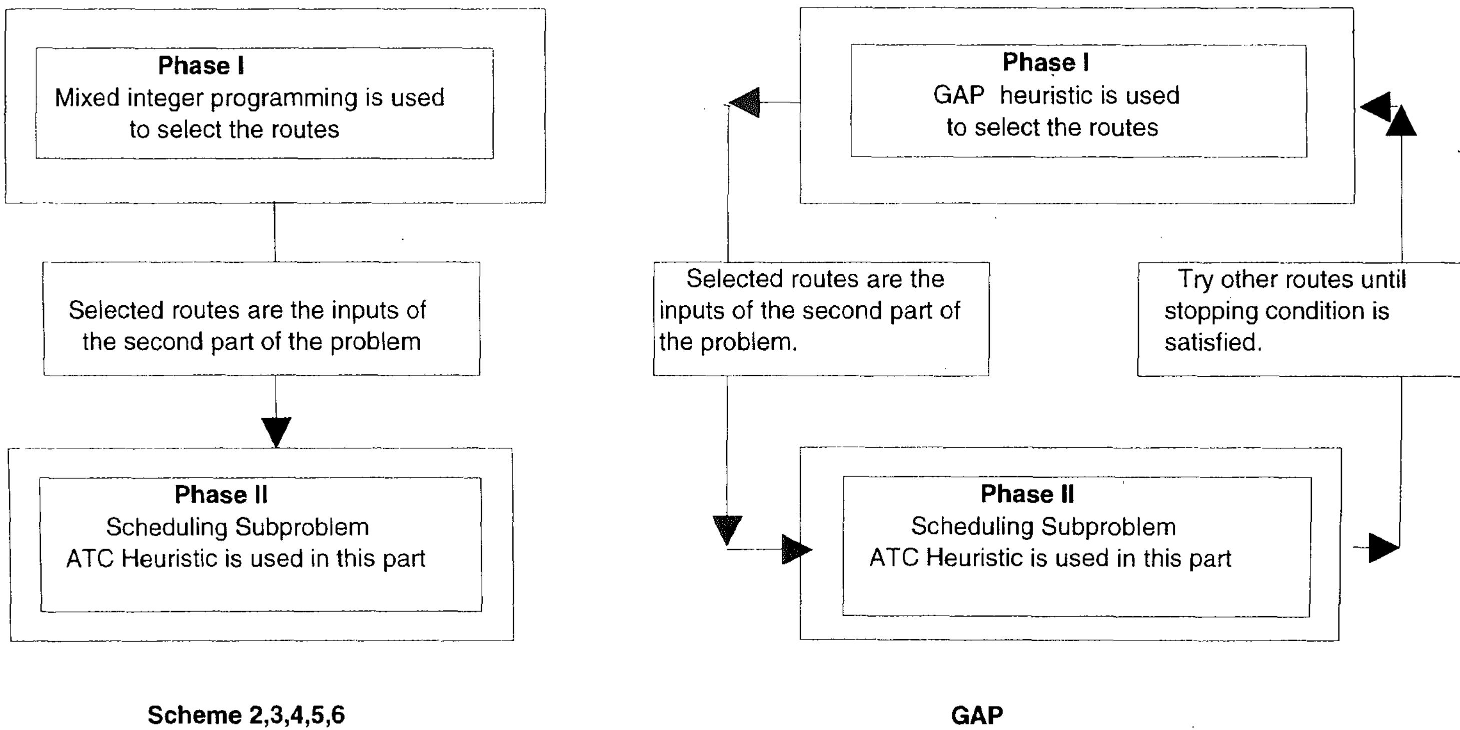

Figure 2 Comparison of GAP with the other schemes

Problem Set 20x5

Table 2 CPU time for the problem set 20x5 for loading and scheduling subproblems

CPU time required to solve the first part by using Lingo

	Lmax	**Lm**	**Lmax+Lm**	**Tard.**	**Lmax+Lm+Tard.**
Prob1	46.42	6.08	14.7	02:10.7	02:28.7
Prob2	02:40.0	5.95	43.64	09:00.0	13:19.7
Prob3	6.21	5.63	18.44	06:32.1	06:06.0
Prob4	15.17	6.27	11.63	10:42.5	09:52.5
Prob5	29.67	5.67	11.63	11:14.6	14:51.9

hr:min:sc 01:02:28.7 =1 hr 2 minutes and 28 seconds

2 Sample is taken for each Problem

(CPU time to schedule the problem ..in sec.)

	Prob1	**Prob2**	**Prob3**	**Prob4**	**Prob5**	**Avg**	**Grand. avg.**
First set	3	4	0	0	3	2	2.2
Second set	3	4	3	1	1	2.4	

Table 3 CPU time for the set 30x10 for loadind and scheduling subproblems

CPU time required to solve the first part by using Lingo

	Lmax	Lm	Lmax+Lm
Prob1	13:53.7	11.7	01:22.5
Prob2	22:18.6	12.55	01:13.2
Prob3	20:51.2	12.68	24.34
Prob4	21:49.1	12.42	59.23
Prob5	30:38.4	12.87	58.86

hr:min:sc 01:02:28.7 =1 hr 2 minutes and 28 seconds

2 Sample is taken for each Problem

(CPU time to schedule the problem ..in sec.)

	Prob1	Prob2	Prob3	Prob4	Prob5	Avg	Grand. avg.
First set	124	252	204	331	271	236.4	213.5
Second set	137	214	162	200	240	190.6	

Table 4 CPU time for the set 5x20 for loading and scheduling subproblems

CPU time required to solve the first part by using Lingo

	Lmax	**Lm**	**Lmax+Lm**	**Tard.**	**Lmax+Lm+Tard.**
Prob1	00:12.9	5.84	7.55	14.25	7.7
Prob2	00:10.3	5.84	8.4	13.34	9.23
Prob3	00:12.0	6.2	8.41	13.79	9.41
Prob4	00:11.1	5.49	8.44	15.23	10.24
Prob5	00:11.9	5.45	7.38	14.79	8.33

hr:min:sc 01:02:28.7 =1 hr 2 minutes and 28 seconds

2 Sample is taken for each Problem

(CPU time to schedule the problem ..in sec.)

	Prob1	**Prob2**	**Prob3**	**Prob4**	**Prob5**	**Avg**	**Grand. avg.**
First set	76	82	76	74	74	76.4	75.1
Second set	75	73	81	79	61	73.8	

Chapter 5

Loading Subproblem

In this section we compare six schemes . The first one is taken from Al-Refai and Wu [1] and the rest is developed in this research. The second scheme is a modified version of the solution proposed by Hutchison *et al* [8]. The rest of the schemes, we either changed the objective function, constraints or both which allow us to evaluate new formulation for the loading part of the problem. While making those changes we aimed to improve system performance and their results are discussed at each step as the schemes are explained.

5.1 Scheme 1

This scheme is taken from Al-Refai and Wu [1] for the purpose of comparison with the other schemes that we proposed. Here we will give a brief overview of their scheme (Figure 3). They group the available routes to the route groups using a hierarchical clustering method (Figure 4). Clustering Algorithm evaluates the degree of resource sharing among the job routings and groups the route which share common resources. Route clusters are formed on a similarity threshold value.

After forming the route groups, routes are assigned to the jobs by solving a generalized assignment subproblem. The objective function of GAP is calculated by a Monte carlo sampling scheme. First route groups are assigned to the jobs and then routes are selected for each job from those route groups.

The generalized assignment problem is concerned with finding the minimum cost assignment of n jobs to m agents such that each job is assigned exactly once and the agent's capacity constraints are not violated (Cattrysse and Van Wassenhove [5]). GAP formulation is as follow

$$\min \sum_i \sum_j c_{ij} x_{ij} \tag{1}$$

s.t

$$\sum_j a_{ij} x_{ij} \leq b_i \quad , i \in I \tag{2}$$

$$\sum_i xij \ = 1 \tag{3}$$

$$xij \ = \ 0 \ or \ 1, \ \ i \in I, \ j \in J \tag{4}$$

where

cij is the cost of assigning job j to agent i

a_{ij} is the capacity of agent i required by job j

b_i is the available capacity of agent i

xij is 1 if job j is assigned to be carried out by agent i and 0 otherwise

(1) is the objective (cost) function. This cost function of the assignment is to be minimized. (2) states that the capacity of agent i is not violated as a result of assignment. (3) states that job j is assigned only once and (4) tells that decision variable is either 1 or 0. GAP is NP-hard and that's why a heuristic method is chosen to solve GAP. VDSH (variable-depth-search heuristic (Figure 5) which is developed by Amini and Racer [2] is used. VDSH heuristic is a two phase heuristic at the first phase initial routes are assigned to the jobs and later this assignment serves as input to the second phase which is the iterative improvement phase. At the first phase, initial assignment phase, initial routes that give balanced workload as much as possible are selected. After initial assignment an iterative improvement phase is used and iteration is applied until the amount of

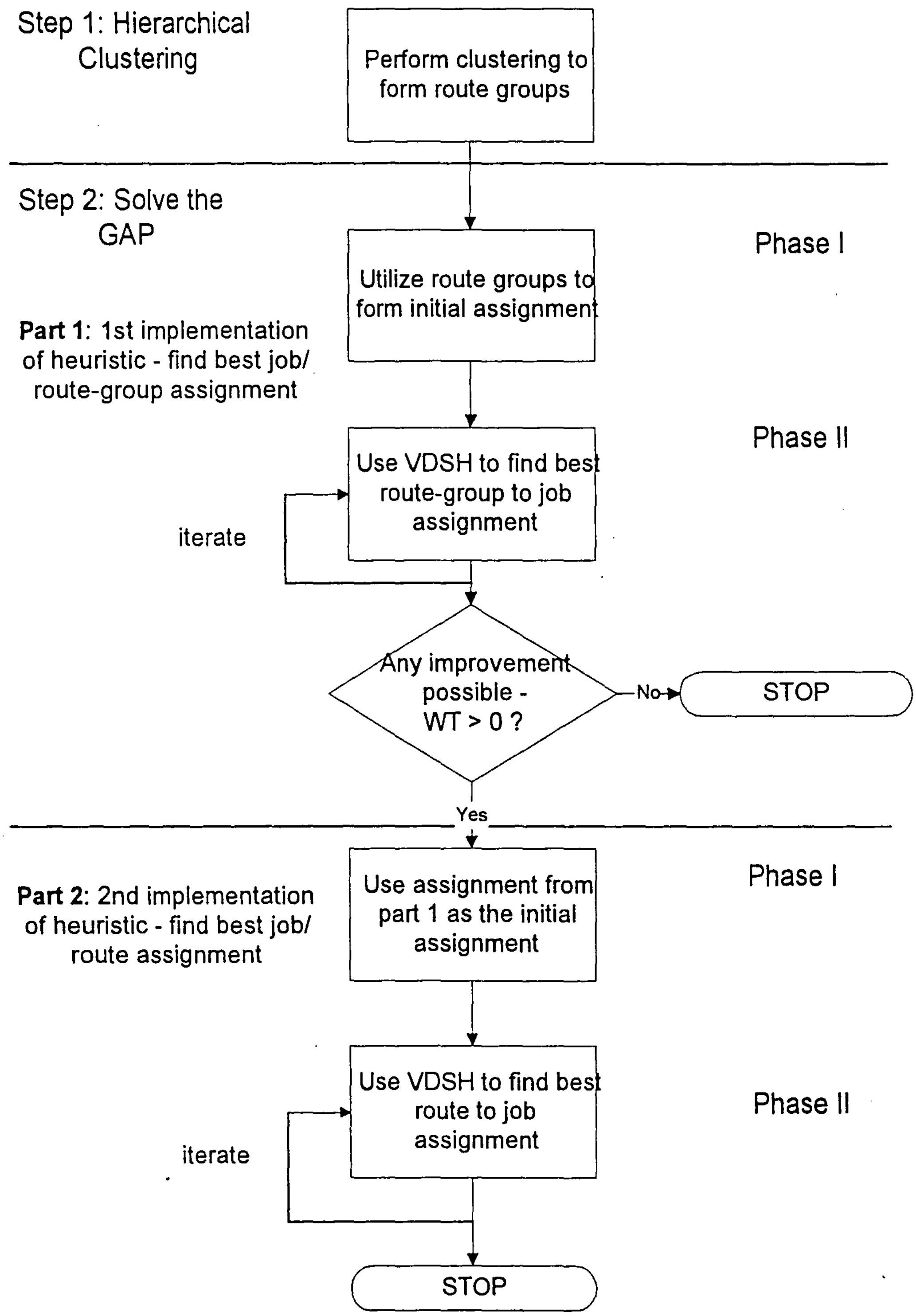

Figure 3 Flowchart of Heuristic Optimization Method (Al-Refai and Wu , pp 5, [1])

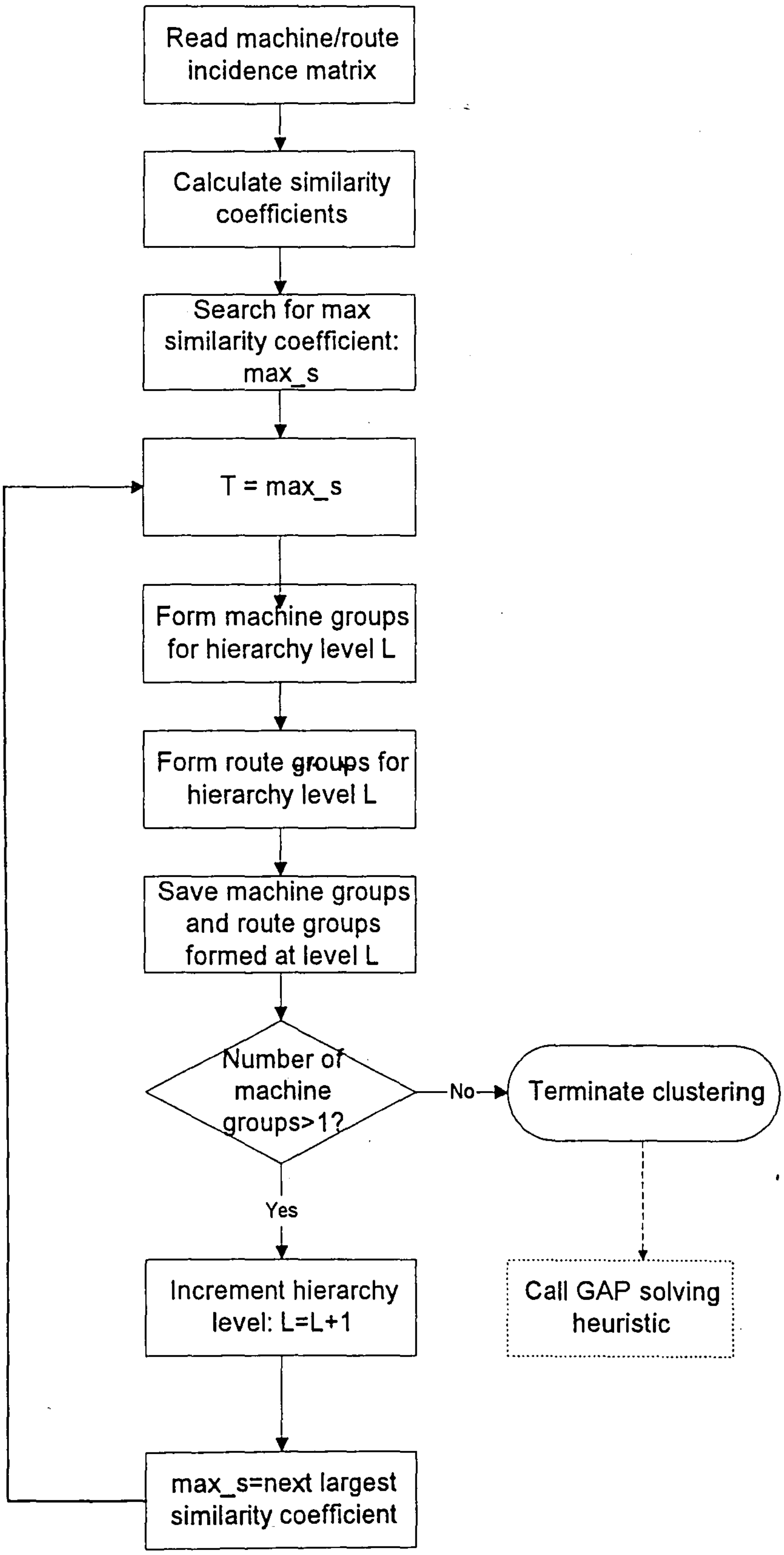

Figure 4 Flowchart of Hierarchical Clustering Algorithm (Al-Refai and Wu, pp 16, [1])

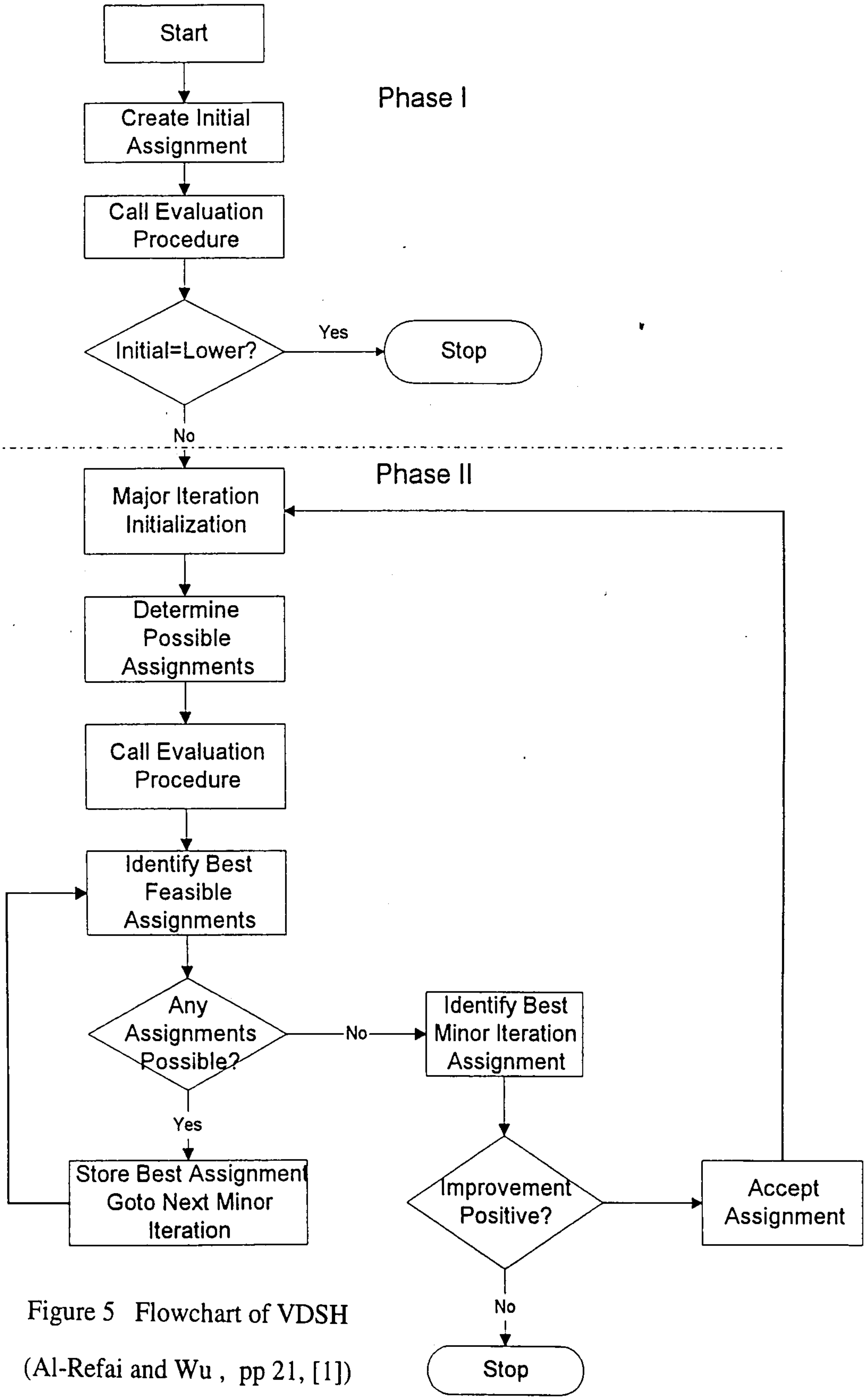

Figure 5 Flowchart of VDSH

(Al-Refai and Wu , pp 21, [1])

improvement is less than a prespecified value. Figure 6 shows that GAP outperforms random selection over the same set of test problems.

5.2 Scheme 2

This scheme is based on the conjecture that scheduling performance is highly dependent on the balance of the machine loading. Well balanced machine load can reduce the congestion on bottleneck machines and increase the throughput rate of the system. Consider the solution of this machine loading problem explicitly at the route selection phase is the main idea behind this particular scheme.

This scheme is modified from Hutchison *et al* [8] . We used the same objective function and tried to minimize the load of the maximum loaded machine. Since the nature of the problem that we are solving is different from theirs we made a modification to the formulation. Hutchison *et al* [8] considered flexibility as alternatives for each operation and assumed that the number of operation are fixed for each job. In our cases there are different (five) routes for each job and the number of operation that changes from one route to another.

The original formulation of the loading problem

$$\min \ L_{max}$$

s.t

$$\sum_{i=1}^{N} \sum_{g=1}^{Q_i} P_{igk(m)} V_{igk(m)} \leq Lmax \quad \text{From } m = 1 \text{ to } M \quad (1)$$

$$\sum_{k=1}^{Z_{ig}} V_{igk(m)} = 1 \quad \text{for} \qquad i = 1 \text{ to } N \quad g = 1 \text{ to } Qi \quad (2)$$

where

$Lmax$: the sum of the processing times on the largest loaded machine

Problem Set 20x5

Table 5 GAP vs. Random route selection

		Avg. Tardiness				
Scheme	**Series**	**Prob1**	**Prob2**	**Prob3**	**Prob4**	**Prob5**
Random	Series1	5496.6	5160.9	2283.6	2590.3	2405.8
GAP (S 1)	Series 2	2008.3	2006.0	1258.8	607.0	994.0

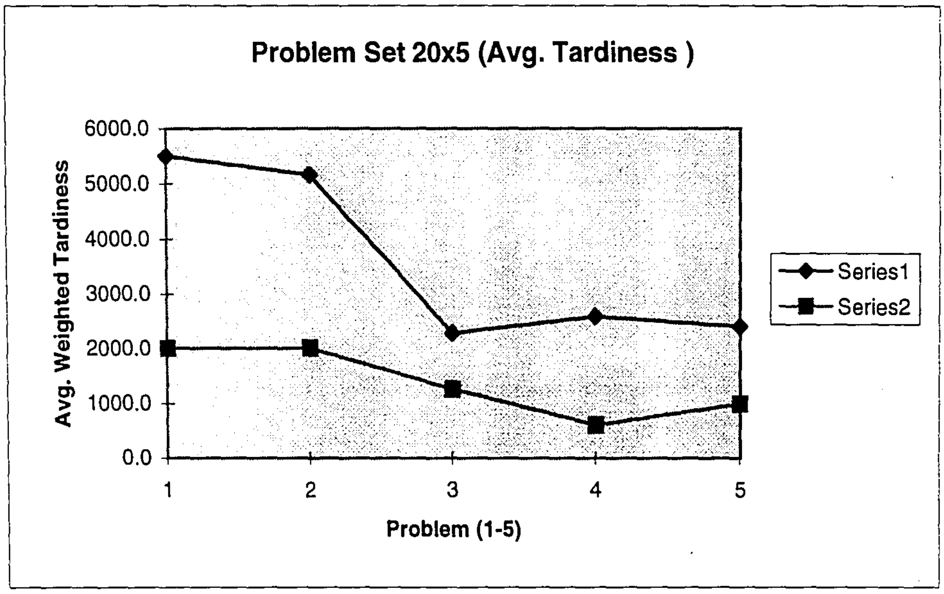

Figure 6 GAP vs. Random route selection

Problem Set 20x5

Table 5 GAP vs. Random route selection

		Avg. Tardiness				
Scheme	**Series**	**Prob1**	**Prob2**	**Prob3**	**Prob4**	**Prob5**
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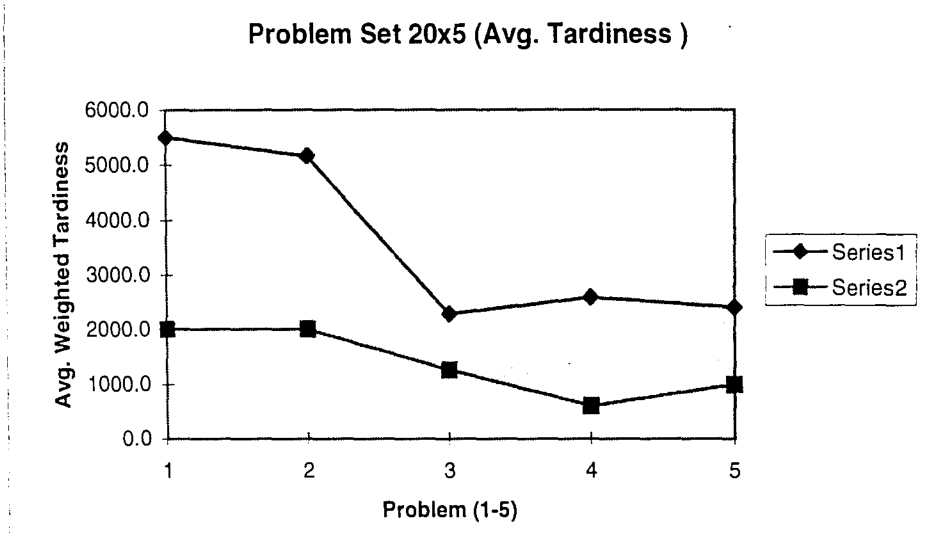

Figure 6 GAP vs. Random route selection

$P_{igk(m)}$: The processing time of the k^{th} option of operation g on machine m of job i

$V_{igk(m)}$: 1 if the k^{th} option of operation g on machine m of job i is used

0 otherwise

First constraint establishes Lmax as the load on the largest loaded machine. Second constraint allows only one alternative to be chosen for each operation. Finally all variables are nonnegative and decision variables are $Vigk(m)$ and $Lmax$.

Our modified formulation is as follows

min Lmax

s.t

$$\sum_{j=1}^{J} \sum_{r_j=1}^{R_j} \sum_{o_{r_j}=1}^{O_{r_j}} P_{jr_j o_{r_j}} V_{jr_j} \leq Lmax \quad \text{for} \quad m = 1 \quad \text{to} \quad M \quad (1)$$

assumption $P_{jr_j o_{r_j}} = P_{jr_j o_{r_j}}$ (if that operation uses machine m)

0 otherwise

$$\sum_{r_j=1}^{R_j} V_{jr_j} = 1 \qquad \text{for} \quad j = 1 \text{ to } J \quad (2)$$

where

j : job number , j = 1 to J

r_j : r^{th} route of job j, r_j = 1 to R_j and R_j=5 for each job

o_{r_j} : o^{th} operation of job j for the route r o_{r_j} = 1 to O_{r_j}

m : machine index

$Lmax$: the sum of the processing times on the largest loaded machine

$P_{jr_jo_{r_j}}$: Processing time of o_{r_j} for the machine m (machine that performs o_{r_j})

V_{jr_j} : 1 if r th route is selected.

0 otherwise

First constraint establishes Lmax as the load on the largest loaded machine. Second constraint allows only one route to be chosen for each job. All variables are nonnegative and decision variables are V_{jr_j} and $Lmax$.

Observing Figures 8,9 and 10 and Tables 8, 9 and 10 we can see that this method gives well balanced machine loading. Figure 8 is a comparison of Random, GAP and Lmax schemes for the test set 20x5. Except for the third case Lmax gives the best performance. Similar result can be observed from problem set 30x10. Related results can be seen from the Tables 19,20,21,22,23 and Figures 19,20 and 21 for the problem set 20x5. Tables 25,26,27,28,29 and 30 and Figures 22,23,and 24 show similar results for the problem set 30x10. For the test set 5x20 as can be seen in Tables 31,32,33,34,35 and 36 and Figures 25,26 and 27, GAP gives the best performance among these three schemes (Random, GAP, Lmax). In our set of problems due dates are calculated by multiplying the total processing time with a constant. Since tardiness changes depending on the due date, the performance of this scheme will be better according to the GAP method for the problems that have due date independent from processing time.

5.3 Scheme 3

Balanced machine loading is desirable, but on the other hand this may force us to chose the routes that has high processing times. Depending of the nature of the problem minimizing the total load may improve the performance of the system. In this scheme we modified the loading problem to minimize the total load of the system . We changed the objective function to minimize the sum of the machine loads instead of minimizing maximum loaded machine. New formulation is as follows:

Problem Set 20x5

Table 6 Comparison of GAP, Lmax and Random route selection

		Avg. Tardiness				
Scheme	**Series**	**Prob1**	**Prob2**	**Prob3**	**Prob4**	**Prob5**
Random	Series 1	5496.6	5160.9	2283.6	2590.3	2405.8
GAP (S 1)	Series 2	2008.3	2006.0	1258.8	607.0	994.0
LMAX (S 2)	Series 3	223.9	68.9	3461.7	0.0	288.5

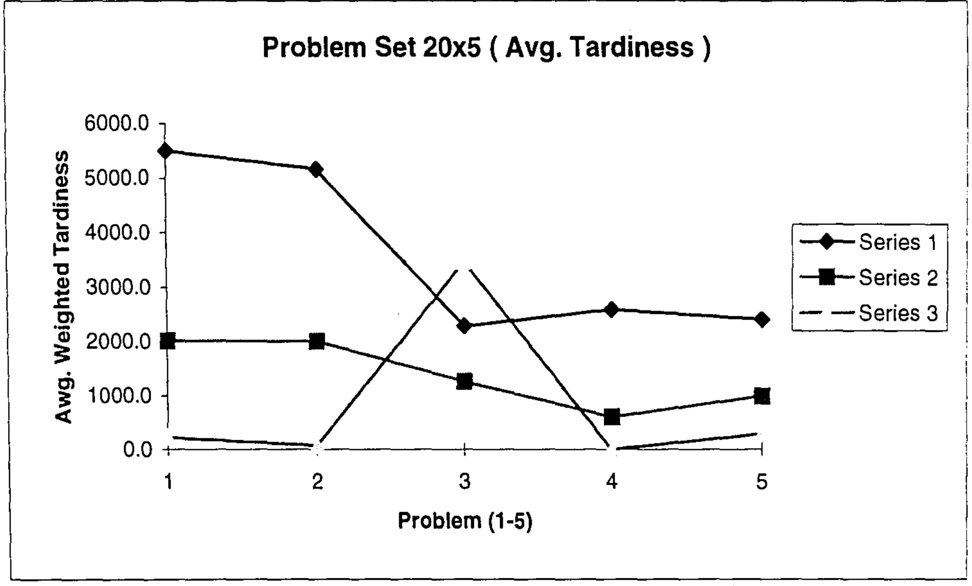

Figure 7 Comparison of GAP, Lmax and Random route selection

Problem Set 30x10

Table 7 Lmax vs. Lm in terms of machine load (Prob1)

		Series 1	Series 2
		Lmax	**Lm**
prob1	Machine 1	394.0	54.0
	Machine 2	394.0	541.0
	Machine 3	394.0	261.0
	Machine 4	358.0	389.0
	Machine 5	394.0	471.0
	Machine 6	394.0	398.0
	Machine 7	394.0	304.0
	Machine 8	392.0	199.0
	Machine 9	343.0	265.0
	Machine 10	0.0	0.0

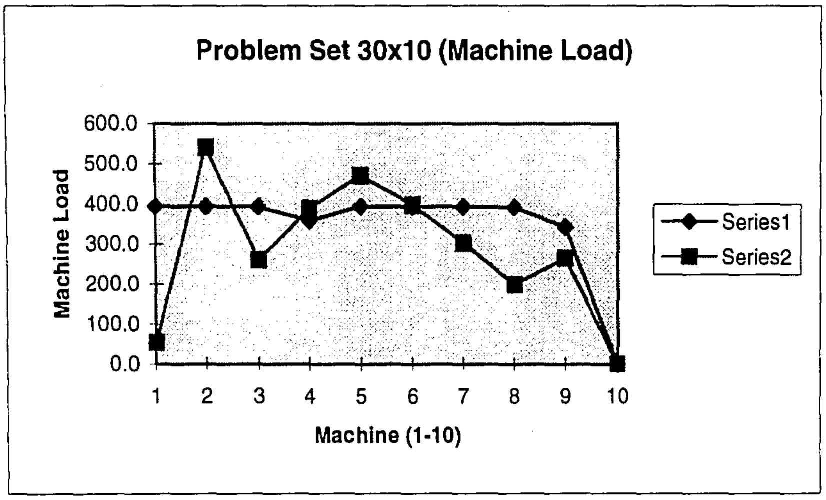

Figure 8 Lmax vs. Lm in terms of machine load (prob1)

Problem Set 30x10

Table 7 Lmax vs. Lm in terms of machine load (Prob1)

		Series 1	Series 2
		Lmax	**Lm**
prob1	Machine 1	394.0	54.0
	Machine 2	394.0	541.0
	Machine 3	394.0	261.0
	Machine 4	358.0	389.0
	Machine 5	394.0	471.0
	Machine 6	394.0	398.0
	Machine 7	394.0	304.0
	Machine 8	392.0	199.0
	Machine 9	343.0	265.0
	Machine 10	0.0	0.0

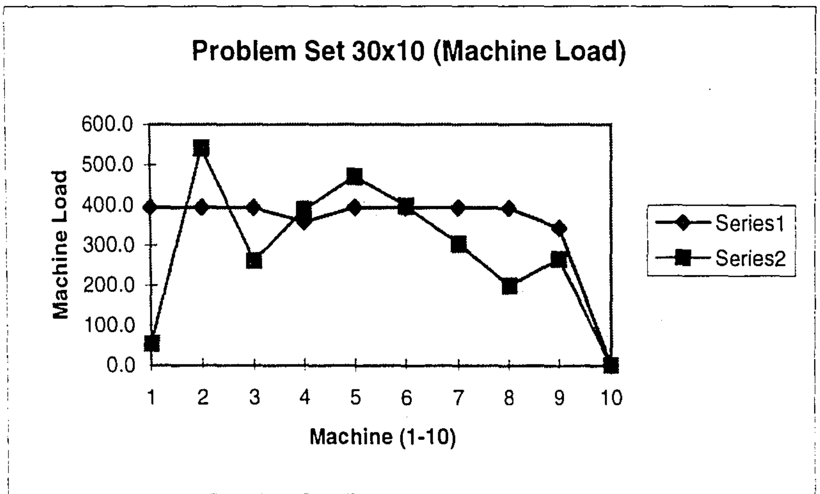

Figure 8 Lmax vs. Lm in terms of machine load (prob1)

Problem Set 20x5

Table 8 Comparison of the schemes 2,3,4,5,6 in terms of machine load

		Load on the machines according to				
		Lmax	**Lm**	**Lmax+Lm**	**Tard.**	**Lmax+Lm+Tard.**
prob1	Machine 1	392.0	258.0	379.0	435.0	414.0
	Machine 2	391.0	268.0	365.0	413.0	410.0
	Machine 3	392.0	371.0	387.0	404.0	403.0
	Machine 4	392.0	425.0	393.0	425.0	416.0
	Machine 5	389.0	537.0	394.0	439.0	415.0
	TOTAL	**1956.0**	**1859.0**	**1918.0**	**2116.0**	**2058.0**
prob2	Machine 1	390.0	253.0	377.0	423.0	423.0
	Machine 2	393.0	283.0	396.0	434.0	434.0
	Machine 3	392.0	613.0	388.0	438.0	438.0
	Machine 4	393.0	278.0	371.0	429.0	429.0
	Machine 5	393.0	426.0	389.0	434.0	434.0
	TOTAL	**1961.0**	**1853.0**	**1921.0**	**2158.0**	**2158.0**
prob3	Machine 1	384.0	253.0	378.0	455.0	388.0
	Machine 2	378.0	278.0	369.0	425.0	403.0
	Machine 3	378.0	385.0	384.0	437.0	410.0
	Machine 4	384.0	449.0	372.0	453.0	404.0
	Machine 5	384.0	462.0	371.0	431.0	405.0
	TOTAL	**1908.0**	**1827.0**	**1874.0**	**2201.0**	**2010.0**
prob4	Machine 1	398.0	230.0	390.0	454.0	400.0
	Machine 2	398.0	253.0	398.0	443.0	416.0
	Machine 3	398.0	456.0	398.0	466.0	418.0
	Machine 4	398.0	559.0	398.0	466.0	410.0
	Machine 5	398.0	389.0	397.0	473.0	424.0
	TOTAL	**1990.0**	**1887.0**	**1981.0**	**2302.0**	**2068.0**
prob5	Machine 1	370.0	322.0	372.0	441.0	441.0
	Machine 2	370.0	420.0	354.0	431.0	431.0
	Machine 3	370.0	379.0	372.0	436.0	436.0
	Machine 4	366.0	302.0	366.0	433.0	433.0
	Machine 5	359.0	367.0	338.0	437.0	437.0
	TOTAL	**1835.0**	**1790.0**	**1802.0**	**2178.0**	**2178.0**

Problem Set 30x10

Table 9a Comparison of the schemes 2,3,4 in terms of machine load

		Load on the machines according to		
		Lmax	**Lm**	**Lmax+Lm**
prob1	Machine 1	394.0	54.0	128.0
	Machine 2	394.0	541.0	420.0
	Machine 3	394.0	261.0	300.0
	Machine 4	358.0	389.0	416.0
	Machine 5	394.0	471.0	348.0
	Machine 6	394.0	398.0	412.0
	Machine 7	394.0	304.0	400.0
	Machine 8	392.0	199.0	310.0
	Machine 9	343.0	265.0	364.0
	Machine 10	0.0	0.0	418.0
	TOTAL	**3457.0**	**2882.0**	**3516.0**
prob2	Machine 1	174.0	184.0	123.0
	Machine 2	381.0	233.0	344.0
	Machine 3	380.0	307.0	376.0
	Machine 4	373.0	413.0	381.0
	Machine 5	381.0	280.0	351.0
	Machine 6	381.0	270.0	287.0
	Machine 7	381.0	349.0	365.0
	Machine 8	376.0	249.0	386.0
	Machine 9	381.0	405.0	384.0
	Machine 10	377.0	552.0	393.0
	TOTAL	**3585.0**	**3242.0**	**3390.0**
prob3	Machine 1	232.0	127.0	127.0
	Machine 2	401.0	333.0	362.0
	Machine 3	401.0	351.0	398.0
	Machine 4	359.0	341.0	363.0
	Machine 5	401.0	357.0	391.0
	Machine 6	401.0	395.0	412.0
	Machine 7	401.0	449.0	394.0
	Machine 8	401.0	447.0	412.0
	Machine 9	401.0	237.0	292.0
	Machine 10	401.0	451.0	407.0
	TOTAL	**3799.0**	**3488.0**	**3558.0**
prob4	Machine 1	437.0	249.0	273.0
	Machine 2	437.0	454.0	463.0
	Machine 3	414.0	384.0	437.0
	Machine 4	437.0	177.0	345.0
	Machine 5	437.0	288.0	401.0
	Machine 6	437.0	389.0	323.0
	Machine 7	420.0	360.0	378.0
	Machine 8	432.0	556.0	465.0
	Machine 9	406.0	476.0	455.0
	Machine 10	437.0	531.0	451.0
	TOTAL	**4294.0**	**3864.0**	**3991.0**

Table 9b

		Load on the machines according to		
		Lmax	**Lm**	**Lmax+Lm**
prob5	Machine 1	415.0	255.0	317.0
	Machine 2	415.0	569.0	425.0
	Machine 3	396.0	201.0	372.0
	Machine 4	415.0	285.0	379.0
	Machine 5	415.0	423.0	372.0
	Machine 6	415.0	447.0	421.0
	Machine 7	415.0	400.0	399.0
	Machine 8	415.0	335.0	404.0
	Machine 9	415.0	287.0	320.0
	Machine 10	415.0	471.0	423.0
	TOTAL	**4131.0**	**3673.0**	**3832.0**

Table 9c

		Lmax	Lm	Lmax+Lm
prob1	Machine 1	394.0	54.0	128.0
	Machine 2	394.0	541.0	420.0
	Machine 3	394.0	261.0	300.0
	Machine 4	358.0	389.0	416.0
	Machine 5	394.0	471.0	348.0
	Machine 6	394.0	398.0	412.0
	Machine 7	394.0	304.0	400.0
	Machine 8	392.0	199.0	310.0
	Machine 9	343.0	265.0	364.0
	Machine 10	0.0	0.0	418.0

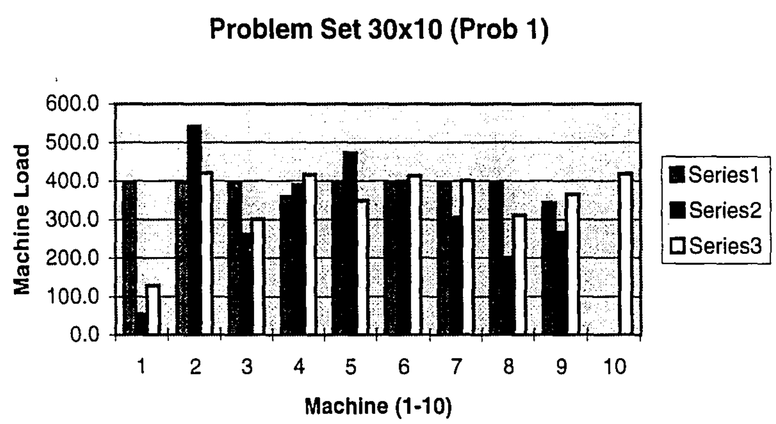

Figure 9a

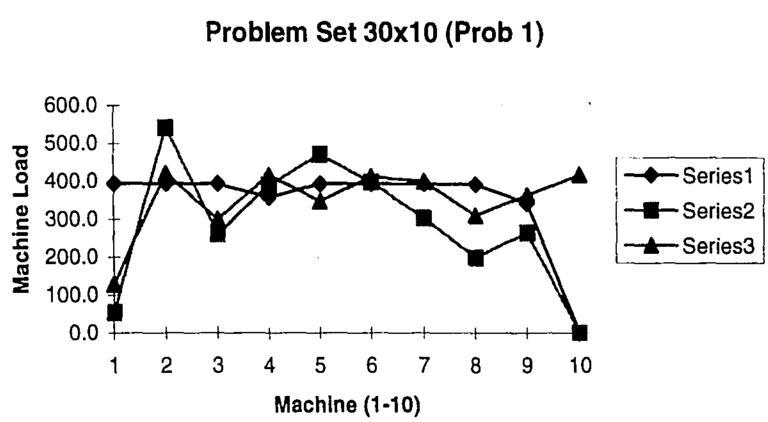

Figure 9b

Comparison of the Schemes 2,3,4 in terms of machine load (Prob1)

Table 9c

		Lmax	Lm	Lmax+Lm
prob1	Machine 1	394.0	54.0	128.0
	Machine 2	394.0	541.0	420.0
	Machine 3	394.0	261.0	300.0
	Machine 4	358.0	389.0	416.0
	Machine 5	394.0	471.0	348.0
	Machine 6	394.0	398.0	412.0
	Machine 7	394.0	304.0	400.0
	Machine 8	392.0	199.0	310.0
	Machine 9	343.0	265.0	364.0
	Machine 10	0.0	0.0	418.0

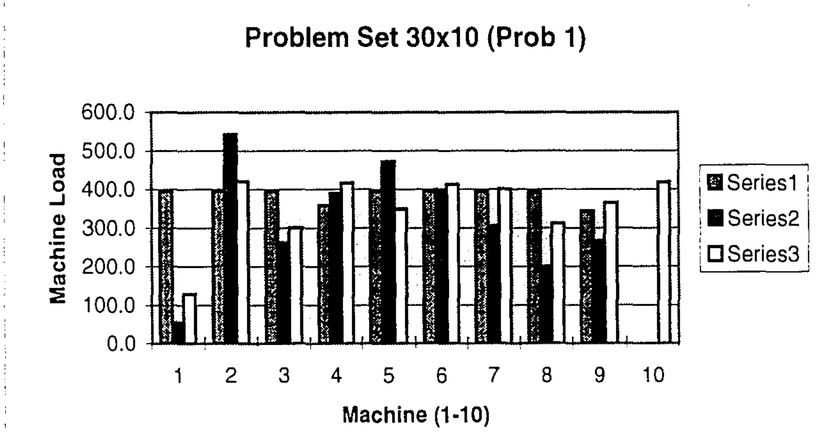

Figure 9a

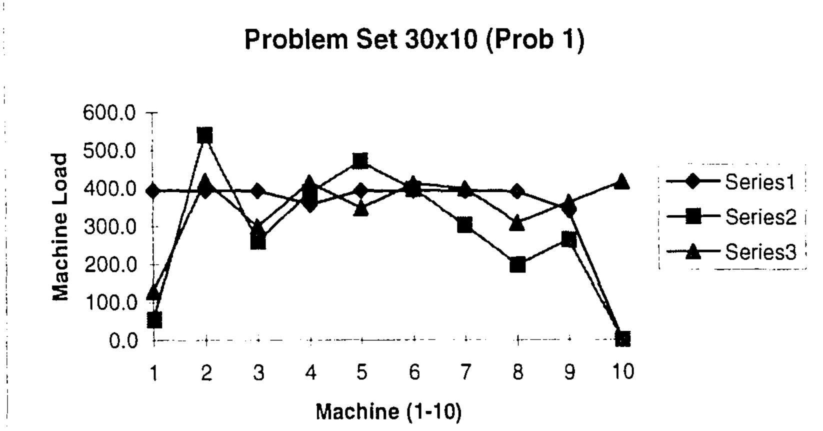

Figure 9b

Comparison of the Schemes 2,3,4 in terms of machine load (Prob1)

Problem Set 5x20

Table 10a Machine load comparison

		Load on the machines according to				
		Lmax	**Lm**	**Lmax+Lm**	**Tard.**	**Lmax+Lm+Tard.**
prob1	Machine 1	156.0	41.0	41.0	54.0	41.0
	Machine 2	156.0	137.0	137.0	104.0	137.0
	Machine 3	156.0	129.0	123.0	88.0	123.0
	Machine 4	156.0	138.0	138.0	156.0	138.0
	Machine 5	156.0	196.0	147.0	123.0	147.0
	Machine 6	156.0	63.0	120.0	153.0	120.0
	Machine 7	156.0	40.0	19.0	83.0	19.0
	Machine 8	156.0	42.0	42.0	89.0	42.0
	Machine 9	156.0	76.0	102.0	141.0	102.0
	Machine 10	156.0	89.0	64.0	71.0	64.0
	Machine 11	71.0	16.0	47.0	71.0	47.0
	Machine 12	156.0	158.0	103.0	125.0	103.0
	Machine 13	156.0	23.0	0.0	26.0	0.0
	Machine 14	156.0	57.0	57.0	73.0	57.0
	Machine 15	156.0	81.0	96.0	116.0	96.0
	Machine 16	156.0	69.0	108.0	136.0	108.0
	Machine 17	156.0	62.0	78.0	123.0	78.0
	Machine 18	156.0	188.0	171.0	109.0	171.0
	Machine 19	156.0	135.0	168.0	128.0	168.0
	Machine 20	156.0	96.0	78.0	141.0	78.0
	TOTAL	**3035.0**	**1836.0**	**1839.0**	**2110.0**	**1839.0**

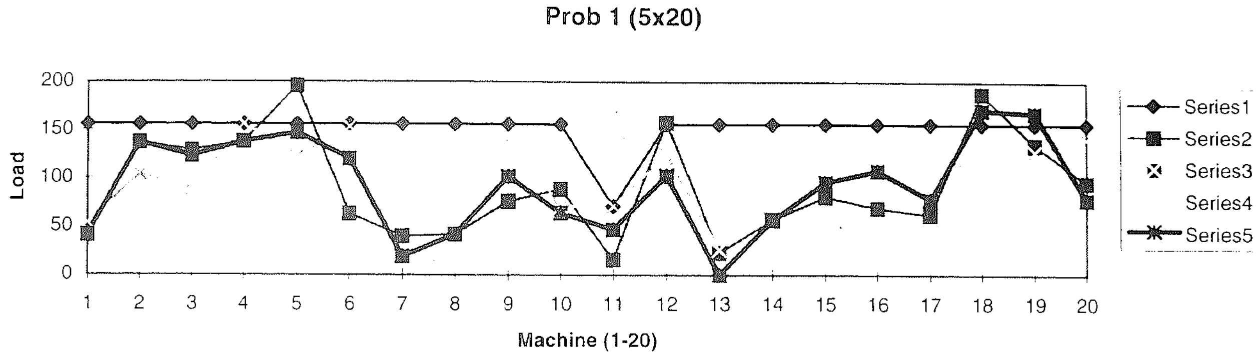

Figure 10a

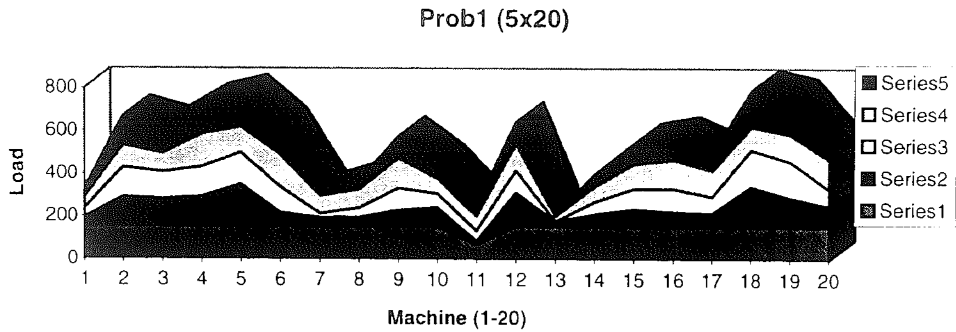

Figure 10b

Machine load comparison for the Prob. 1

where

Series 1	Series 2	Series 3	Series 4	Series 5
Lmax	**Lm**	**Lmax+Lm**	**Tard.**	**Lmax+Lm+Tard.**

Prob 1 (5x20)

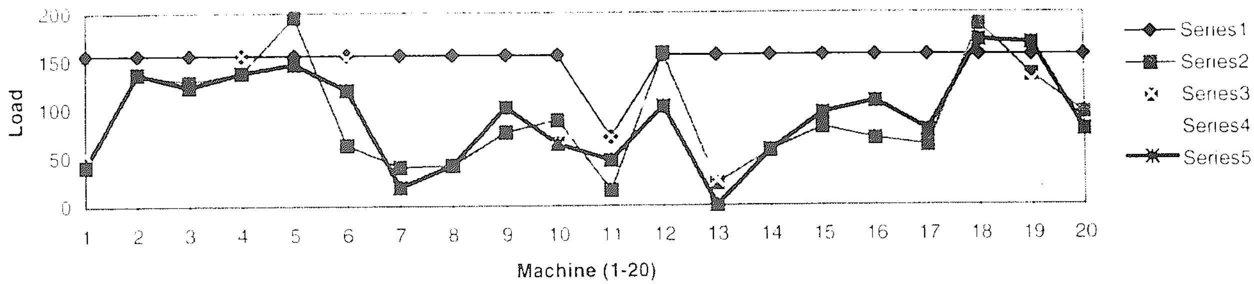

Figure 10a

Prob1 (5x20)

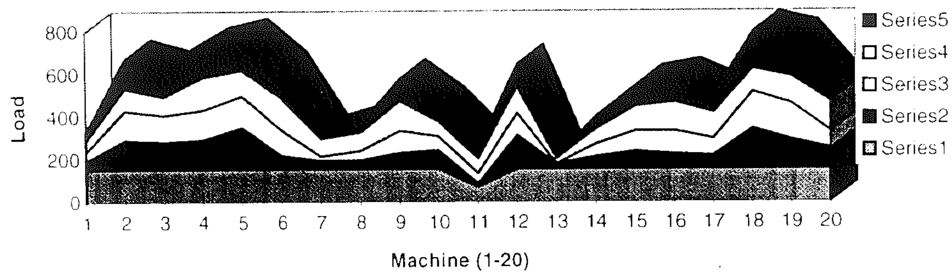

Figure 10b

Machine load comparison for the Prob. 1

where

Series 1	Series 2	Series 3	Series 4	Series 5
Lmax	**Lm**	**Lmax+Lm**	**Tard.**	**Lmax+Lm+Tard.**

Problem Set 5x20

Table 10b

Load on the machines according to

		Lmax	Lm	Lmax+Lm	Tard.	Lmax+Lm+Tard.
prob2	Machine 1	112.0	76.0	76.0	112.0	76.0
	Machine 2	139.0	125.0	125.0	139.0	125.0
	Machine 3	91.0	71.0	71.0	91.0	71.0
	Machine 4	149.0	91.0	139.0	124.0	139.0
	Machine 5	149.0	93.0	38.0	104.0	38.0
	Machine 6	88.0	125.0	119.0	88.0	119.0
	Machine 7	149.0	133.0	154.0	149.0	154.0
	Machine 8	149.0	169.0	143.0	130.0	143.0
	Machine 9	149.0	95.0	78.0	125.0	78.0
	Machine 10	41.0	25.0	41.0	41.0	41.0
	Machine 11	149.0	140.0	151.0	121.0	151.0
	Machine 12	149.0	67.0	89.0	149.0	89.0
	Machine 13	149.0	80.0	112.0	96.0	112.0
	Machine 14	149.0	75.0	65.0	102.0	65.0
	Machine 15	149.0	59.0	81.0	115.0	81.0
	Machine 16	59.0	22.0	38.0	59.0	38.0
	Machine 17	149.0	90.0	54.0	0.0	54.0
	Machine 18	149.0	133.0	136.0	79.0	136.0
	Machine 19	149.0	94.0	90.0	73.0	90.0
	Machine 20	149.0	144.0	144.0	147.0	144.0
	TOTAL	**2616.0**	**1907.0**	**1944.0**	**2044.0**	**1944.0**

Table 10c

		Load on the machines according to				
		Lmax	**Lm**	**Lmax+Lm**	**Tard.**	**Lmax+Lm+Tard.**
prob3	Machine 1	145.0	43.0	100.0	57.0	100.0
	Machine 2	145.0	22.0	39.0	94.0	39.0
	Machine 3	145.0	165.0	146.0	109.0	146.0
	Machine 4	145.0	77.0	107.0	127.0	107.0
	Machine 5	145.0	59.0	40.0	40.0	40.0
	Machine 6	145.0	70.0	70.0	70.0	70.0
	Machine 7	145.0	131.0	131.0	89.0	131.0
	Machine 8	145.0	201.0	153.0	112.0	153.0
	Machine 9	145.0	88.0	31.0	47.0	31.0
	Machine 10	145.0	141.0	107.0	109.0	107.0
	Machine 11	145.0	152.0	128.0	128.0	128.0
	Machine 12	145.0	62.0	64.0	75.0	64.0
	Machine 13	145.0	93.0	77.0	131.0	77.0
	Machine 14	114.0	94.0	120.0	114.0	120.0
	Machine 15	145.0	61.0	61.0	99.0	61.0
	Machine 16	145.0	102.0	107.0	119.0	107.0
	Machine 17	145.0	105.0	154.0	110.0	154.0
	Machine 18	145.0	78.0	97.0	145.0	97.0
	Machine 19	145.0	121.0	149.0	145.0	149.0
	Machine 20	122.0	99.0	99.0	122.0	99.0
	TOTAL	**2846.0**	**1964.0**	**1980.0**	**2042.0**	**1980.0**

Table 10d

Load on the machines according to

		Lmax	Lm	Lmax+Lm	Tard.	Lmax+Lm+Tard.
prob4	Machine 1	144.0	119.0	73.0	73.0	73.0
	Machine 2	105.0	77.0	105.0	105.0	105.0
	Machine 3	144.0	68.0	137.0	137.0	137.0
	Machine 4	97.0	98.0	97.0	97.0	97.0
	Machine 5	144.0	86.0	64.0	64.0	64.0
	Machine 6	144.0	25.0	68.0	68.0	68.0
	Machine 7	144.0	66.0	110.0	110.0	110.0
	Machine 8	144.0	119.0	101.0	101.0	101.0
	Machine 9	144.0	43.0	99.0	99.0	99.0
	Machine 10	144.0	172.0	90.0	90.0	90.0
	Machine 11	144.0	42.0	118.0	118.0	118.0
	Machine 12	144.0	70.0	89.0	89.0	89.0
	Machine 13	144.0	88.0	144.0	144.0	144.0
	Machine 14	144.0	113.0	136.0	136.0	136.0
	Machine 15	144.0	104.0	103.0	103.0	103.0
	Machine 16	144.0	181.0	139.0	139.0	139.0
	Machine 17	42.0	18.0	42.0	42.0	42.0
	Machine 18	49.0	56.0	49.0	49.0	49.0
	Machine 19	144.0	196.0	140.0	140.0	140.0
	Machine 20	65.0	53.0	65.0	65.0	65.0
	TOTAL	**2518.0**	**1794.0**	**1969.0**	**1969.0**	**1969.0**

Table 10e

		Load on the machines according to				
		Lmax	**Lm**	**Lmax+Lm**	**Tard.**	**Lmax+Lm+Tard.**
prob5	Machine 1	146.0	141.0	141.0	146.0	141.0
	Machine 2	146.0	0.0	0.0	0.0	0.0
	Machine 3	146.0	114.0	114.0	144.0	114.0
	Machine 4	146.0	118.0	118.0	133.0	118.0
	Machine 5	146.0	149.0	149.0	140.0	149.0
	Machine 6	42.0	42.0	42.0	42.0	42.0
	Machine 7	53.0	53.0	53.0	53.0	53.0
	Machine 8	146.0	108.0	108.0	102.0	108.0
	Machine 9	146.0	43.0	43.0	92.0	43.0
	Machine 10	114.0	61.0	61.0	114.0	61.0
	Machine 11	146.0	116.0	116.0	115.0	116.0
	Machine 12	146.0	143.0	143.0	124.0	143.0
	Machine 13	146.0	128.0	128.0	106.0	128.0
	Machine 14	146.0	103.0	103.0	58.0	103.0
	Machine 15	29.0	40.0	40.0	29.0	40.0
	Machine 16	116.0	97.0	97.0	116.0	97.0
	Machine 17	146.0	135.0	135.0	122.0	135.0
	Machine 18	133.0	79.0	79.0	133.0	79.0
	Machine 19	146.0	54.0	54.0	70.0	54.0
	Machine 20	88.0	66.0	66.0	88.0	66.0
	TOTAL	**2473.0**	**1790.0**	**1790.0**	**1927.0**	**1790.0**

$$\min \sum_{m=1}^{M} L(m)$$

s.t

$$\sum_{j=1}^{J} \sum_{r_j=1}^{R_j} \sum_{o_{r_j}=1}^{O_{r_j}} Pjr_j o_{r_j} Vjr_j \leq L(m) \quad \text{for} \quad m = 1 \quad \text{to } M \quad (1)$$

assumption $\quad Pjr_j o_{r_j} = Pjr_j o_{r_j}$ (if that operation uses machine m)

0 otherwise

$$\sum_{r_j=1}^{R_j} Vjr_j = 1 \qquad \text{for} \quad j = 1 \text{ to } J \qquad (2)$$

where

Lm : the load on machine m

(1) states that the total processing time on machine m is less than or equal to the load of that machine. All variables are nonnegative and decision variables are V_{jr_j} and L(m).

As shown in Figures 12,13,14 and 15 and Tables 8,9,10,13,14 and 15 this scheme reduces total machine load and allows less total load for the system. However, reduced total load does not necessarily means lower tardiness. In our test problems, due dates are found by multiplying the total processing times with a fixed constant. Since due dates are total processing time dependent, choosing smaller processing times gives us smaller due dates which means our constraint also becomes more strict, in other words routes which has less total processing time have tighter due dates . But still we attain good results in this situation. If due dates are fixed regardless of processing time then this method improves the system performance even more.

Problem Set 20x5

Table 11 Comparison of GAP, Lmax, Lm

		Avg. Tardiness				
Scheme	**Series**	**Prob1**	**Prob2**	**Prob3**	**Prob4**	**Prob5**
GAP (S 1)	Series 1	2008.3	2006.0	1258.8	607.0	994.0
LMAX (S 2)	Series 2	223.9	68.9	3461.7	0.0	288.5
Lm (S 3)	Series 3	2020.1	3469.3	115.2	296.9	41.6

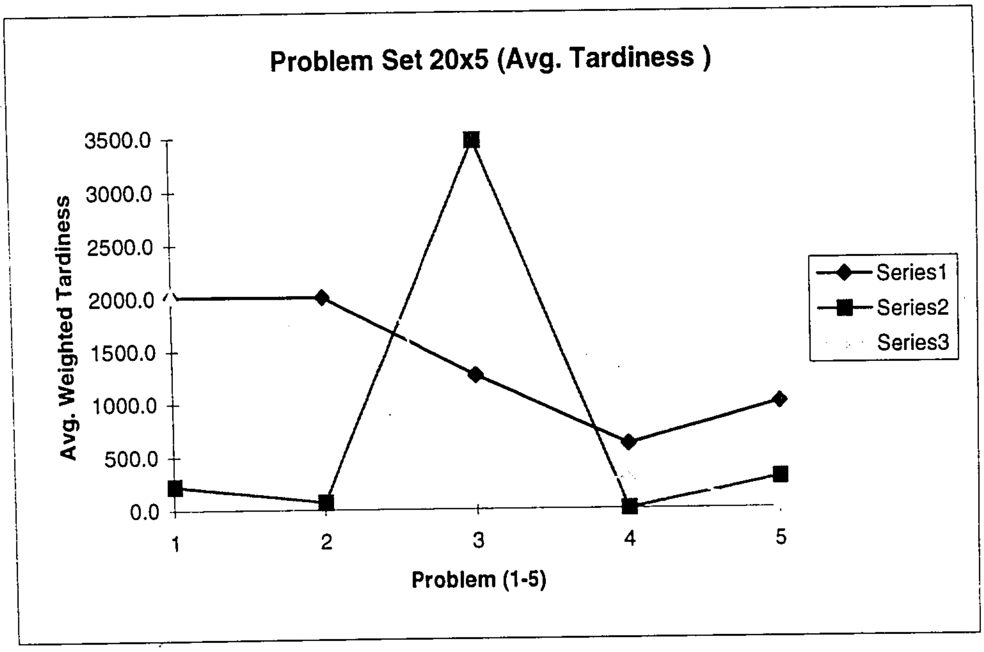

Figure 11 Comparision of GAP, Lmax and Lm

Problem Set 20x5

Table 12 Lmax vs. Lm in terms of total machine load

	Series 1	Series 2
Total M/C	**Lmax**	**Lm**
Prob1	1956	1859
Prob2	1961	1853
Prob3	1908	1827
Prob4	1990	1887
Prob5	1835	1790

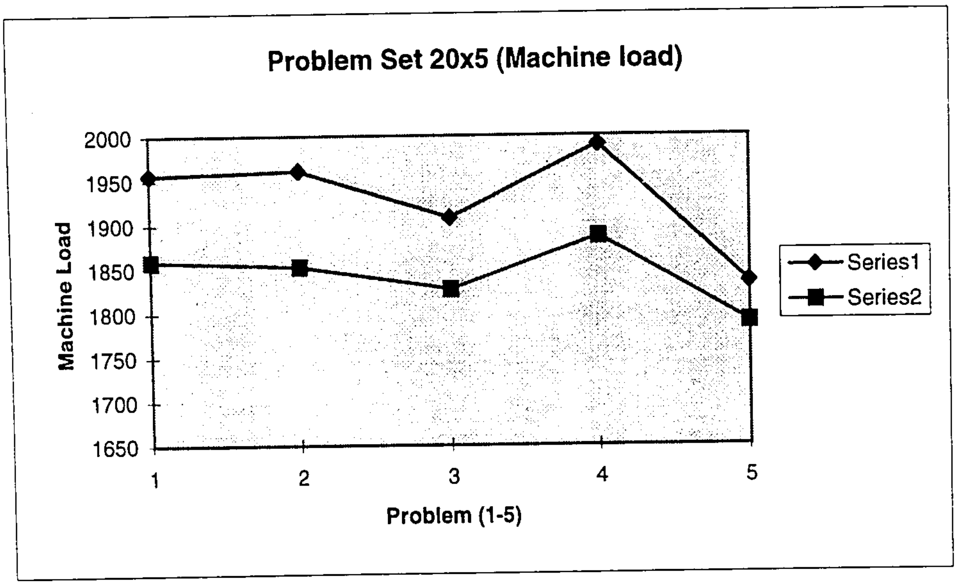

Figure 12 Lmax vs. Lm in terms of total machine load

5

Problem Set 20x5

Table 12 Lmax vs. Lm in terms of total machine load

	Series 1	Series 2
Total M/C	**Lmax**	**Lm**
Prob1	1956	1859
Prob2	1961	1853
Prob3	1908	1827
Prob4	1990	1887
Prob5	1835	1790

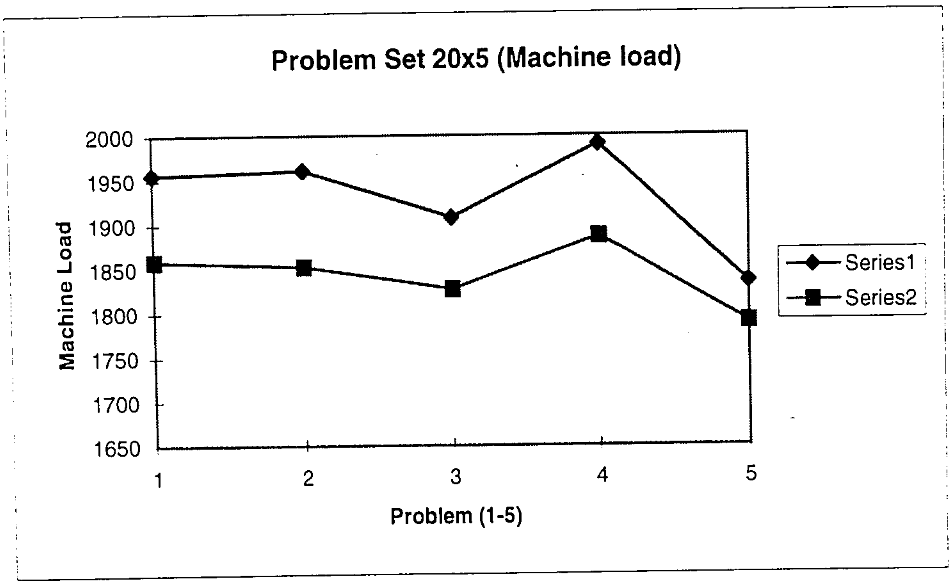

Figure 12 Lmax vs. Lm in terms of total machine load

Problem Set 20x5

Table 13

Total M/C Load	Series 1 Lmax	Series 2 Lm	Series 3 Lmax+Lm	Series 4 Tard.	Series 5 Lmax+Lm+Tard.
Prob1	1956.0	1859.0	1918.0	2116.0	2058.0
Prob2	1961.0	1853.0	1921.0	2158.0	2158.0
Prob3	1908.0	1827.0	1874.0	2201.0	2010.0
Prob4	1990.0	1887.0	1981.0	2302.0	2068.0
Prob5	1835.0	1790.0	1802.0	2178.0	2178.0

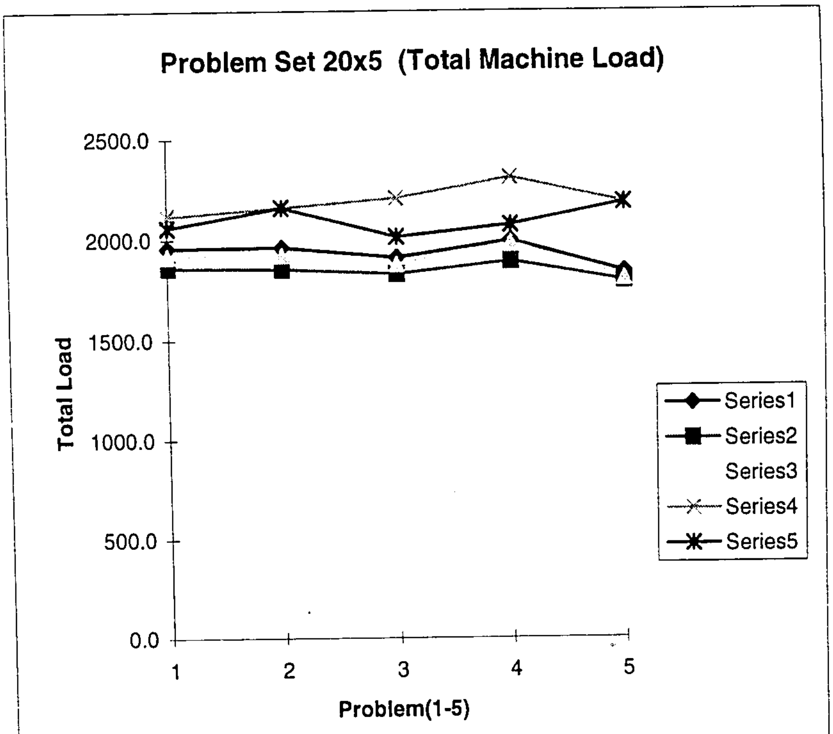

Figure 13

Comparison of the schemes 2,3,4,5,6 in terms of total machine load

Problem Set 30x10

Table 14 Scheme 2,3,4 (Total machine load)

	Series 1	Series 2	Series 3
Total M/C Load	**Lmax**	**Lm**	**Lmax+Lm**
Prob1	3457.0	2882.0	3516.0
Prob2	3585	3242	3390
Prob3	3799	3488	3558
Prob4	4294	3864	3991
Prob5	4131	3673	3832

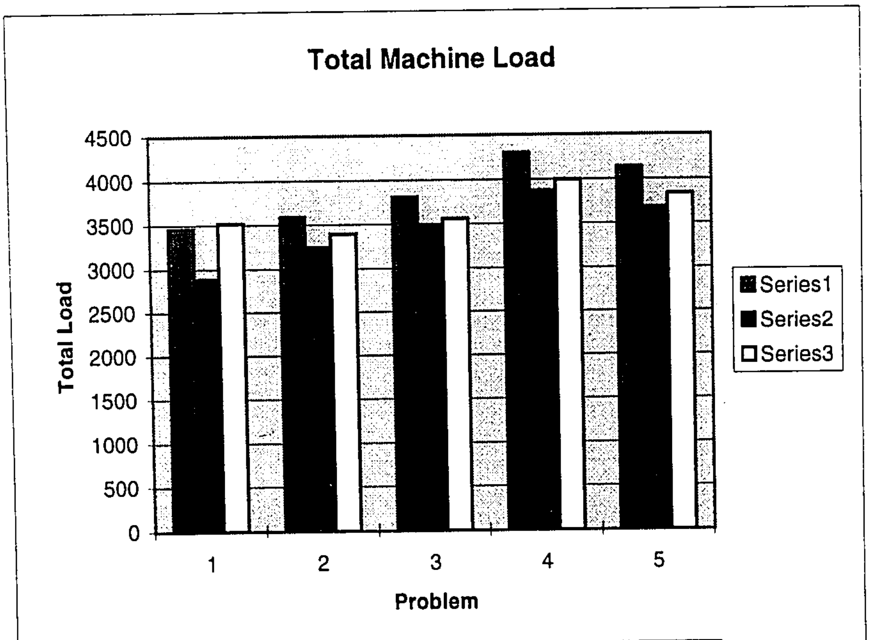

Figure 14 Scheme 2,3,4 (Total machine load)

Problem Set 30x10

Table 14 Scheme 2,3,4 (Total machine load)

	Series 1	Series 2	Series 3
Total M/C Load	**Lmax**	**Lm**	**Lmax+Lm**
Prob1	3457.0	2882.0	3516.0
Prob2	3585	3242	3390
Prob3	3799	3488	3558
Prob4	4294	3864	3991
Prob5	4131	3673	3832

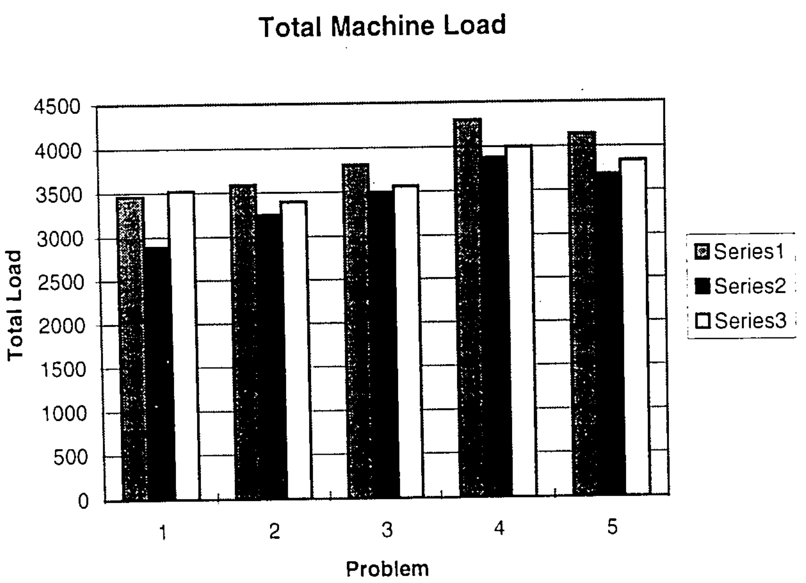

Figure 14 Scheme 2,3,4 (Total machine load)

Problem Set 5x20

Table 15 Total machine load comparison

Total M/C Load	Series 1 **Lmax**	Series 2 **Lm**	Series 3 **Lmax+Lm**	Series 4 **Tard.**	Series 5 **Lmax+Lm+Tard**
Prob1	3035.0	1836.0	1839.0	2110.0	1839.0
Prob2	2616.0	1907.0	1944.0	2044.0	1944.0
Prob3	2846.0	1964.0	1980.0	2042.0	1980.0
Prob4	2518.0	1794.0	1969.0	1969.0	1969.0
Prob5	2473.0	1790.0	1790.0	1927.0	1790.0

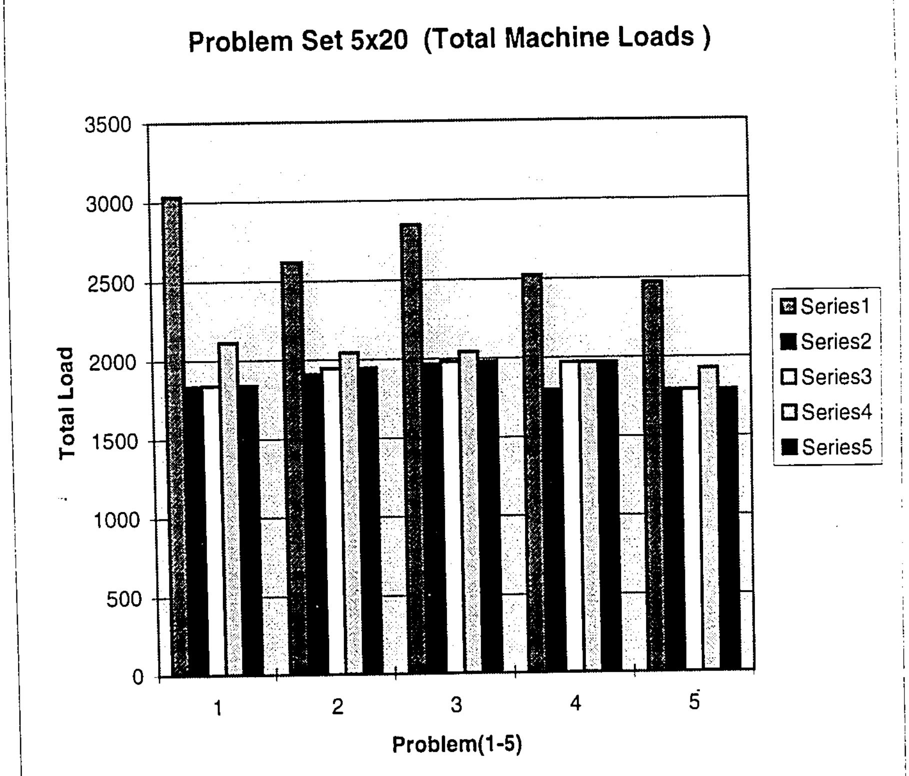

Figure 15a Total machine load comparision

Problem Set 5x20

Table 15 Total machine load comparison

	Series 1	Series 2	Series 3	Series 4	Series 5
Total M/C Load	**Lmax**	**Lm**	**Lmax+Lm**	**Tard.**	**Lmax+Lm+Tard**
Prob1	3035.0	1836.0	1839.0	2110.0	1839.0
Prob2	2616.0	1907.0	1944.0	2044.0	1944.0
Prob3	2846.0	1964.0	1980.0	2042.0	1980.0
Prob4	2518.0	1794.0	1969.0	1969.0	1969.0
Prob5	2473.0	1790.0	1790.0	1927.0	1790.0

Problem Set 5x20 (Total Machine Loads)

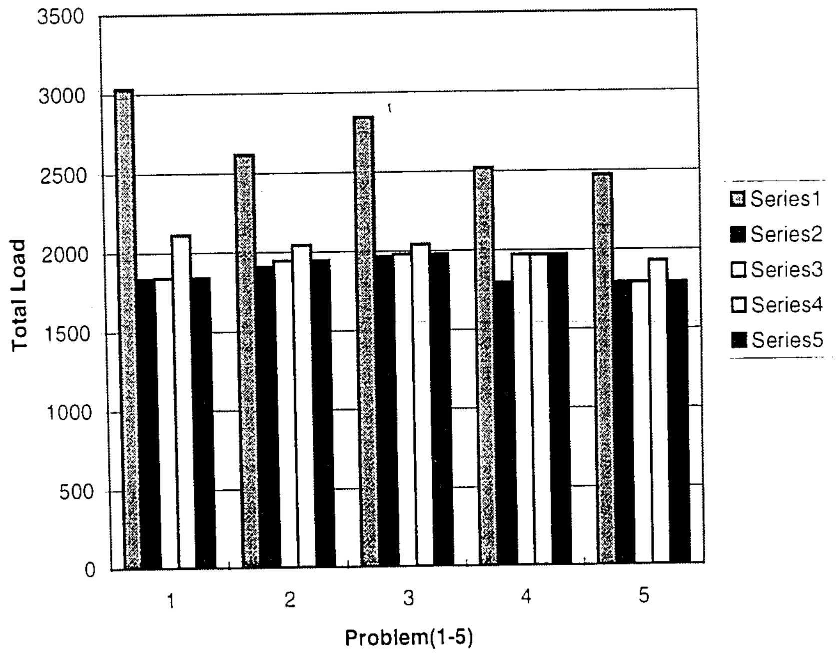

Figure 15a Total machine load comparision

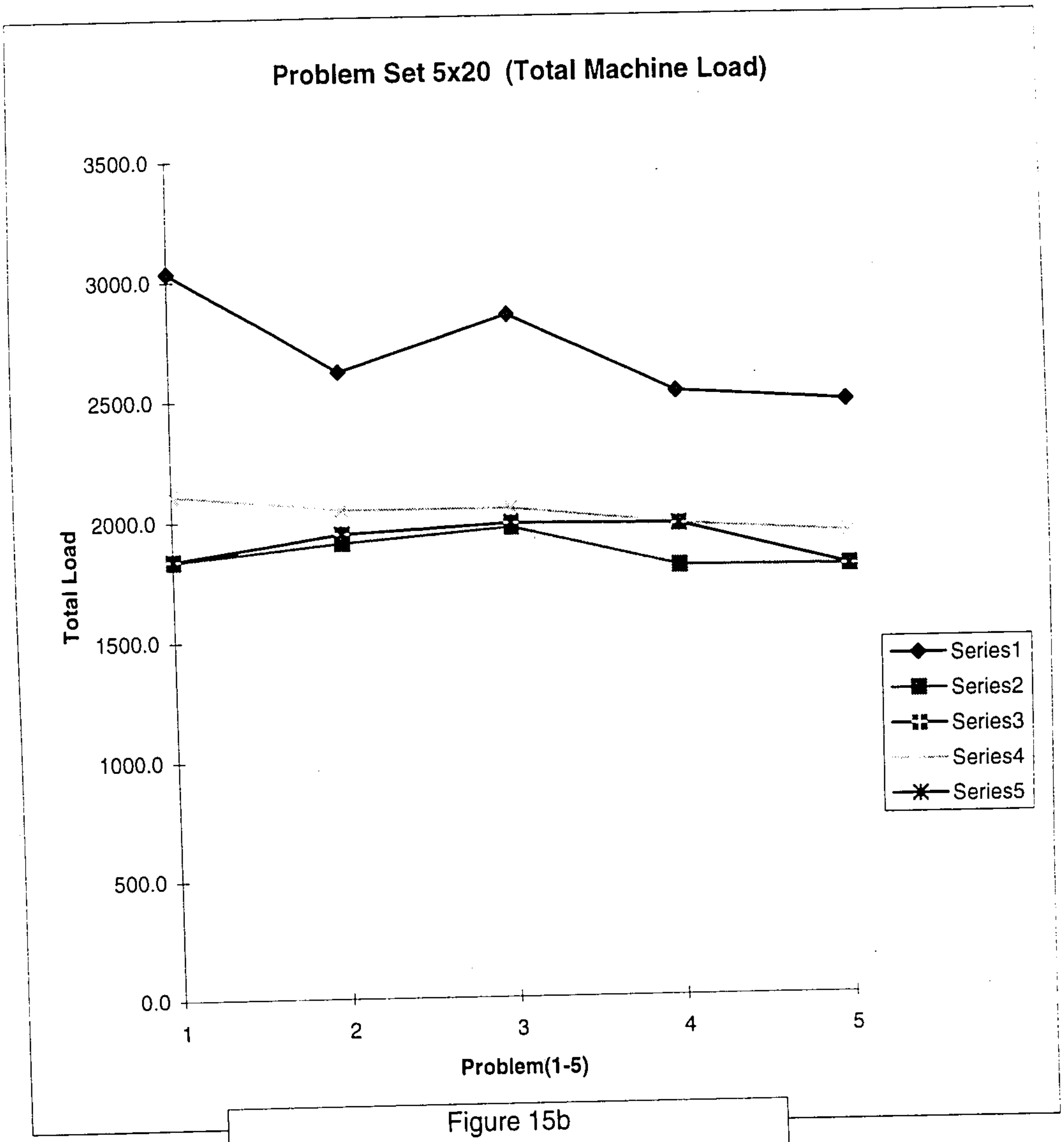
Problem Set 5x20 (Total Machine Load)
3500.0
3000.0
2500.0
2000.0
1500.0
1000.0
500.0
0.0
Total Load
1
2
3
4
5
Problem(1-5)
Series1
Series2
Series3
Series4
Series5

Figure 15b

5.4 Scheme 4

Second scheme gives well balanced machine loading but it doesn't give the least load for the system. The third scheme gives the least load for the system, but now we can't obtain balanced machine loading . There is a high probability for congestion for some machines and this can be seen from Tables 7,8,9 and 10 and Figures 7,21 and 26. For example for problem set 20x5 the load on machine 5 is 537 , while the load on machine 1 is 258 (Table 8). This can be seen for all problems from tables and figures given above. If we look at the same problem (Table 8) as an example the highest load for a machine is 392 and the lowest load for a machine is 389 and most of the machines have the same laod. Generally machine loads are almost the same. There is a small gap among the machine loads according to the scheme 2. But if we look at the total load for the same problem the total load for scheme 2 is 1956 and the total load for scheme 3 is 1859, minimum load for that problem. This is not an unusual example and similar results can be observed for the other problems. In this scheme we tried to reduce the total load and obtain balanced machine loading. Here our objective function is to minimize the total machine load plus five times the load of the maximum loaded machine. Five is a constant used to give more weight to Lmax to get well balanced machine load while reducing the total load.

The following formulation is used for this scheme.

$$\min \left(\sum_{m=1}^{M} \mathrm{L(m)} + 5\,\mathrm{L}max \right)$$

s.t

$$\sum_{j=1}^{J} \sum_{r_j=1}^{R_j} \sum_{o_{r_j}=1}^{O_{r_j}} \mathrm{P}_{jr_j o_{r_j}} \mathrm{V}_{jr_j} \leq \mathrm{L}(m) \quad \text{for} \quad \mathrm{m} = 1 \quad \text{to} \quad \mathrm{M} \quad (1)$$

assumption $\quad \mathrm{P}_{jr_j o_{r_j}} = \mathrm{P}_{jr_j o_{r_j}}$ (if that operation uses machine m)

0 otherwise

$$L(m) \leq Lmax \qquad\qquad m = 1 \text{ to } M \quad (2)$$

$$\sum_{r_j=1}^{R_j} Vjr_j = 1 \qquad\qquad \text{for } j = 1 \text{ to } J \quad (3)$$

(1) states that the total processing time on machine m is less than or equal to the load of that machine , (2) guarantees that load on each machine is less than the load on the maximum loaded machine. All variables are nonnegative and decision variables are V_{jr_j} , Lm and $Lmax$.

From Tables 16,17,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35 and 36 and Figures 6,17,19,20,21,22,23,24,25,26 and 27 we can see that most of the time this scheme gives better performance than the previous schemes.

5.5 Scheme 5

Until now we worked on decomposed problems and never worried about the due dates. Result of the scheduling subproblem highly dependent to the due dates. As the due dates get smaller, constraint becomes more strict and this effects the scheduling performance in terms of tardiness. Since solution of the first subproblem is an input to the scheduling subproblem that means if we can consider due date in the first phase we may expect better performance overall. We developed a formulation that might improve the solution. Later we modified that formulation to make it more efficient in terms of computing time. Before modification we couldn't solve the problem number 4 for group 20x5 before 10 cpu hr but after modification we get the result in 10 minute 42 second (cpu time) (see Table 11). Related formulations are as follows:

Problem Set 20x5

Table 16 Comparison of GAP, Lmax,Lm and Lmax+Lm

		Avg. Tardiness				
Scheme	**Series**	**Prob1**	**Prob2**	**Prob3**	**Prob4**	**Prob5**
GAP (S 1)	Series 1	2008.3	2006.0	1258.8	607.0	994.0
LMAX (S 2)	Series 2	223.9	68.9	3461.7	0.0	288.5
Lm (S 3)	Series 3	2020.1	3469.3	115.2	296.9	41.6
Lmax+Lm (S 4)	Series 4	47.2	618.6	0.0	0.0	0.0

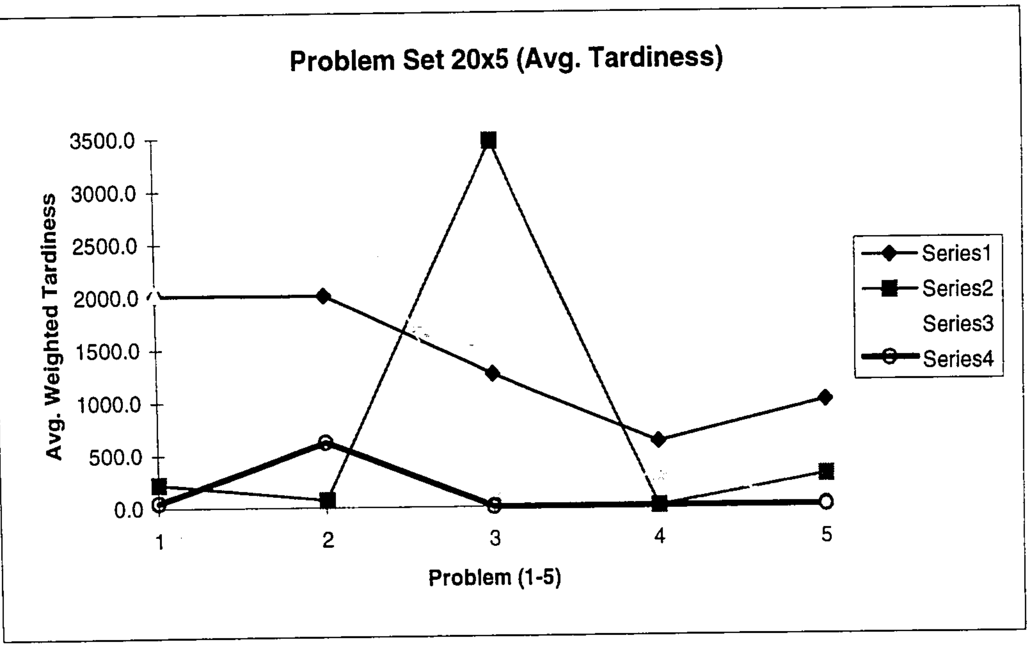

Figure 16 Comparison of GAP, Lmax, Lm and Lmax+Lm

Original formulation

$$\min \left(\sum_{j=1}^{J} Wj\, PTj \right)$$

s.t

$$\sum_{j=1}^{J} \sum_{r_j=1}^{R_j} \sum_{o_{r_j}=1}^{O_{r_j}} Pjr_j o_{r_j} Vjr_j \leq L(m) \quad \text{for } m = 1 \text{ to } M \qquad (1)$$

assumption $\quad Pjr_j o_{r_j} = Pjr_j o_{r_j}$ (if that operation uses machine m)

0 otherwise

$$\sum_{r_j=1}^{R_j} Djr_j \; Vjr_j = Dj \qquad \text{for } j = 1 \text{ to } J \qquad (2)$$

$$\sum_{r_j=1}^{R_j} \sum_{o_{r_j}=1}^{O_{r_j}} Pjr_j o_{r_j} Vjr_j = TPj \qquad \text{for } j = 1 \text{ to } J \qquad (3)$$

$$L(LMj_r) - Dj \leq PTj \qquad \text{for } j = 1 \text{ to } J \qquad (4)$$

$$TPj - Dj \leq PTj \qquad \text{for } j = 1 \text{ to } J \qquad (5)$$

$$\sum_{r_j=1}^{R_j} Vjr_j = 1 \qquad \text{for } j = 1 \text{ to } J \qquad (6)$$

where

Wj : Weight of job j

PTj : Possible tardiness of job j

Djr_j : Due date of job j if route r_j is selected

Dj : Due date of job j according to the selected route

TPj : Total processing time of job j according to selected route

LMj_r : Last machine that operates the last operation for job j if route r_j is selected

The objective function here is to minimize the weighted expected tardiness. The routes selected according to this criteria might improve the results but since mixed integer programming belongs to the class of NP-complete problems and the problems that we were working on were too large to apply this formulation so we made further assumptions in order to simplify the formulation.

First constraint states that the total processing time on machine m is less than or equal to the load of that machine . Second constraint gives us the due date for the selected route. Third constraint gives the total processing time for job j if route r is selected. LMj_r is the last machine that operates the last operation of job j if route r_j is selected and TPj is the total processing time of job j according to selected route. That means EFj (Expected finish of job j) should be greater than TPj . If there were no idle time then we would say that EFj is less than or equal to L (LMj_r) (load on the machine LMj_r) . We know for sure that for our examples constraint five is always true since due dates are calculated by multiplying the TPj by a constant which is greater than one. But for the problems that due dates are not dependent to the processing times we still need that constraint. The last constraint allow us to select only one route for each job.

After some further assumptions and modifications we get the following formulation for this scheme.

$$\min \; \left(\; \left(\sum_{j=1}^{J} \mathrm{Wj\,PTj} \right) + 5\,\mathrm{L}max \right)$$

s.t

$$\sum_{j=1}^{J} \sum_{r_j=1}^{R_j} \sum_{o_{r_j}=1}^{O_{r_j}} \mathrm{P}jr_j\,o_{r_j} \mathrm{V}jr_j \leq \mathrm{L}max \quad \text{for} \quad \mathrm{m}=1 \quad \text{to} \quad \mathrm{M} \quad (1)$$

assumption $\mathrm{P}jr_j\,o_{r_j} = \mathrm{P}jr_j\,o_{r_j}$ (if that operation uses machine m)

0 otherwise

$$\sum_{r_j=1}^{R_j} \mathrm{D}jr_j \; \mathrm{V}jr_j = \mathrm{Dj} \qquad \text{for} \quad \mathrm{j}=1 \quad \text{to} \quad \mathrm{J} \quad (2)$$

$$\mathrm{L}max - \mathrm{Dj} \leq \mathrm{PTj} \qquad \text{for} \quad \mathrm{j}=1 \quad \text{to} \quad \mathrm{J} \quad (3)$$

$$\sum_{r_j=1}^{R_j} Vjr_j = 1 \qquad \text{for} \quad j = 1 \text{ to } J \quad (4)$$

We eliminated the fifth constraint, since we don't need it for the problems that we are working . 5$Lmax$ is added to the objective function in order to get balanced machine load. Lmax can be considered as L(LMj_r) of the previous example if we get a well balanced machine loading then all L(LMj_r) will be near to $Lmax$. First and second group of examples are tested according to this scheme but for the third group it took more than 17 cpu hr and we couldn't still get the optimal solution before the machine run out of memory . Sixth scheme is a further modification of scheme five. Unlike the previous schemes, here and in the next scheme process planning and scheduling considered simultaneously instead of sequentially.

Now if we look at the figure 12 we can see that this scheme gives promising result for some problems. Since we made some assumptions that can affect the result if we play with the constant and make some more experiments we may reach better method that can outperform the previous schemes.

From Tables 17,19,20,21,22,23 and 24 and Figures 17,19,20 and 21 we can see that most of the time this scheme gives the best results. But for the problem set 5x20, from Tables 31,32,33,34,35 and 36 and Figures 25,26 and 27 we get poor results.. This may be the result of machine loading. In the problem set 20x5 we have 5 machines and well balanced machine load but in the set 5x20 we have 20 machines and poor balanced machine load compared to the set 20x5. according to the constraints (1) and (3) Lmax is very important in this scheme. As we get better balanced machine load we get better solution too.

5.6 Scheme 6

Scheme five doesn't take into account the total machine load. In order to get more rigid (doesn't change easily according to the nature of the problem) solution for the

Problem Set 20x5

Table 17 Comparison of the schemes 1,2,3,4,5

		Avg. Tardiness				
Scheme	**Series**	**Prob1**	**Prob2**	**Prob3**	**Prob4**	**Prob5**
GAP (S 1)	Series 1	2008.3	2006.0	1258.8	607.0	994.0
LMAX (S 2)	Series 2	223.9	68.9	3461.7	0.0	288.5
Lm (S 3)	Series 3	2020.1	3469.3	115.2	296.9	41.6
Lmax+Lm (S 4)	Series 4	47.2	618.6	0.0	0.0	0.0
Tard. (S 5)	Series 5	53.2	132.4	20.8	0.0	0.0

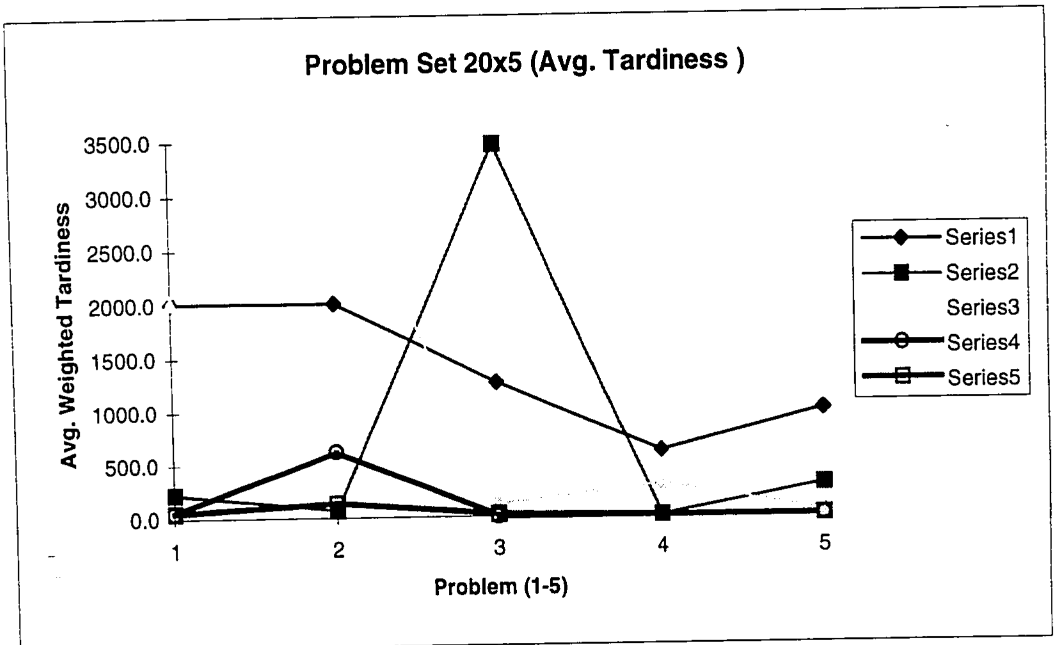

Figure 17 Comparison of the schemes 1,2,3,4,5

problem we added total load to the objective function. Another aim was to minimize the total load while balancing the machine load. one more constraint is added to the previous formulation to get the following formulation. Constraint two states that load on each machine should be less than or equal to the load on the maximum loaded machine.

$$\min \left(\sum_{j=1}^{J} Wj\ PTj + 5\,Lmax + \sum_{m=1}^{M} L(m) \right)$$

s.t

$$\sum_{j=1}^{J} \sum_{r_j=1}^{R_j} \sum_{o_{r_j}=1}^{O_{r_j}} P_{jr_j o_{r_j}} V_{jr_j} = L(m) \quad \text{for } m = 1 \text{ to } M \quad (1)$$

assumption $Pjr_j\, o_{r_j} = Pjr_j\, o_{r_j}$ (if that operation uses machine m)

0 otherwise

$$L(m) \leq Lmax \qquad \text{for } m = 1 \text{ to } M \quad (2)$$

$$\sum_{r_j=1}^{R_j} D_{jr_j} V_{jr_j} = Dj \qquad \text{for } j = 1 \text{ to } J \quad (3)$$

$$Lmax - Dj \leq PTj \qquad \text{for } j = 1 \text{ to } J \quad (4)$$

$$\sum_{r_j=1}^{R_j} V_{jr_j} = 1 \qquad \text{for } j = 1 \text{ to } J \quad (5)$$

From Figure 18 we can see that adding total load to the objective function reduces the total load of the system. This scheme gives always less total load compared to the previous scheme.

Problem Set 5x20

Table 18 Scheme 5 vs. Scheme 6 in terms of total machine load

	Series 1	Series 2
Total M/C	**Tard.**	**Lmax+Lm+Tard.**
Prob1	2110.0	1839.0
Prob2	2044	1944
Prob3	2042	1980
Prob4	1969	1969
Prob5	1927	1790

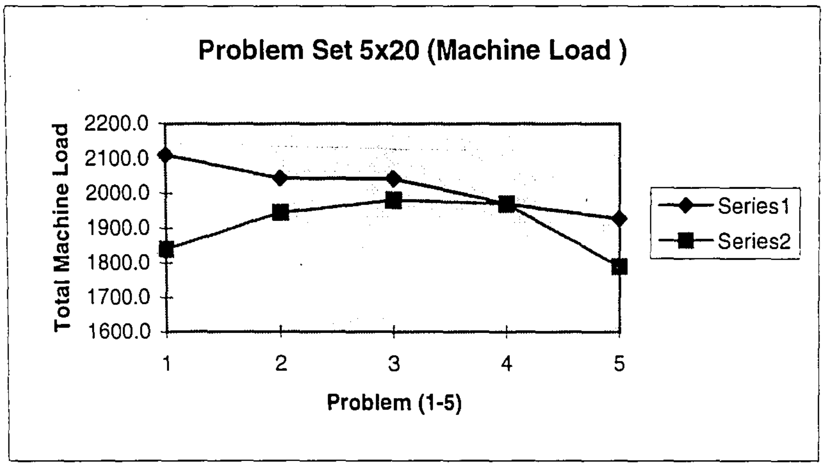

Figure 18 Scheme 5 vs.Scheme 6 in terms of total machine load

Problem Set 5x20

Table 18 Scheme 5 vs. Scheme 6 in terms of total machine load

	Series 1	Series 2
Total M/C	**Tard.**	**Lmax+Lm+Tard.**
Prob1	2110.0	1839.0
Prob2	2044	1944
Prob3	2042	1980
Prob4	1969	1969
Prob5	1927	1790

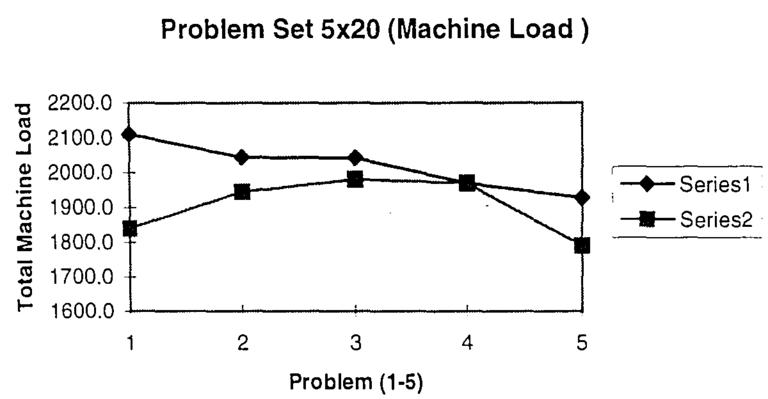

Figure 18 Scheme 5 vs.Scheme 6 in terms of total machine load

Chapte 6

Scheduling Subproblem

After solving the loading part of the problem we get Vjr_j values that shows the routes selected for each job. These selected routes are the inputs to the second part of the problem. When we determine the routes we reduce the problem to the job shop scheduling problem. In this part we used ATC heuristic to schedule the jobs. The solution of the second part is explained at the evaluation procedure.

6.1 Evaluation Procedure

Evaluation procedure which is taken from Brennan and Wu [4] is used at the second part of the problem. After this procedure completion time of the jobs, operation sequence and the weighted tardiness are determined.

Procedure EVALUATE

1. for o = 1 to Number of Operations

   Processing time at operation o = (Expected time at operation o) * unif [1-Delta] [1+Delta]

2. Evaluate schedule using a dynamic dispatching method.

   2a. Begin at t = 0 with each job ready to begin its first operation and all machines available.

   2b. For each job that is ready whose next operation requires a machine that is also ready, compute a priority index using the expected time for the operation di. Note: an operation is not ready until all pervious operations in that job have been completed.

   If no such operation/machine pair exists, move time forward to the next smallest time on the event clock and repeat step 2b.

Otherwise, schedule the operation/machine pair with the largest priority.

2c. Schedule the job and machine to become available on the event clock after a perturbed processing time di'.

2.d Repeat step 2 until all operations have been completed. Save the time at which each job was completed, Ci.

3. Compute Weighted Tardiness (WT)

3.a WTi = 0 if Ci < ddi (due date of job i)
WTi = Ci - ddi if Ci > ddi

3.b WT = WT1 + WT2 +......+ WTi + ...+ WTn

4. Repeat steps 1-3 until SAMPLE values for WT have been collected.

5. Z = (Min WT + 4*Avg WT + Max WT) / 6 (source Al-Refai and Wu , pp.18 [1])

Here we used a linear combination of the minimum, average and maximum tardiness values instead of the mean weighted tardiness this is done to capture the skeweness of the weighted tardiness values. For the two different input (selected routes for scheduling) with the same weighted tardiness values this objective function will favor the input that has more lower weighted tardiness values. Brennan and Wu[4] showed that this objective function which is based on the PERT method of project scheduling is a better estimator of scheduling performance according to the mean weighted tardiness.

After selecting the routes (inputs) first we scheduled them without considering any disruptions. Later we considered disruptions such as machine breakdowns, unavailability of operators etc. by adding perturbation to the processing times. Processing times are perturbed DELTA % in step 1. We used three different levels of perturbation. 5%, 10% and 15%. All results are given in a chart as a comparison after the conclusion.

In step two all jobs are scheduled and finishing times of the jobs are found. While scheduling ATC (Apparent Tardiness Cost) heuristic is used (Vepsalainen and Morton [15]). According to this dynamic dispatching heuristic priorities of the jobs for the given machine k ,which are available at that time, are calculated according to the following form.

$$\text{Priority}_{jk}(t) = (W_j / d_{jk}) \left[\exp\{ -(dd_j - l_{jk} - t)^+ / k' \, d_{kav} \} \right]$$

where

$\text{Priority}_{jk}(t)$: priority of job j for machine k at time t.

t : event clock

W_j : weight of job j

d_{jk} : is the required time to process job j on machine k at time(clock) t

dd_j : due date of job j

k' : look ahaed parameter and 2 is used for this parameter in the experiments

d_{kav} : is the average processing time expected for machine k at time t.

$_{jk}$: Static estimate of total lead time of job j from its arrival at machine k until the job is completed. Sum of the remaining processing time is accepted as l_{jk} in our calculations.

At step 3 we used five as the number of SAMPLE for the experiment with perturbed processing time. We repeated scheduling for five different perturbed processing times and at step five we computed the linear combination of the minimum, average and maximum values. The reason behind this objective function is to consider the skewness of the population of weighted tardiness values.

Chapter 7

Conclusions

There are many works reported in literature in the area of integrated process planning and scheduling. Research done in this area shows that integration of the two functions improve the overall performance. These functions have conflicting goals and process planners can chose same machine repeatedly without knowing the situation on the shopfloor or worrying about scheduling problems. Since their process plan selections are the inputs of the scheduling function, poor inputs may not be efficient when considering shopfloor conditions. Integrated approaches can eliminate most of these drawbacks.

The loading subproblem is formulated as a mixed integer programming which belongs to NP-complete class. To increase the number of variables and constraints makes the solution inefficient in terms of computational time. All related cpu times are given at Tables 10,19 and 28. For the problem sets we are testing for the schemes that we are comparing, we obtained the results in a reasonable time. From the tables and figures following this chapter it is not hard to see that random route selection is very poor compared to the other schemes. There is no unique scheme that outperforms all the others for all test problems. For the problem set 20x5 schemes 2,4,5,6 work well, For the set 30x10 schemes 2,3 and 4, all, outperform GAP heuristic. For the set 5x20 scheme 5 is a poor solution it is because of the machine load. Since there are 20 machines and balanced machine loading is very important for the formulation of scheme 5 we couldn't get similar promising results as we did in previous sets. We can give more weights to the Lmax at the objective function and run all the experiments with the new objective function but this may be a good works that can be done for the future. Due dates also play important role in this set. Since there are more operations per route in this set the slack (Due date - completion time of the job) gets bigger as the total processing time increases or vice a versa. That's why GAP gave results as good as the other schemes and this too, comparing the schemes with fixed due date, is a good future work in this area.

At this point it appears that the schemes that we developed are promising approaches in this area. More experiments for different set of problems in different characteristics such as fixed due date with respect to different routes, varying number of operations per route , need to be tested. We made 1024 experiment in this research and more needs to be done to get a more reliable scheme. All the remaining comparisions for the problem sets 20x5, 30x10 and 5x20 are given after this chapter starting Table 11 and Figure 19.

Problem Set 20x5

Table 19 Comparison of the schemes 2,3,4,5,,6 with Random route selection

	Perturbation Level	0%	5%	15%	25%	Avg
prob1	Random	4810.0	5020.4	5593.0	6562.9	**5496.6**
	LMAX	215.0	222.9	220.5	237.3	**223.9**
	Lm	1853.0	1955.8	2249.1	2022.3	**2020.1**
	Lmax+Lm	0.0	49.0	102.5	37.3	**47.2**
	Tard.	0.0	1.1	116.5	95.2	**53.2**
	Lmax+Lm+Tard.	0.0	0.0	0.0	0.0	**0.0**
prob2	Random	4259.0	4228.7	5393.1	6762.8	**5160.9**
	LMAX	0.0	56.1	106.3	113.3	**68.9**
	Lm	3587.0	3711.2	3186.4	3392.7	**3469.3**
	Lmax+Lm	591.0	601.6	615.6	666.1	**618.6**
	Tard.	92.0	116.3	76.1	245.2	**132.4**
	Lmax+Lm+Tard.	92.0	63.4	159.3	110.9	**106.4**
prob3	Random	1193.0	1722.2	2529.7	3689.3	**2283.6**
	LMAX	3301.0	3379.3	3702.3	3464.1	**3461.7**
	Lm	95.0	104.3	195.4	66.2	**115.2**
	Lmax+Lm	0.0	0.0	0.0	0.0	**0.0**
	Tard.	0.0	0.0	66.9	16.2	**20.8**
	Lmax+Lm+Tard.	0.0	0.0	0.0	0.0	**0.0**
prob4	Random	1834.0	2056.8	2743.6	3726.9	**2590.3**
	LMAX	0.0	0.0	0.0	0.0	**0.0**
	Lm	266.0	246.9	289.7	384.9	**296.9**
	Lmax+Lm	0.0	0.0	0.0	0.0	**0.0**
	Tard.	0.0	0.0	0.0	0.0	**0.0**
	Lmax+Lm+Tard.	0.0	0.0	0.0	0.0	**0.0**
prob5	Random	1745.0	1837.4	2448.1	3592.7	**2405.8**
	LMAX	0.0	10.0	6.1	1138.1	**288.5**
	Lm	0.0	19.3	32.2	114.9	**41.6**
	Lmax+Lm	0.0	0.0	0.0	0.0	**0.0**
	Tard.	0.0	0.0	0.0	0.0	**0.0**
	Lmax+Lm+Tard.	0.0	0.0	0.0	7.7	**1.9**

Problem Set 20x5

Table 20

Scheme	Series	Prob1	Prob2	Prob3	Prob4	Prob5
			Avg. Tardiness			
Random	Series1	5496.6	5160.9	2283.6	2590.3	2405.8
LMAX (S 2)	Series2	223.9	68.9	3461.7	0.0	288.5
Lm (S 3)	Series3	2020.1	3469.3	115.2	296.9	41.6
Lmax+Lm (S 6)	Series4	47.2	618.6	0.0	0.0	0.0
Tard. (S 5)	Series5	53.2	132.4	20.8	0.0	0.0
Lmax+Lm+Tard. (S 6)	Series6	0.0	106.4	0.0	0.0	1.9

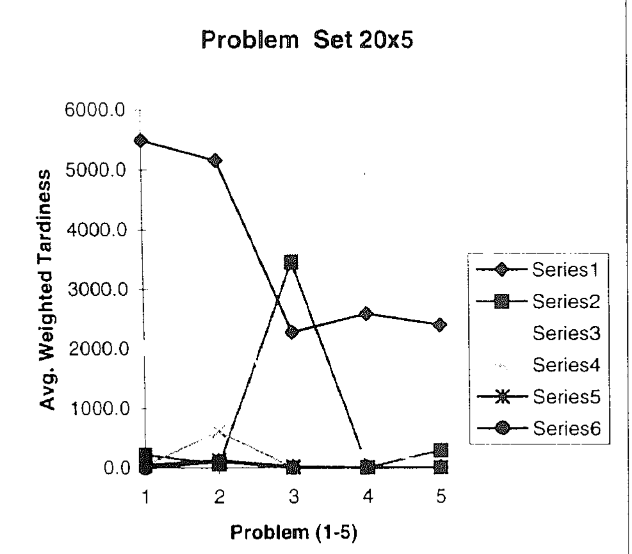

Figure 19a

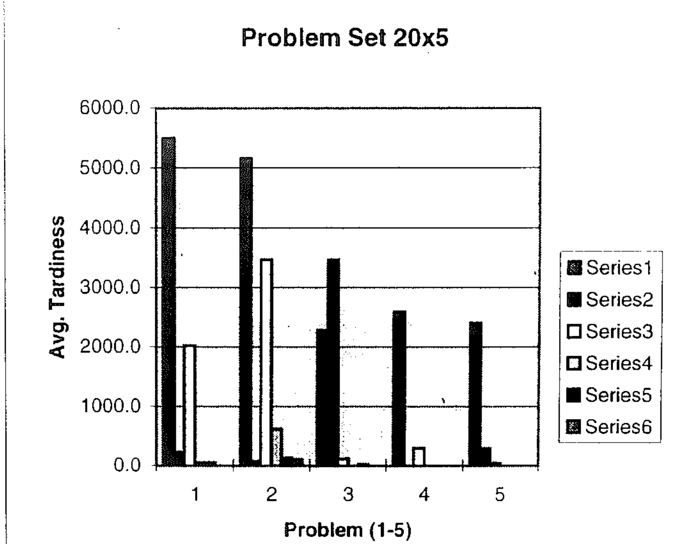

Figure 19b

Comparison of the schemes 2,3,4,5,6 with the random route selection

Problem Set 20x5

Table 20

Scheme	Series	Prob1	Prob2	Prob3	Prob4	Prob5
			Avg. Tardiness			
Random	Series1	5496.6	5160.9	2283.6	2590.3	2405.8
LMAX (S 2)	Series2	223.9	68.9	3461.7	0.0	288.5
Lm (S 3)	Series3	2020.1	3469.3	115.2	296.9	41.6
Lmax+Lm (S 6)	Series4	47.2	618.6	0.0	0.0	0.0
Tard. (S 5)	Series5	53.2	132.4	20.8	0.0	0.0
Lmax+Lm+Tard. (S 6)	Series6	0.0	106.4	0.0	0.0	1.9

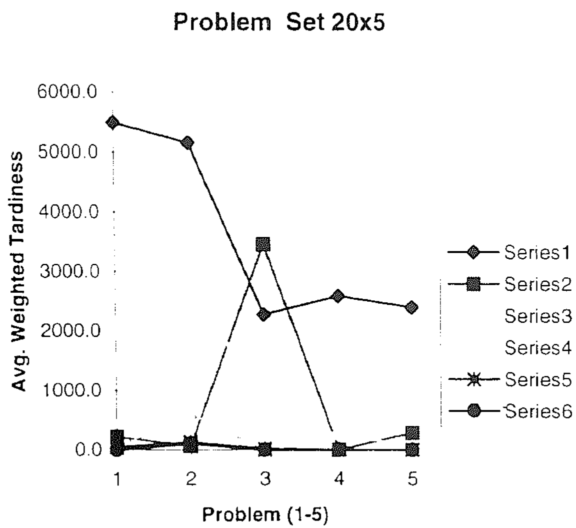

Figure 19a

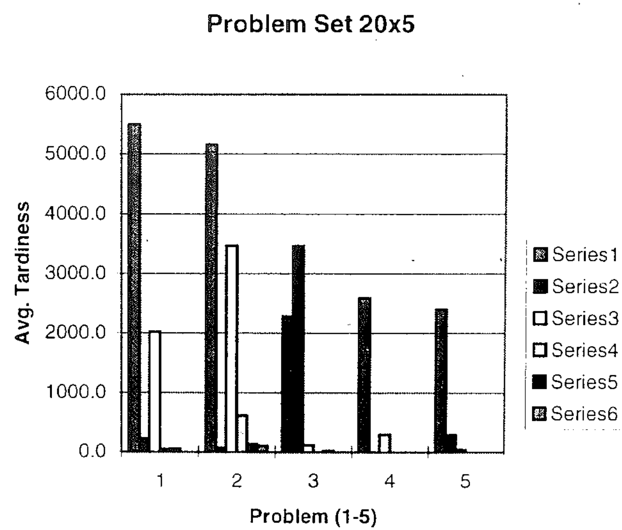

Figure 19b

Comparison of the schemes 2,3,4,5,6 with the random route selection

Problem Set 20x5

Table 21 Comparison of the schemes 1,2,3,4,5,6

	Perturbation Level	0%	5%	15%	25%	Avg
prob1	GAP	1335.0	1316.0	2019.0	3363.0	2008.3
	LMAX	215.0	222.9	220.5	237.3	223.9
	Lm	1853.0	1955.8	2249.1	2022.3	2020.1
	Lmax+Lm	0.0	49.0	102.5	37.3	47.2
	Tard.	0.0	1.1	116.5	95.2	53.2
	Lmax+Lm+Tard.	0.0	0.0	0.0	0.0	0.0
prob2	GAP	921.0	1422.0	2220.0	3461.0	2006.0
	LMAX	0.0	56.1	106.3	113.3	68.9
	Lm	3587.0	3711.2	3186.4	3392.7	3469.3
	Lmax+Lm	591.0	601.6	615.6	666.1	618.6
	Tard.	92.0	116.3	76.1	245.2	132.4
	Lmax+Lm+Tard.	92.0	63.4	159.3	110.9	106.4
prob3	GAP	131.0	480.0	1489.0	2935.0	1258.8
	LMAX	3301.0	3379.3	3702.3	3464.1	3461.7
	Lm	95.0	104.3	195.4	66.2	115.2
	Lmax+Lm	0.0	0.0	0.0	0.0	0.0
	Tard.	0.0	0.0	66.9	16.2	20.8
	Lmax+Lm+Tard.	0.0	0.0	0.0	0.0	0.0
prob4	GAP	0.0	173.0	578.0	1677.0	607.0
	LMAX	0.0	0.0	0.0	0.0	0.0
	Lm	266.0	246.9	289.7	384.9	296.9
	Lmax+Lm	0.0	0.0	0.0	0.0	0.0
	Tard.	0.0	0.0	0.0	0.0	0.0
	Lmax+Lm+Tard.	0.0	0.0	0.0	0.0	0.0
prob5	GAP	302.0	573.0	1093.0	2008.0	994.0
	LMAX	0.0	10.0	6.1	1138.1	288.5
	Lm	0.0	19.3	32.2	114.9	41.6
	Lmax+Lm	0.0	0.0	0.0	0.0	0.0
	Tard.	0.0	0.0	0.0	0.0	0.0
	Lmax+Lm+Tard.	0.0	0.0	7.7	0.0	1.9

Problem Set 20x5

Table 22

Scheme	Series	Prob1	Prob2	Prob3	Prob4	Prob5
		Avg. Tardiness				
GAP (S 1)	Series 1	2008.3	2006.0	1258.8	607.0	994.0
LMAX (S 2)	Series 2	223.9	68.9	3461.7	0.0	288.5
Lm (S 3)	Series 3	2020.1	3469.3	115.2	296.9	41.6
Lmax+Lm (S 4)	Series 4	47.2	618.6	0.0	0.0	0.0
Tard. (S 5)	Series 5	53.2	132.4	20.8	0.0	0.0
Lmax+Lm+Tard. (S 6)	Series 6	0.0	106.4	0.0	0.0	1.9

S 1 = Scheme 1

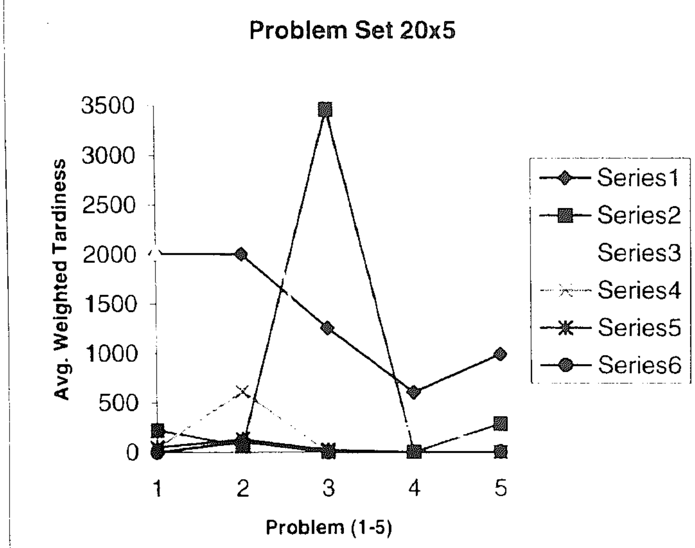

Figure 20a

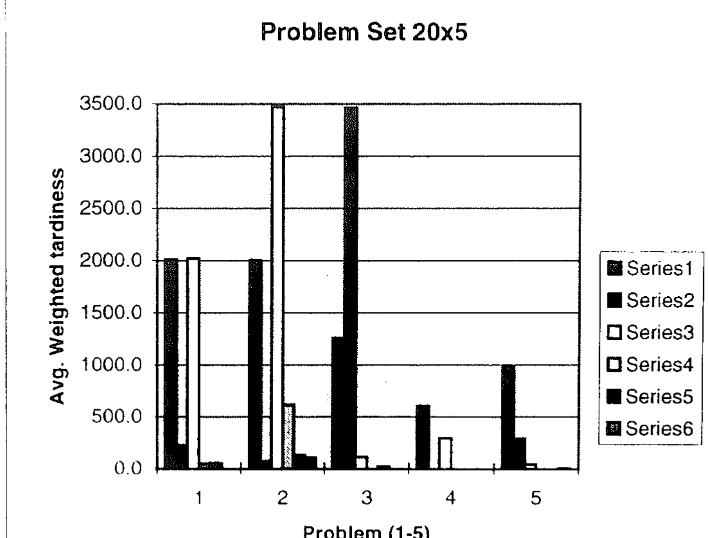

Figure 20b

Comparison of the schemes 1,2,3,4,5,6

Problem Set 20x5

Table 22

Scheme	Series	Prob1	Prob2	Prob3	Prob4	Prob5
		Avg. Tardiness				
GAP (S 1)	Series 1	2008.3	2006.0	1258.8	607.0	994.0
LMAX (S 2)	Series 2	223.9	68.9	3461.7	0.0	288.5
Lm (S 3)	Series 3	2020.1	3469.3	115.2	296.9	41.6
Lmax+Lm (S 4)	Series 4	47.2	618.6	0.0	0.0	0.0
Tard. (S 5)	Series 5	53.2	132.4	20.8	0.0	0.0
Lmax+Lm+Tard. (S 6)	Series 6	0.0	106.4	0.0	0.0	1.9

S 1 = Scheme 1

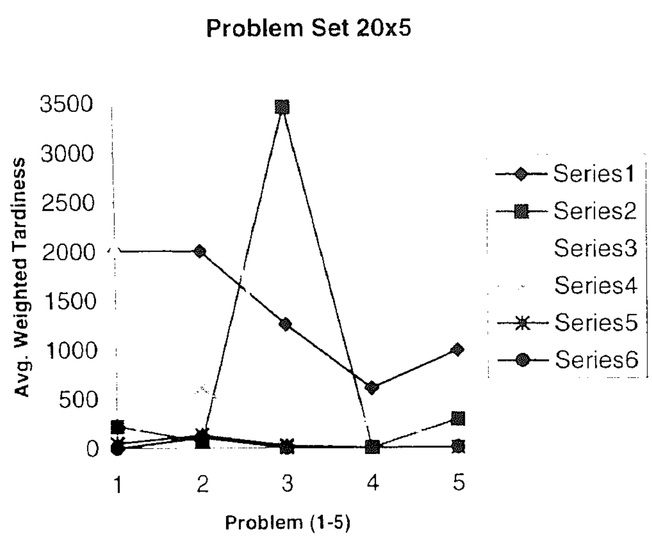

Figure 20a

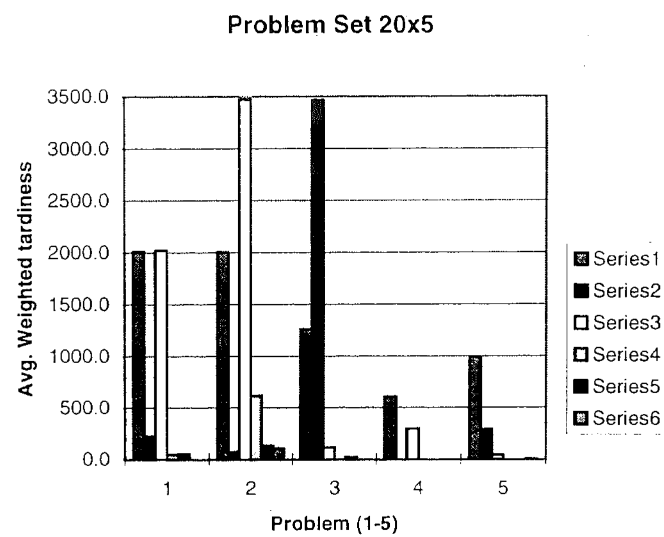

Figure 20b

Comparison of the schemes 1,2,3,4,5,6

Problem Set 20x5

Table 23 Comparison of the schemes 1,2,3,4,5,6

	Problem	Prob1	Prob2	Prob3	Prob4	Prob5	SUM	AVG.
0%	GAP	1335.0	921.0	131.0	0.0	302.0	2689.0	537.8
	LMAX	215.0	0.0	3301.0	0.0	0.0	3516.0	703.2
	Lm	1853.0	3587.0	95.0	266.0	0.0	5801.0	1160.2
	Lmax+Lm	0.0	591.0	0.0	0.0	0.0	591.0	118.2
	Tard.	0.0	92.0	0.0	0.0	0.0	92.0	18.4
	Lmax+Lm+Tard.	0.0	92.0	0.0	0.0	0.0	92.0	18.4
5%	GAP	1316.0	4228.7	1722.2	2056.8	1837.4	11161.1	2232.2
	LMAX	222.9	56.1	3379.3	0.0	10.0	3668.3	733.7
	Lm	1955.8	3711.2	104.3	246.9	19.3	6037.6	1207.5
	Lmax+Lm	49.0	601.6	0.0	0.0	0.0	650.6	130.1
	Tard.	1.1	116.3	0.0	0.0	0.0	117.4	23.5
	Lmax+Lm+Tard.	0.0	63.4	0.0	0.0	0.0	63.4	12.7
15%	GAP	2019.0	5393.1	2529.7	2743.6	2448.1	15133.5	3026.7
	LMAX	220.5	106.3	3702.3	0.0	6.1	4035.1	807.0
	Lm	2249.1	3186.4	195.4	289.7	32.2	5952.9	1190.6
	Lmax+Lm	102.5	615.6	0.0	0.0	0.0	718.1	143.6
	Tard.	116.5	76.1	66.9	0.0	0.0	259.5	51.9
	Lmax+Lm+Tard.	0.0	159.3	0.0	0.0	0.0	159.3	31.9
25%	GAP	3363.0	6762.8	3689.3	3726.9	3592.7	21134.7	4226.9
	LMAX	237.3	113.3	3464.1	0.0	1138.1	4952.8	990.6
	Lm	2022.3	3392.7	66.2	384.9	114.9	5981.0	1196.2
	Lmax+Lm	37.3	666.1	0.0	0.0	0.0	703.4	140.7
	Tard.	95.2	245.2	16.2	0.0	0.0	356.6	71.3
	Lmax+Lm+Tard.	0.0	110.9	0.0	0.0	7.7	118.6	23.7
Avg.	GAP	2008.3	5160.9	2283.6	2590.3	2405.8	14448.9	2889.8
	LMAX	223.9	68.9	3461.7	0.0	288.5	4043.1	808.6
	Lm	2020.1	3469.3	115.2	296.9	41.6	5943.1	1188.6
	Lmax+Lm	47.2	618.6	0.0	0.0	0.0	665.8	133.2
	Tard.	53.2	132.4	20.8	0.0	0.0	206.4	41.3
	Lmax+Lm+Tard.	0.0	106.4	0.0	0.0	1.9	108.3	21.7

Problem Set 20x5

Table 24

Avg. Tardiness
Over all perturbation level
(0%,5%,15%,25%)

		Perturbation Levels				
Series		**0%**	**5%**	**15%**	**25%**	**Avg**
Series 1	**GAP**	537.8	2232.2	3026.7	4226.9	2889.8
Series 2	**LMAX**	703.2	733.7	807.0	990.6	808.6
Series 3	**Lm**	1160.2	1207.5	1190.6	1196.2	1188.6
Series 4	**Lmax+Lm**	118.2	130.1	143.6	140.7	133.2
Series 5	**Tard.**	18.4	23.5	51.9	71.3	41.3
Series 6	**Lmax+Lm+Tard.**	18.4	12.7	31.9	23.7	21.7

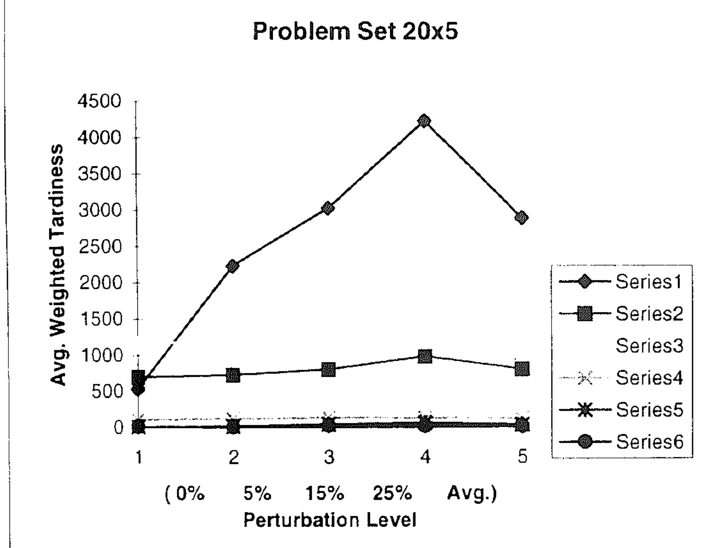

Figure 21a

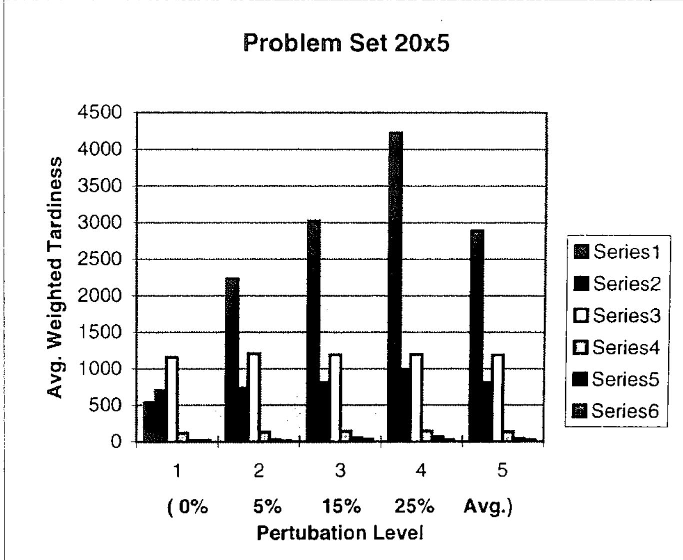

Figure 22b

Comparison of the schemes 1,2,3,4,5,6 in terms of avg. weighted tardiness over all perturbation level

Problem Set 20x5

Table 24

	Series		0%	5%	15%	25%	Avg
			Perturbation Levels				
Avg. Tardiness	Series 1	**GAP**	537.8	2232.2	3026.7	4226.9	2889.8
Over all perturbation level	Series 2	**LMAX**	703.2	733.7	807.0	990.6	808.6
(0%,5%,15%,25%)	Series 3	**Lm**	1160.2	1207.5	1190.6	1196.2	1188.6
	Series 4	**Lmax+Lm**	118.2	130.1	143.6	140.7	133.2
	Series 5	**Tard.**	18.4	23.5	51.9	71.3	41.3
	Series 6	**Lmax+Lm+Tard.**	18.4	12.7	31.9	23.7	21.7

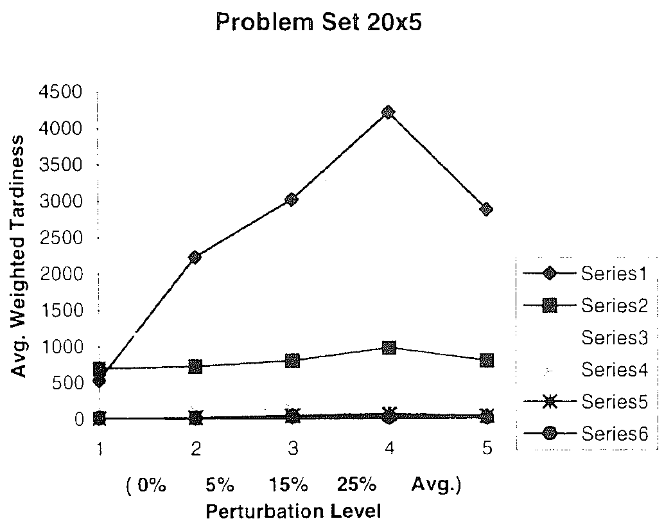

Figure 21a

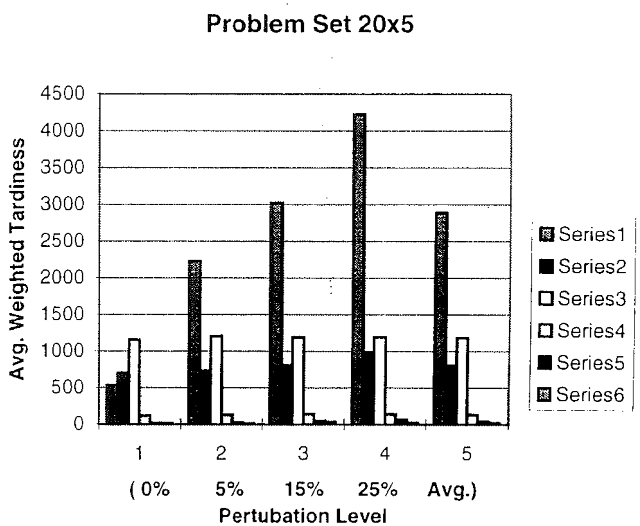

Figure 22b

Comparison of the schemes 1,2,3,4,5,6 in terms of avg. weighted tardiness over all perturbation level

Problem Set 30x10

Table 25 Comparison of the schemes 2,3,4 with the random route selection

	Perturbation Level	0%	5%	15%	25%	Avg
prob1	Random	2997.0	3508.7	4147.6	5875.0	**4132.1**
	LMAX	90.0	103.4	494.7	105.4	**198.4**
	Lm	72.0	60.1	261.0	445.6	**209.7**
	Lmax+Lm	414.0	308.0	96.6	187.5	**251.5**
prob2	Random	1422.0	1396.8	2053.4	3342.9	**2053.8**
	LMAX	15.1	62.0	73.6	63.7	**53.6**
	Lm	44.0	38.5	39.7	44.2	**41.6**
	Lmax+Lm	0.0	0.0	0.0	0.7	**0.2**
prob3	Random	1878.0	2018.4	2694.7	4176.1	**2691.8**
	LMAX	0.0	4.5	3.0	0.0	**1.9**
	Lm	0.0	0.0	0.0	0.0	**0.0**
	Lmax+Lm	13.0	0.0	5.1	10.1	**7.0**
prob4	Random	1730.0	1862.3	2982.5	4474.0	**2762.2**
	LMAX	0.0	0.0	0.0	155.8	**39.0**
	Lm	130.0	190.0	153.9	199.8	**168.4**
	Lmax+Lm	0.0	0.0	0.0	122.1	**30.5**
prob5	Random	4152.0	3950.9	4803.9	6389.9	**4824.2**
	LMAX	0.0	62.3	52.8	63.8	**44.7**
	Lm	102.0	106.2	87.7	99.6	**98.9**
	Lmax+Lm	0.0	0.0	55.5	74.0	**32.4**

Problem Set 30x10

Table 26

Avg. Tardiness

Scheme	Series	Prob1	Prob2	Prob3	Prob4	Prob5
Random	Series1	4132.1	2053.8	2691.8	2762.2	4824.2
LMAX (S 2)	Series2	198.4	53.6	1.9	39.0	44.7
Lm (S 3)	Series3	209.7	41.6	0.0	168.4	98.9
Lmax+Lm (S 4)	Series4	251.5	0.2	7.0	30.5	32.4

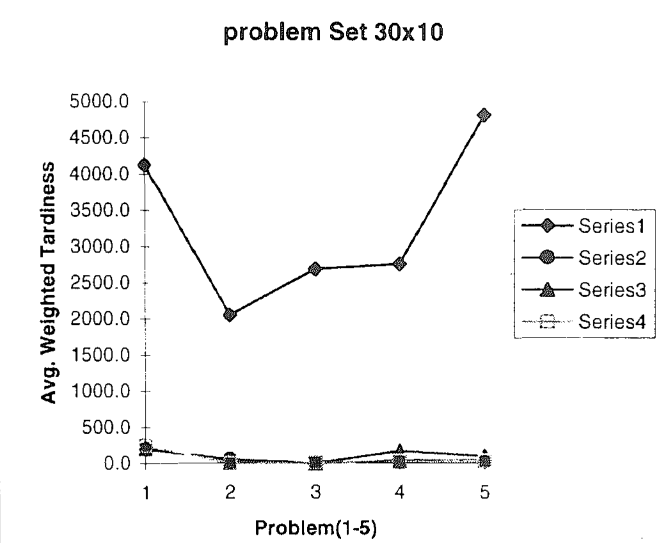

Figure 22a

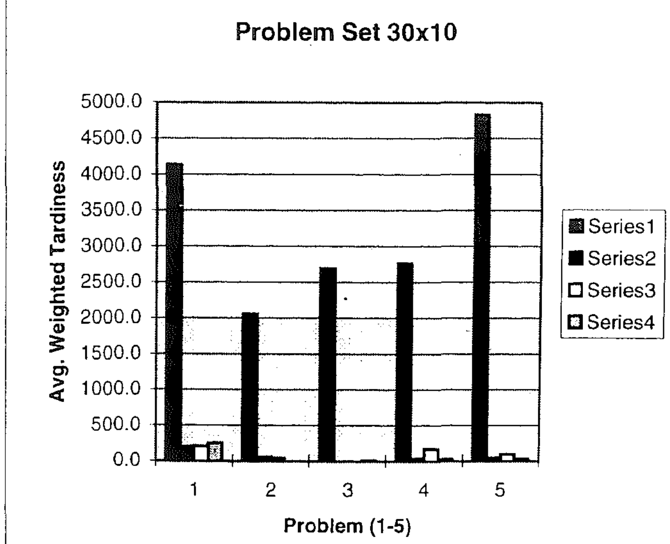

Figure 22b

Comparison of the scheme 2,3,4 with the random route selection

Problem Set 30x10

Table 26

Avg. Tardiness

Scheme	Series	Prob1	Prob2	Prob3	Prob4	Prob5
Random	Series1	4132.1	2053.8	2691.8	2762.2	4824.2
LMAX (S 2)	Series2	198.4	53.6	1.9	39.0	44.7
Lm (S 3)	Series3	209.7	41.6	0.0	168.4	98.9
Lmax+Lm (S 4)	Series4	251.5	0.2	7.0	30.5	32.4

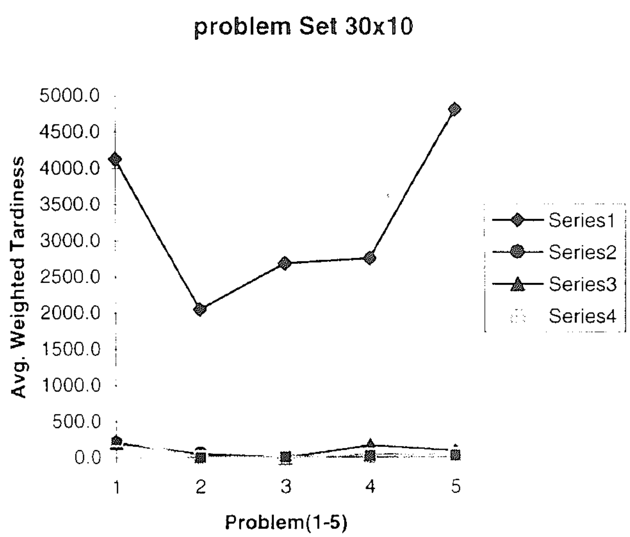

Figure 22a

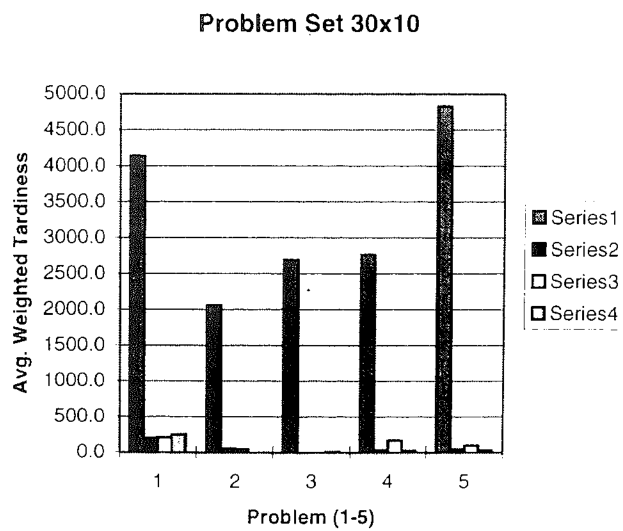

Figure 22b

Comparison of the scheme 2,3,4 with the random route selection

Problem Set 30x10

Table 27 Comparison of the schemes 1,2,3,4

	Perturbation Level	0%	5%	15%	25%	Avg
prob1	GAP	268.0	748.0	2005.4	3623.0	1661.1
	LMAX	90.0	103.4	494.7	105.4	198.4
	Lm	72.0	60.1	261.0	445.6	209.7
	Lmax+Lm	414.0	308.0	96.6	187.5	251.5
prob2	GAP	21.0	175.1	539.6	1533.2	567.2
	LMAX	15.1	62.0	73.6	63.7	53.6
	Lm	44.0	38.5	39.7	44.2	41.6
	Lmax+Lm	0.0	0.0	0.0	0.7	0.2
prob3	GAP	0.0	128.4	594.9	1302.0	506.3
	LMAX	0.0	4.5	3.0	0.0	1.9
	Lm	0.0	0.0	0.0	0.0	0.0
	Lmax+Lm	13.0	0.0	5.1	10.1	7.0
prob4	GAP	19.0	199.5	710.9	1456.4	596.5
	LMAX	0.0	0.0	0.0	155.8	39.0
	Lm	130.0	190.0	153.9	199.8	168.4
	Lmax+Lm	0.0	0.0	0.0	122.1	30.5
prob5	GAP	16.0	151.2	458.9	1117.3	435.9
	LMAX	0.0	62.3	52.8	63.8	44.7
	Lm	102.0	106.2	87.7	99.6	98.9
	Lmax+Lm	0.0	0.0	55.5	74.0	32.4

Problem Set 30x10

Table 28

Scheme	Series	Avg. Tardiness Prob1	Prob2	Prob3	Prob4	Prob5
GAP (S 1)	Series 1	1661.1	567.2	506.3	596.5	435.9
LMAX (S 2)	Series 2	198.4	53.6	1.9	39.0	44.7
Lm (S 3)	Series 3	209.7	41.6	0.0	168.4	98.9
Lmax+Lm (S 4)	Series 4	251.5	0.2	7.0	30.5	32.4

S 1 = Scheme 1

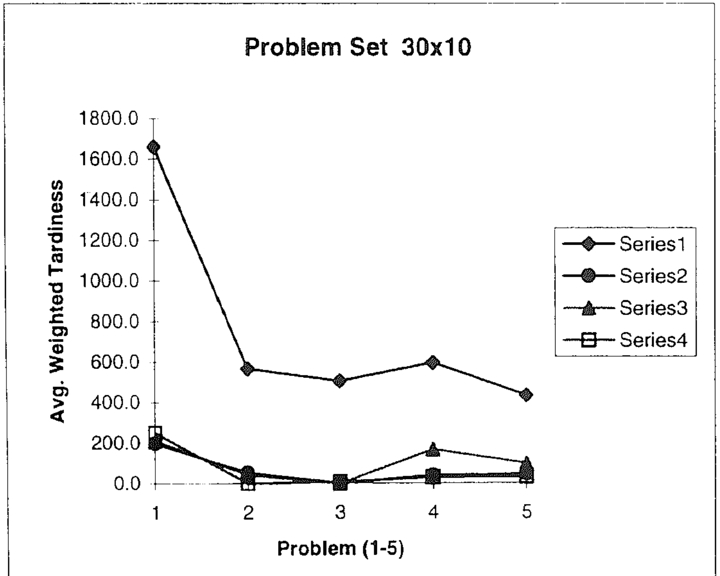

Figure 23a

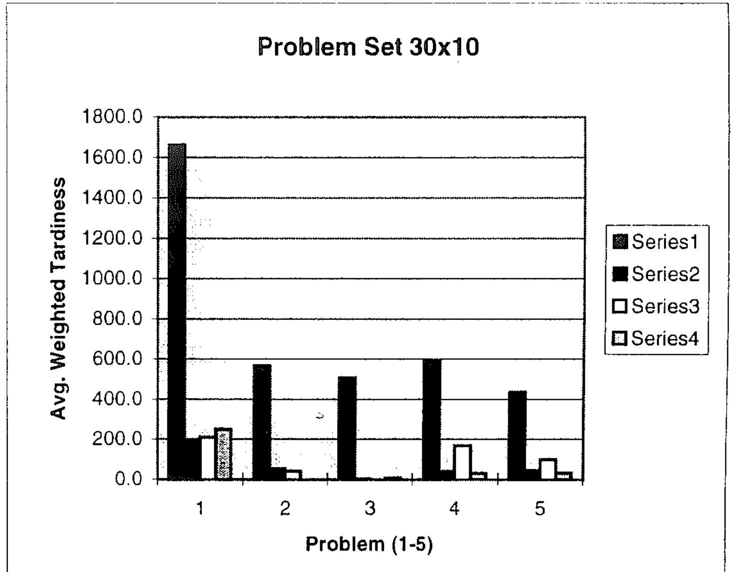

Figure 23b

Comparison of the schemes 1,2,3,4

Problem Set 30x10

Table 28

Avg. Tardiness

Scheme	**Series**	**Prob1**	**Prob2**	**Prob3**	**Prob4**	**Prob5**
GAP (S 1)	Series 1	1661.1	567.2	506.3	596.5	435.9
LMAX (S 2)	Series 2	198.4	53.6	1.9	39.0	44.7
Lm (S 3)	Series 3	209.7	41.6	0.0	168.4	98.9
Lmax+Lm (S 4)	Series 4	251.5	0.2	7.0	30.5	32.4

S 1 = Scheme 1

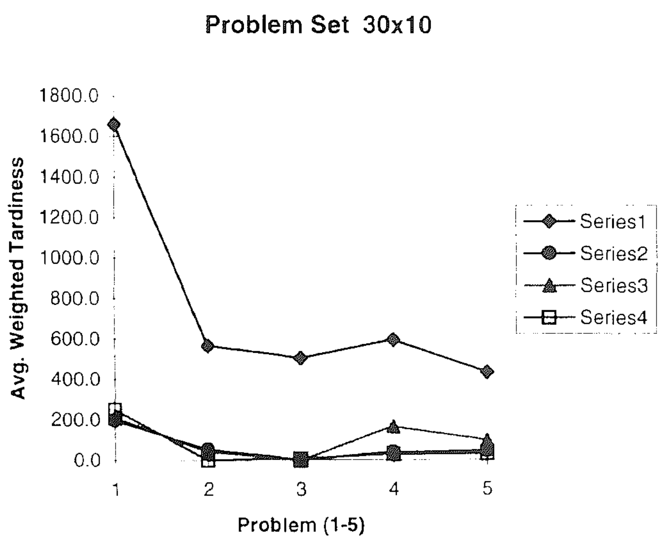

Figure 23a

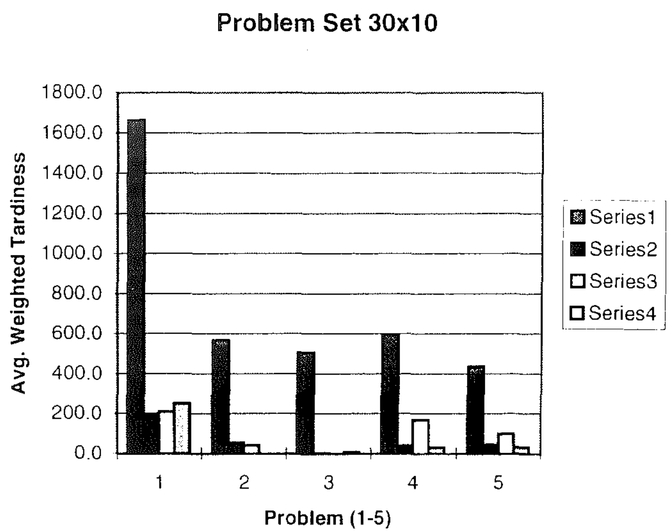

Figure 23b

Comparison of the schemes 1,2,3,4

Problem Set 30x10

Table 29 Comparison of the schemes 1,2,3,4

	Problem	Prob1	Prob2	Prob3	Prob4	Prob5	SUM	AVG.
0%	GAP	268.0	21.0	0.0	19.0	16.0	324.0	64.8
	LMAX	90.0	15.1	0.0	0.0	0.0	105.1	21.0
	Lm	72.0	44.0	0.0	130.0	102.0	348.0	69.6
	Lmax+Lm	414.0	0.0	13.0	0.0	0.0	427.0	85.4
5%	GAP	748.0	175.1	128.4	199.5	151.2	1402.2	280.4
	LMAX	103.4	62.0	4.5	0.0	62.3	232.2	46.4
	Lm	60.1	38.5	0.0	190.0	106.2	394.8	79.0
	Lmax+Lm	308.0	0.0	0.0	0.0	0.0	308.0	61.6
15%	GAP	2005.4	539.6	594.9	710.9	458.9	4309.7	861.9
	LMAX	494.7	73.6	3.0	0.0	52.8	624.0	124.8
	Lm	261.0	39.7	0.0	153.9	87.7	542.3	108.5
	Lmax+Lm	96.6	0.0	5.1	0.0	55.5	157.2	31.4
25%	GAP	3623.0	1533.2	1302.0	1456.4	1117.3	9031.9	1806.4
	LMAX	105.4	63.7	0.0	155.8	63.8	388.8	77.8
	Lm	445.6	44.2	0.0	199.8	99.6	789.1	157.8
	Lmax+Lm	187.5	0.7	10.1	122.1	74.0	394.4	78.9
Avg.	GAP	1661.1	567.2	506.3	596.5	435.9	3767.0	753.4
	LMAX	198.4	53.6	1.9	39.0	44.7	337.5	67.5
	Lm	209.7	41.6	0.0	168.4	98.9	518.6	103.7
	Lmax+Lm	251.5	0.2	7.0	30.5	32.4	321.6	64.3

Problem Set 30x10

Table 30

	Series		Perturbation Levels 0%	5%	15%	25%	Avg
Avg. Tardiness	Series 1	**GAP**	64.8	280.4	861.9	1806.4	753.4
Over all perturbation level	Series 2	**LMAX**	21.0	46.4	124.8	77.8	67.5
(0%,5%,15%,25%)	Series 3	**Lm**	69.6	79.0	108.5	157.8	103.7
	Series 4	**Lmax+Lm**	85.4	61.6	31.4	78.9	64.3

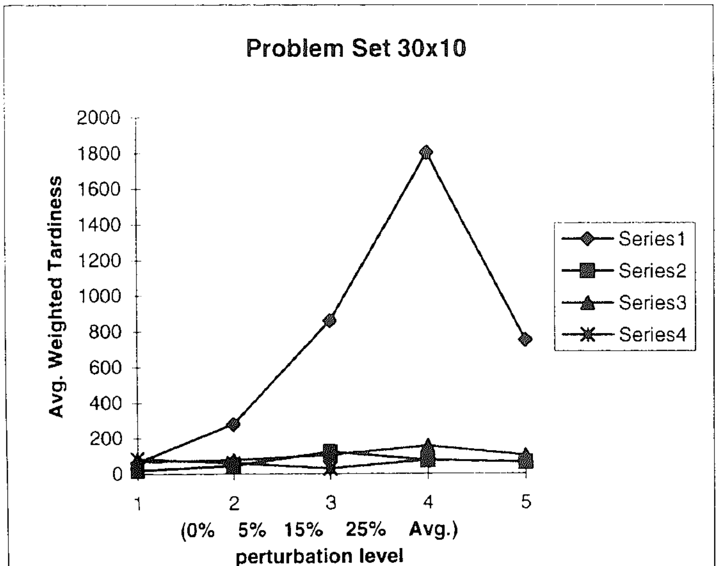

Figure 24a

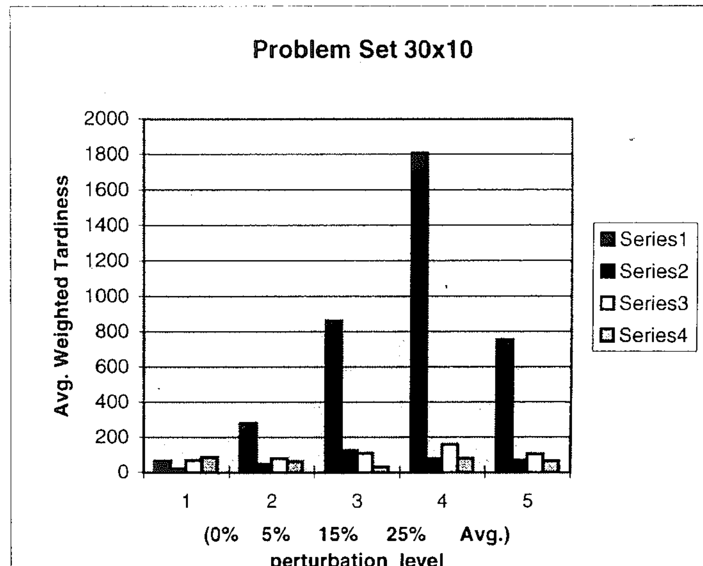

Figure 24b

Comparison of the schemes 1,2,3,4 in terms of avg. tardiness over all perturbation level

Problem Set 30x10

Table 30

	Series		Perturbation Levels 0%	5%	15%	25%	Avg
Avg. Tardiness	Series 1	**GAP**	64.8	280.4	861.9	1806.4	753.4
Over all perturbation level	Series 2	**LMAX**	21.0	46.4	124.8	77.8	67.5
(0%,5%,15%,25%)	Series 3	**Lm**	69.6	79.0	108.5	157.8	103.7
	Series 4	**Lmax+Lm**	85.4	61.6	31.4	78.9	64.3

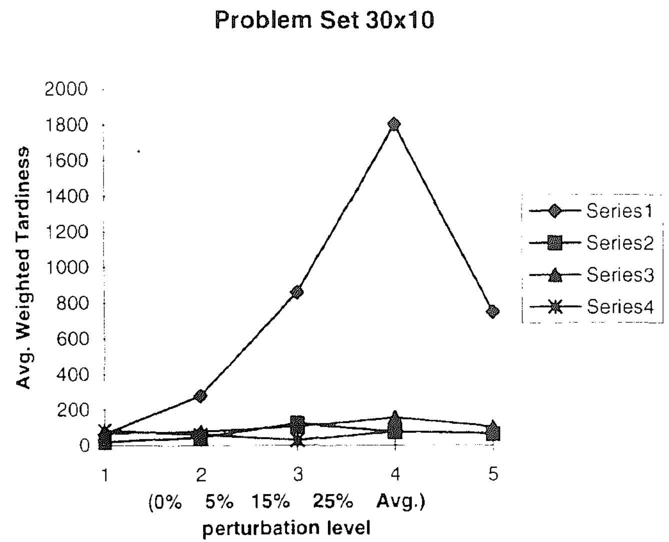

Figure 24a

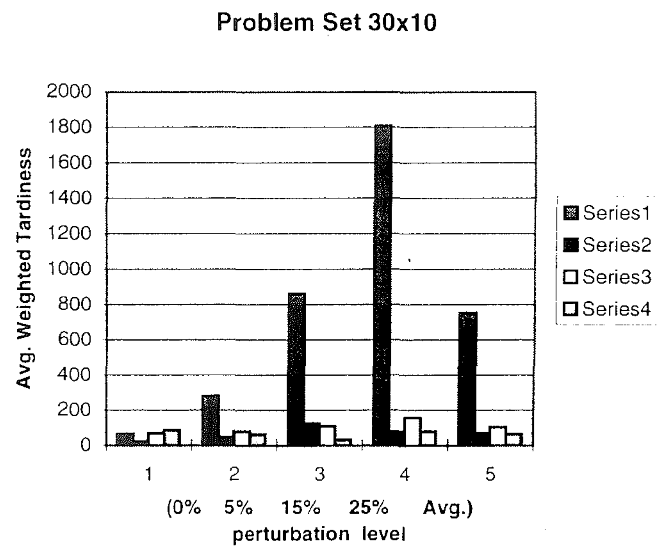

Figure 24b

Comparison of the schemes 1,2,3,4 in terms of avg. tardiness over all perturbation level

Problem Set 5x20

Table 31 Comparison of the schemes 2,3,4,5,6 with the Random route selection

	Perturbation Level	0%	5%	15%	25%	Avg
prob1	Random	229.0	390.0	675.3	908.7	**550.8**
	LMAX	284.0	386.1	482.9	331.5	**371.1**
	Lm	39.0	40.2	13.1	27.7	**30.0**
	Lmax+Lm	45.0	43.3	20.0	49.6	**39.5**
	Tard.	284.0	548.8	350.1	300.8	**370.9**
	Lmax+Lm+Tard.	45.0	41.9	23.3	34.0	**36.1**
prob2	Random	134.0	155.6	275.7	432.2	**249.4**
	LMAX	297.0	298.4	347.0	363.3	**326.4**
	Lm	345.0	343.3	302.7	304.3	**323.8**
	Lmax+Lm	297.0	295.7	410.7	307.5	**327.7**
	Tard.	297.0	307.6	313.3	326.4	**311.1**
	Lmax+Lm+Tard.	297.0	298.6	321.8	349.3	**316.7**
prob3	Random	78.0	116.9	390.9	749.2	**333.8**
	LMAX	400.0	451.5	422.7	363.5	**409.4**
	Lm	0.0	0.0	0.0	10.2	**2.6**
	Lmax+Lm	278.0	10.7	2.2	8.5	**74.8**
	Tard.	519.0	1257.5	1233.2	1093.1	**1025.7**
	Lmax+Lm+Tard.	278.0	4.6	27.8	30.4	**85.2**
prob4	Random	327.0	418.0	839.7	1047.0	**657.9**
	LMAX	636.0	599.6	386.7	425.3	**511.9**
	Lm	0.0	0.0	0.0	11.0	**2.7**
	Lmax+Lm	636.0	511.9	388.8	393.9	**482.6**
	Tard.	636.0	517.2	502.6	406.6	**515.6**
	Lmax+Lm+Tard.	636.0	605.1	540.6	401.5	**545.8**
prob5	Random	353.0	399.8	498.7	651.1	**475.7**
	LMAX	353.0	399.0	498.7	651.1	**475.7**
	Lm	580.0	574.3	321.3	453.5	**482.3**
	Lmax+Lm	580.0	578.5	391.7	275.4	**456.4**
	Tard.	236.0	228.7	255.8	177.5	**224.5**
	Lmax+Lm+Tard.	580.0	499.3	401.7	480.2	**490.3**

Problem Set 5x20

Table 32

Avg. Tardiness

Scheme	Series	Prob1	Prob2	Prob3	Prob4	Prob5
Random	Series1	550.8	249.4	333.8	657.9	475.7
LMAX (S 2)	Series2	371.1	326.4	409.4	511.9	475.7
Lm (S 3)	Series3	30.0	323.8	2.6	2.7	482.3
Lmax+Lm (S 4)	Series4	39.5	327.7	74.8	482.6	456.4
Tard. (S 5)	Series5	370.9	311.1	1025.7	515.6	224.5
Lmax+Lm+Tard. (S 6)	Series6	36.1	316.7	85.2	545.8	490.3

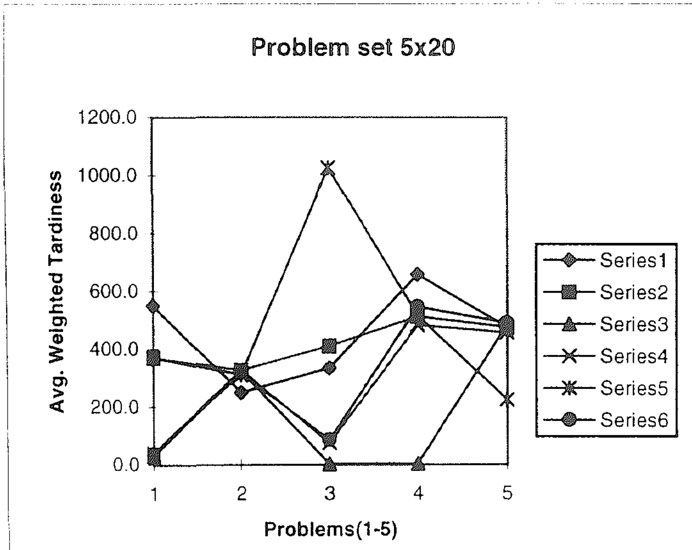

Figure 25a

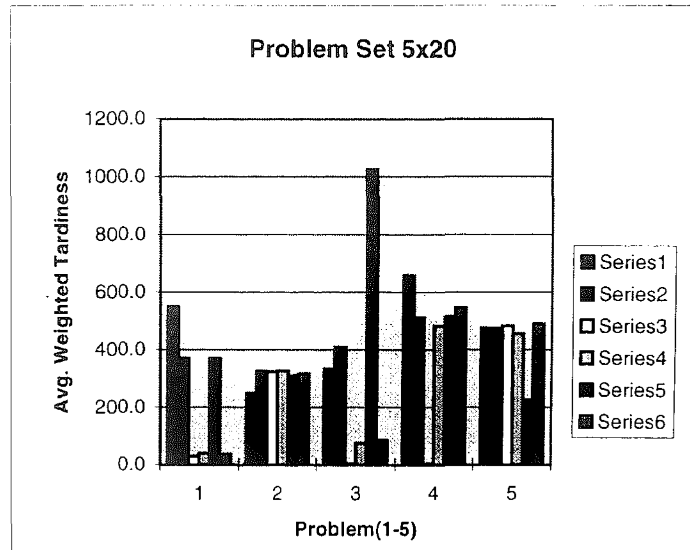

Figure 25b

Comparison of the schemes 2,3,4,5,6 with the random route selection

Problem Set 5x20

Table 32

Scheme	Series	Avg. Tardiness Prob1	Prob2	Prob3	Prob4	Prob5
Random	Series1	550.8	249.4	333.8	657.9	475.7
LMAX (S 2)	Series2	371.1	326.4	409.4	511.9	475.7
Lm (S 3)	Series3	30.0	323.8	2.6	2.7	482.3
Lmax+Lm (S 4)	Series4	39.5	327.7	74.8	482.6	456.4
Tard. (S 5)	Series5	370.9	311.1	1025.7	515.6	224.5
Lmax+Lm+Tard. (S 6)	Series6	36.1	316.7	85.2	545.8	490.3

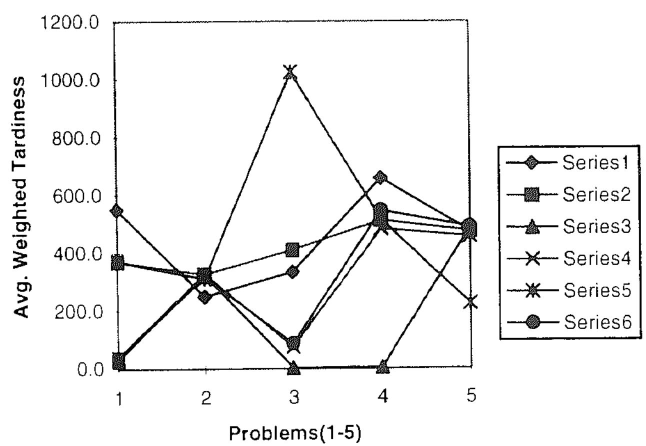

Figure 25a

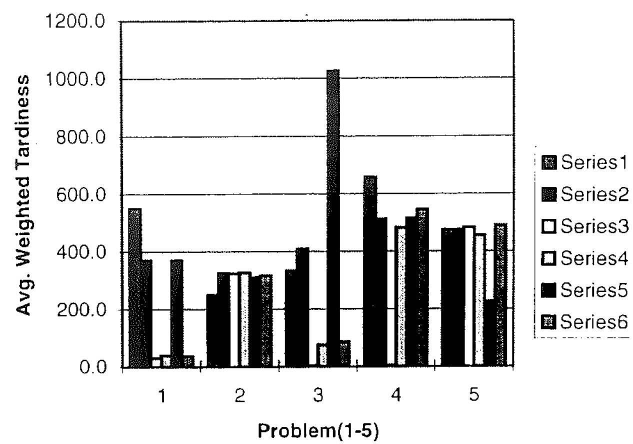

Figure 25b

Comparison of the schemes 2,3,4,5,6 with the random route selection

Problem Set 5x20

Table 33 Comparison of the Schemes 1,2,3,4,5,6

	Perturbation Level	0%	5%	15%	25%	Avg
prob1	GAP	66.0	118.8	448.9	818.1	363.0
	LMAX	284.0	386.1	482.9	331.5	371.1
	Lm	39.0	40.2	13.1	27.7	30.0
	Lmax+Lm	45.0	43.3	20.0	49.6	39.5
	Tard.	284.0	548.8	350.1	300.8	370.9
	Lmax+Lm+Tard.	45.0	41.9	23.3	34.0	36.1
prob2	GAP	0.0	25.6	324.8	707.7	264.5
	LMAX	297.0	298.4	347.0	363.3	326.4
	Lm	345.0	343.3	302.7	304.3	323.8
	Lmax+Lm	297.0	295.7	410.7	307.5	327.7
	Tard.	297.0	307.6	313.3	326.4	311.1
	Lmax+Lm+Tard.	297.0	298.6	321.8	349.3	316.7
prob3	GAP	0.0	37.5	121.8	282.8	110.5
	LMAX	400.0	451.5	422.7	363.5	409.4
	Lm	0.0	0.0	0.0	10.2	2.6
	Lmax+Lm	278.0	10.7	2.2	8.5	74.8
	Tard.	519.0	1257.5	1233.2	1093.1	1025.7
	Lmax+Lm+Tard.	278.0	4.6	27.8	30.4	85.2
prob4	GAP	10.0	46.9	270.7	489.5	204.3
	LMAX	636.0	599.6	386.7	425.3	511.9
	Lm	0.0	0.0	0.0	11.0	2.7
	Lmax+Lm	636.0	511.9	388.8	393.9	482.6
	Tard.	636.0	517.2	502.6	406.6	515.6
	Lmax+Lm+Tard.	636.0	605.1	540.6	401.5	545.8
prob5	GAP	0.0	4.4	103.0	291.4	99.7
	LMAX	236.0	245.6	226.6	251.6	240.0
	Lm	580.0	574.3	321.3	453.5	482.3
	Lmax+Lm	580.0	578.5	391.7	275.4	456.4
	Tard.	236.0	228.7	255.8	177.5	224.5
	Lmax+Lm+Tard.	580.0	499.3	401.7	480.2	490.3

Problem Set 5x20

Table 34

Avg. Tardiness

Scheme	Series	Prob1	Prob2	Prob3	Prob4	Prob5
GAP (S 1)	Series 1	363.0	264.5	110.5	204.3	99.7
LMAX (S 2)	Series 2	371.1	326.4	409.4	511.9	240.0
Lm (S 3)	Series 3	30.0	323.8	2.6	2.7	482.3
Lmax+Lm (S 4)	Series 4	39.5	327.7	74.8	482.6	456.4
Tard. (S 5)	Series 5	370.9	311.1	1025.7	515.6	224.5
Lmax+Lm+Tard. (S 6)	Series 6	36.1	316.7	85.2	545.8	490.3

S 1 = Scheme 1

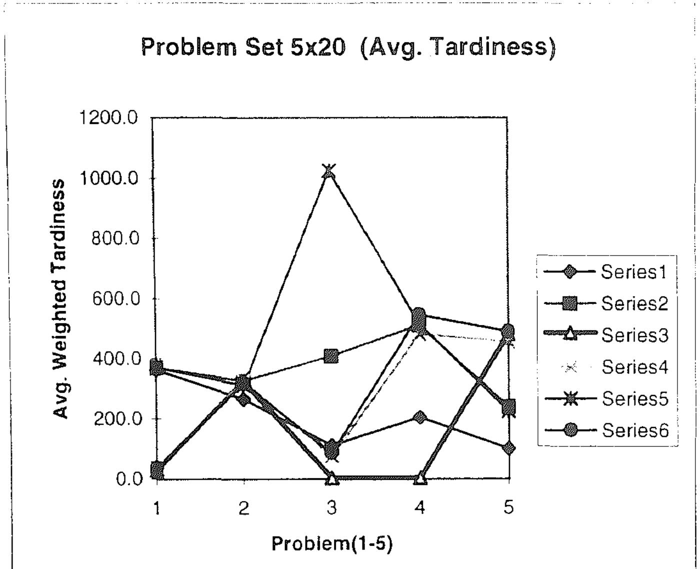

Figure 26a

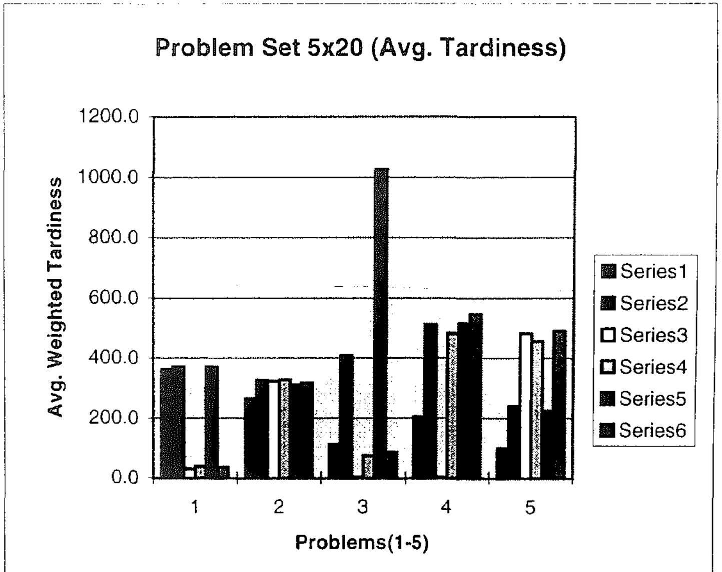

Figure 26b

Comparison of the schemes 1,2,3,4,5,6

Problem Set 5x20

Table 34

Avg. Tardiness

Scheme	Series	Prob1	Prob2	Prob3	Prob4	Prob5
GAP (S 1)	Series 1	363.0	264.5	110.5	204.3	99.7
LMAX (S 2)	Series 2	371.1	326.4	409.4	511.9	240.0
Lm (S 3)	Series 3	30.0	323.8	2.6	2.7	482.3
Lmax+Lm (S 4)	Series 4	39.5	327.7	74.8	482.6	456.4
Tard. (S 5)	Series 5	370.9	311.1	1025.7	515.6	224.5
Lmax+Lm+Tard. (S 6)	Series 6	36.1	316.7	85.2	545.8	490.3
S 1 = Scheme 1						

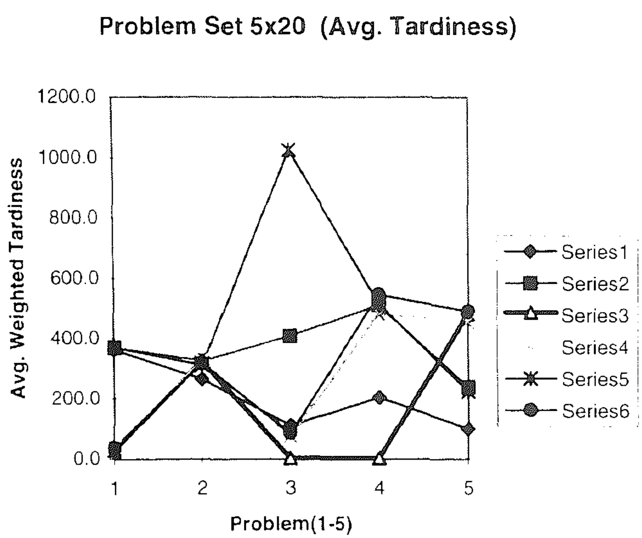

Figure 26a

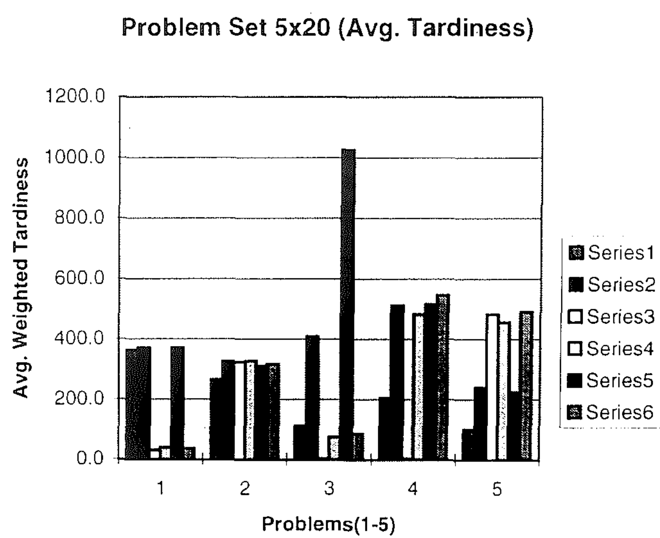

Figure 26b

Comparison of the schemes 1,2,3,4,5,6

Problem Set 5x20

Table 35 Comparision of the schemes 1,2,3,4,5,6

	Problem	Prob1	Prob2	Prob3	Prob4	Prob5	SUM	AVG.
0%	GAP	66.0	0.0	0.0	10.0	0.0	76.0	15.2
	LMAX	284.0	297.0	400.0	636.0	236.0	1853.0	370.6
	Lm	39.0	345.0	0.0	0.0	580.0	964.0	192.8
	Lmax+Lm	45.0	297.0	278.0	636.0	580.0	1836.0	367.2
	Tard.	284.0	297.0	519.0	636.0	236.0	1972.0	394.4
	Lmax+Lm+Tard.	45.0	297.0	278.0	636.0	580.0	1836.0	367.2
5%	GAP	118.8	25.6	37.5	46.9	4.4	233.2	46.6
	LMAX	386.1	298.4	451.5	599.6	245.6	1981.2	396.2
	Lm	40.2	343.3	0.0	0.0	574.3	957.9	191.6
	Lmax+Lm	43.3	295.7	10.7	511.9	578.5	1440.0	288.0
	Tard.	548.8	307.6	1257.5	517.2	228.7	2859.8	572.0
	Lmax+Lm+Tard.	41.9	298.6	4.6	605.1	499.3	1449.4	289.9
15%	GAP	448.9	324.8	121.8	270.7	103.0	1269.2	253.8
	LMAX	482.9	347.0	422.7	386.7	226.6	1866.0	373.2
	Lm	13.1	302.7	0.0	0.0	321.3	637.0	127.4
	Lmax+Lm	20.0	410.7	2.2	388.8	391.7	1213.3	242.7
	Tard.	350.1	313.3	1233.2	502.6	255.8	2655.1	531.0
	Lmax+Lm+Tard.	23.3	321.8	27.8	540.6	401.7	1315.3	263.1
25%	GAP	818.1	707.7	282.8	489.5	291.4	2589.5	517.9
	LMAX	331.5	363.3	363.5	425.3	251.6	1735.2	347.0
	Lm	27.7	304.3	10.2	11.0	453.5	806.7	161.3
	Lmax+Lm	49.6	307.5	8.5	393.9	275.4	1034.8	207.0
	Tard.	300.8	326.4	1093.1	406.6	177.5	2304.3	460.9
	Lmax+Lm+Tard.	34.0	349.3	30.4	401.5	480.2	1295.4	259.1
Avg.	GAP	363.0	264.5	110.5	204.3	99.7	1042.0	208.4
	LMAX	371.1	326.4	409.4	511.9	240.0	1858.9	371.8
	Lm	30.0	323.8	2.6	2.7	482.3	841.4	168.3
	Lmax+Lm	39.5	327.7	74.8	482.6	456.4	1381.0	276.2
	Tard.	370.9	311.1	1025.7	515.6	224.5	2447.8	489.6
	Lmax+Lm+Tard.	36.1	316.7	85.2	545.8	490.3	1474.0	294.8

Problem Set 5x20

Table 36

	Series		Perturbation Levels 0%	5%	15%	25%	Avg
Avg. Tardiness	Series 1	**GAP**	15.2	46.6	253.8	517.9	208.4
Over all perturbation level	Series 2	**LMAX**	370.6	396.2	373.2	347.0	371.8
(0%,5%,15%,25%)	Series 3	**Lm**	192.8	191.6	127.4	161.3	168.3
	Series 4	**Lmax+Lm**	367.2	288.0	242.7	207.0	276.2
	Series 5	**Tard.**	394.4	572.0	531.0	460.9	489.6
	Series 6	**Lmax+Lm+Tard.**	367.2	289.9	263.1	259.1	294.8

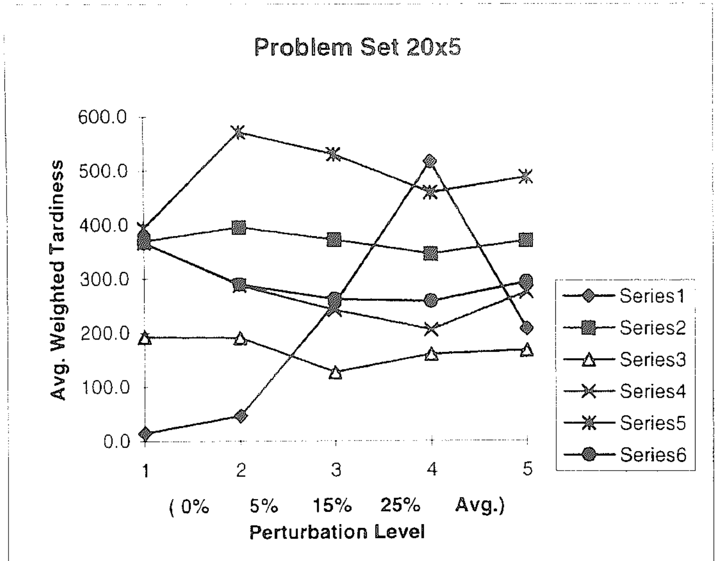

Figure 27a

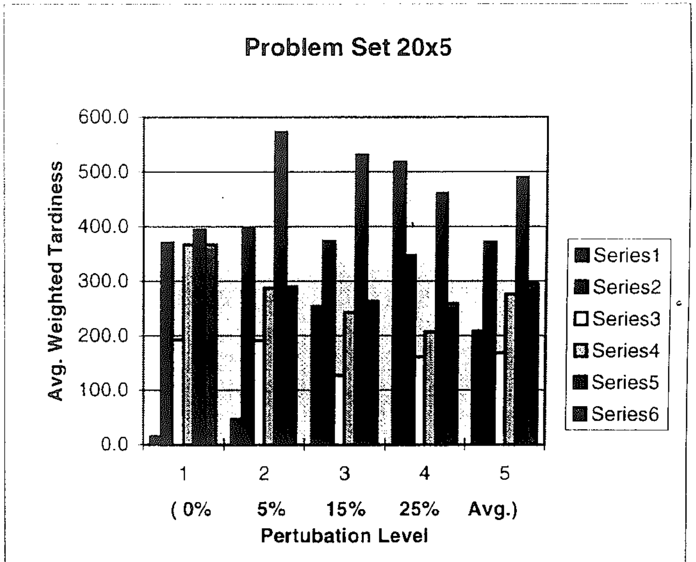

Figure 27b

Comparison of the schemes according to the perturbation levels

Problem Set 5x20

Table 36

	Series		Perturbation Levels 0%	5%	15%	25%	Avg
Avg. Tardiness	Series 1	**GAP**	15.2	46.6	253.8	517.9	208.4
Over all perturbation level	Series 2	**LMAX**	370.6	396.2	373.2	347.0	371.8
(0%,5%,15%,25%)	Series 3	**Lm**	192.8	191.6	127.4	161.3	168.3
	Series 4	**Lmax+Lm**	367.2	288.0	242.7	207.0	276.2
	Series 5	**Tard.**	394.4	572.0	531.0	460.9	489.6
	Series 6	**Lmax+Lm+Tard.**	367.2	289.9	263.1	259.1	294.8

Problem Set 20x5

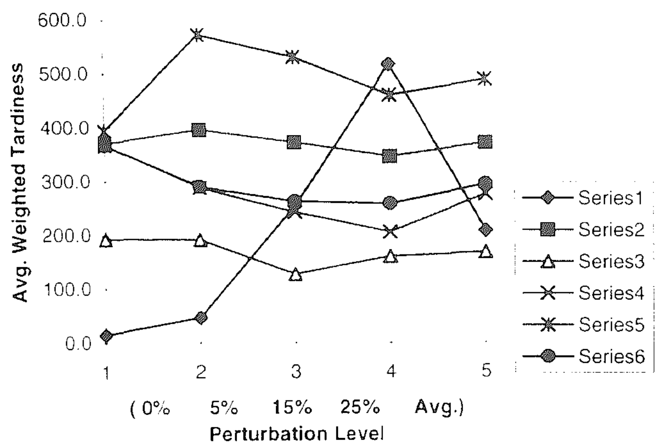

Figure 27a

Problem Set 20x5

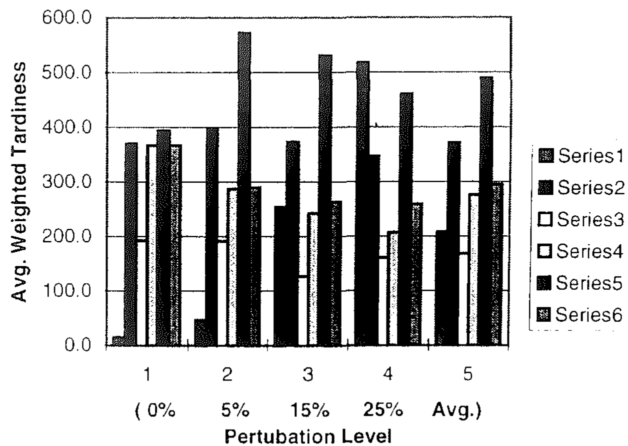

Figure 27b

Comparison of the schemes according to the perturbation levels

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Biography

H. Ibrahim Demir is a graduate student at Lehigh University. He was born in Sivas, Turkey on 4/20/71. Gazi and Elif are his father's and mother's names respectively. He was accepted to Bilkent University in Turkey with a full Scholarship and received his B.S. degree in Industrial Engineering from Bilkent in 1993. He was awarded with a full scholarship by the Turkish Ministry of Education for graduate study in USA in 1994. With the approval of this thesis he is obtaining his M.S. degree in Industrial engineering department from Lehigh University in 1996. Production Planning, Scheduling and Inventtory Control are his main interest areas .

END

OF

TITLE