AN EXPERIMENTAL INVESTIGATION OF PROCESSING TIME VARIATION AND OPERATING POLICIES IN A DUAL-CONSTRAINED JOB SHOP PRODUCTION SYSTEM

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ABSTRACT

This study presents an experimental investigation of various operating policies in a dual-constrained job shop under two conditions of operation processing times variation. The job shop consisted of five workcenters each contained a different machine, and three workers were available to operate these machines. SLAM II simulation language was used to simulate the shop and generate experimental data. ANOVA procedure, Tukey range test, bar charts, and graphs were used in the analysis of the data collected. An operating policy was defined as a combination of a sequencing rule and a worker assignment rule. Five sequencing and seven worker assignment rules were considered. Variation of processing times showed significant effects on operating policies performance in terms of the shop measures considered. Sequencing rules were found to have more impact on the performance of operating policies than worker assignment rules. In conclusion, shop management should be highly concerned with establishing processing times as close as possible to the actual ones, and should maintain persistent control over shop operations in order to eliminate causes that may eventually lead to significant deviations in predicted and/or standard operation processing times.

Keywords: Job Shop, Dual Consrained, Simulation, Sequencing, Production Scheduling.

INTRODUCTION

The traditional job shop scheduling problem has been subjected to extensive research [3], [6], and [16]. Most research on job shop production systems has been largely concerned with the sequencing aspect of single-constrained job shops, in which the only constraining factor is machine availability. More recently, researchers have recognized and considered another constraining factor in the job shop environment; the worker factor that is capable of operating the machines. A job shop production system that is limited by its machine and worker availability (i.e., having fewer workers than machines) is referred to as a dual-constrained job shop. In such a job shop, processing a job requires the availability of both a machine and a worker, and hence a job may be delayed because of the unavailability of a machine or worker or both. Although analytical techniques have been applied to simple dual-constrained job shop settings [1], [5] and [6], the results obtained showed no indication that analytical techniques held great promise for studying more complex job shop settings. Therefore, simulation has been the most used methodology for studying dual-constrained job shops [7], [8], [10], [12], [17], [18], [20], and [21].

The previous research on dual-constrained job shops has focused on the sequencing rule, the worker assignment rule, and has examined a limited number of such rules. No consideration has been given to the effect of job processing time variation. In reality, actual job processing times differ from expected ones due to both avoidable and unavoidable delays. In the dual-constrained job shop of this study three basic decisions were considered to model its operation. These are: the sequencing rule decision, the worker assignment rule decision, and the decision regarding the level of job processing times variation. The sequencing rule decision is related to the selection of the sequencing rule to be used to determine which job, of those in queue at a workcenter, should be processed next. While the worker assignment rule decision is related to the selection of the worker assignment rule to be used to determine the workcenter an available worker should be assigned to. A worker becomes available for reassignment when he completes a job. Processing time variations are incorporated by adding deviations sampled from a normal density function with zero mean. The extent of variation was controlled by using different standard deviations of the normal distribution. Processing time variation with normal distribution was used in [4] and [5].

The purpose of this research is to investigate the relative effectiveness of various operating policies on the performance of a hypothetical dynamic dual-constrained job shop production system under two levels of job processing time variation. An operating policy was defined as a combination of a sequencing rule and a worker assignment rule. In addition, the relative effectiveness of the employed sequencing rules and worker assignment rules in these operating policies on shop performance, under each of the two levels of the processing time variation considered, were also analyzed.

RESEARCH METHODOLOGY

Since no analytical techniques exist for the analysis of dynamic dual-constrained job shops, computer simulation was selected as the research vehicle for this study. SLAM II simulation language [14] was used to model the operation of the dual-constrained job shop. The workcenters of the job shop were modeled in network form. Job routings, job number of operations, job due dates, the calculations of sequencing rules and worker assignment rules were maintained in discrete-event subroutines written in FORTRAN programming language. The following sections describe job characteristics, job shop characteristics and simulation model, available work force, performance criteria considered, experimental design and conditions.

Job Characteristics

Upon arrival, a job was assigned a job routing, a job due date, and expected job processing times on machines. An arriving job was equally likely to be assigned a routing from sixteen predetermined routings. In this way job recycling was not allowed. The sixteen predetermined job routings are shown in Figure (1). Job routings, associated job types and job due dates were assigned to arriving jobs by calling a discrete-event subroutine at EVENT node labelled EVT0. Job due dates were internally determined by the shop scheduler according to the total work content method with a multiplier of 4. Thus the due date of a job was set to equal 4 times its total expected processing times on the machines (workcenters) on its routing.

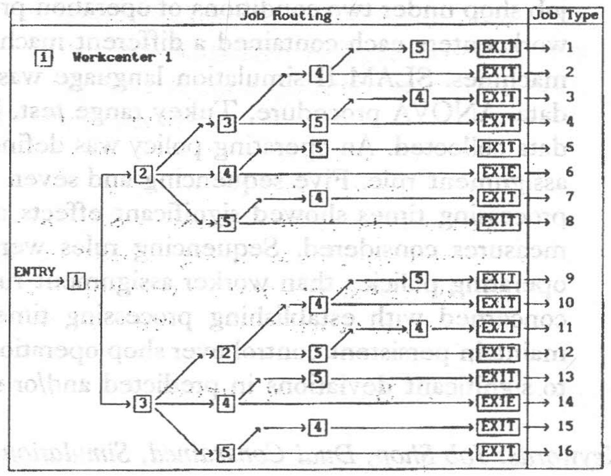

Figure 1. Set of sixteen predetermined job routings.

Job Shop Characteristics and Simulation Model

The hypothetical dynamic dual-constrained job shop considered consists of five workcenters. Each contains one machine. The machines are different in the sense that the operation performed by a machine in a given workcenter can not be performed by the machine in any of the other workcenters. A workcenter can only be visited once by a given job. No pre-emption of jobs is allowed, and machines are not allowed to break down. A constrained resource (worker) must be assigned to a machine before it can be operative in the simulation. Figure (2) shows the job shop configuration and materials flow.

The initial average shop utilization factor was set to 86% by varying job mean interarrival time and mean machine (job) processing times under the first in shop first served sequencing rule and the largest number in queue worker assignment rule with no variation in processing times. This average shop utilization level resembled the actual average utilization level reported by manufacturing firms [21]. Job interarrival time and machine processing times were random variables generated from a negative exponential probability density function with mean interarrival time of 2.0 (in time units)and machine processing time means of 1.7, 1.2, 1.1, 1.2, and 1.1 (in time units) for workcenters (machines) #1, #2, #3, #4, and #5, respectively. These values for the means were selected to achieve a shop utilization level of about 86% as mentioned earlier. Different random number streams and seeds were used to assure independence. Figure (3) presents the SLAM II network model of the job shop. Verification of the simulation model was made through detailed review of model logic and individual testing of subroutines in the formulation stage. In addition, several test runs involving different operating policies were made, and at selected intervals a variety of job, workcenter and worker information was printed by the SLAM II trace at each event occurrence. The simulated movement of jobs and workers was then analyzed and found to be functioning as planned.

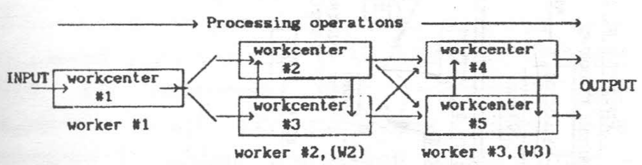

Figure 2. Job shop configuration and materials flow.

Work Force

Three workers were employed to operate the five machines. Worker #1 was permanently assigned to operate the machine in workcenter #1. The time of worker #2 (W2) was shared between workcenters #2 and #3, while the time of worker #3 (W3) was shared between workcenters #4 and #5 as shown in Figure 2. Workers are assumed to be completely and equally efficient in operating machines. Workers #2 and #3 were assigned to their respective workcenters according to the worker assignment rule being followed upon job completion.

Performance Criteria

Five performance measures were used to evaluate shop performance. These measures are: mean flow time ($\bar{F}$), maximum tardiness (T_{max}), average number of jobs in the shop ($\bar{N}_S$), total worker transfers between workcenters (TWT), and number of late jobs ($\bar{N}_S$).

Operating Policies and Processing Time Variation

The basic interest in this study is to determine the effectiveness of employing one operating policy versus a different operating policy to analyze whether the variation in the job processing times has any bearing on the relative effectiveness of the operating policy. An operating policy is defined as a combination of a sequencing rule and a worker assignment rule. Five sequencing rules and seven worker assignment rules were used in this simulation. Thus, a total of 35 operating policies (combinations; 7X5) were considered.

The sequencing rules considered are:

(1) First in shop, first served (FISF). The job which has been in the shop the longest period of time will be processed first.
(2) First in queue, first served (FIQF). The job which has been in the queue the longest period of time will be processed first.
(3) Shortest processing time, first served (SPTF). The job having the shortest actual processing time for the next operation will be processed first.
(4) Earliest due date, first served (EDDF). The job with the earliest due date will be processed first.
(5) Largest number of operations, first served (LNOF). The job having the largest number of operations will be processed first.

A worker becomes available for reassignment when he completes a job. The worker assignment rules considered in this study are:

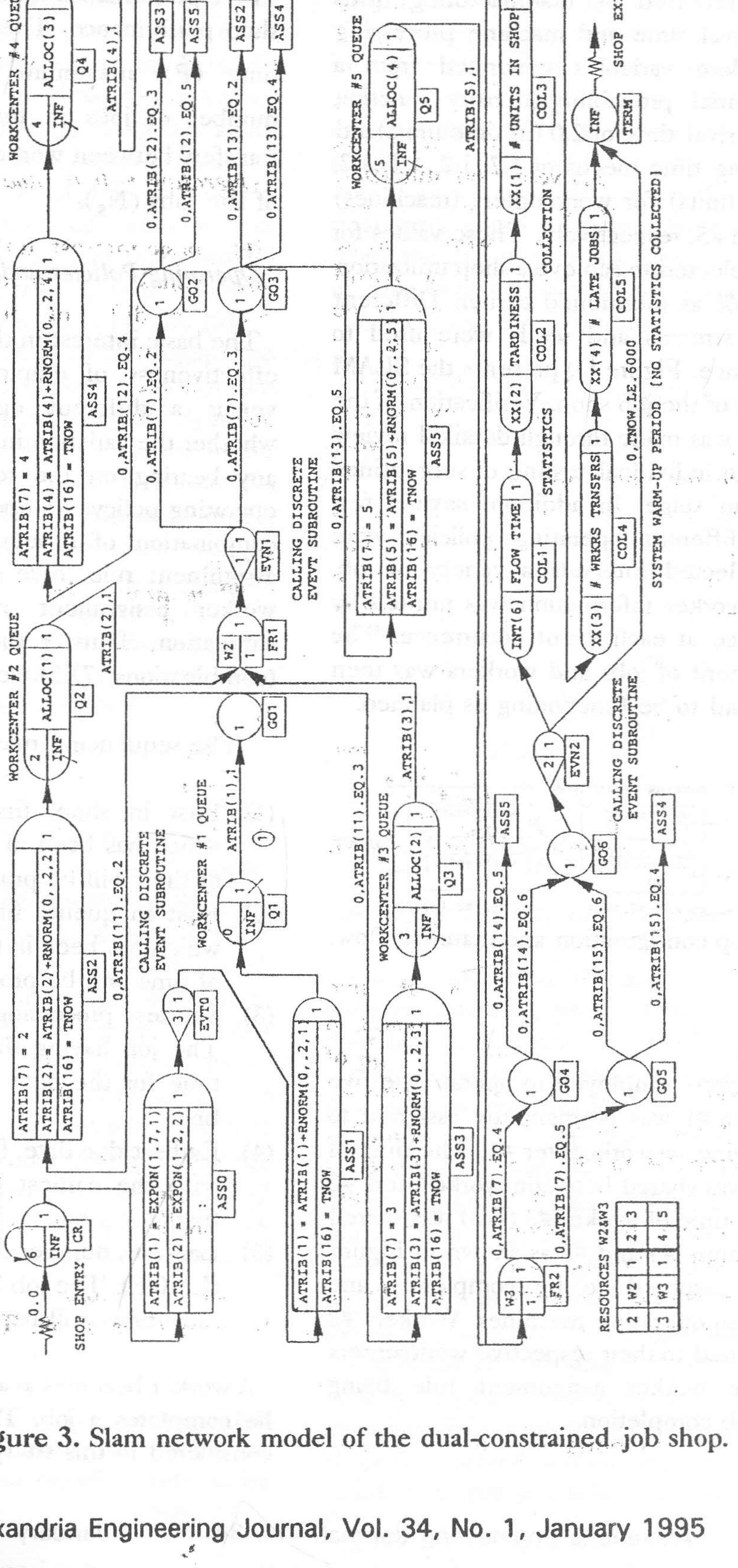

Figure 3. Slam network model of the dual-constrained job shop.

(1) Assign available worker to the workcenter whose queue has the largest number of jobs (LNQ).
(2) Assign available worker to the workcenter whose queue has the largest average queue waiting time (AQW).
(3) Assign available worker to the workcenter whose first rank job in its queue has been in the shop the longest period of time (FIS). A counterpart of the FISF sequencing rule.
(4) Assign available worker to the workcenter whose first rank job in its queue has been in the queue the longest period of time (FIQ). A counterpart of the FIQF sequencing rule.
(5) Assign available worker to the workcenter whose first rank job in its queue has the shortest actual processing time for the next operation (SPT). A counterpart of the SPTF sequencing rule.
(6) Assign available worker to the workcenter whose first rank job in its queue has the earliest due date (EDD). A counterpart of the EDDF sequencing rule.
(7) Assign available worker to the workcenter whose first rank job in its queue has the largest number of operations (LNO). A counterpart of the LNOF sequencing rule.

Two levels of processing time variation were considered: Low Variation (LV), and High Variation (HV). To incorporate these processing time variations, actual job processing times were computed by adding a deviation sampled from a normal density function with a mean of zero. The actual processing time of a job on a machine was computed as follows:

Actual job processing time on a machine = Expected job processing time on

that machine + N(0.0,s)

where N is a value sampled from the normal distribution with a mean of 0.0 and a standard deviation of σ=0.2 for Low Variation (LV), and σ=0.6 for High Variation (HV). These values for s were selected to provide a low variation of approximately 15%, and a high variation of approximately 50% of the average machine processing time in the job shop. The normal deviations generated were added to the expected job processing time once the job under consideration arrives at a workcenter queue. This can be observed from Figure (3).

Based on the above mentioned explanation, a combination of the worker assignment rule LNQ and the FISF sequencing rule represents an operating policy which is, symbolically, referred to as $\begin{Bmatrix}\text{LNQ}\\ \text{FISF}\end{Bmatrix}$. Thus under each of the two defined levels of job processing time variation, there are 35 operating policies to employ in the operation of the shop.

Experimental Design and Conditions

A set of two experiments was considered. A primary experiment and an auxiliary experiment. The primary experiment conducted as a two-factor factorial design. The first factor (A) represented the job processing time variation at two levels: Low Variation (LV) and High Variation (HV), and the second factor (B) represented the operating policy employed in the operation of the job shop with 35 levels. A total of 70 factor combinations was considered. The experimental factors and their levels are shown in Table (1).

Table 1. Primary experimental factors and levels.

Factors	Factor Levels										
A: Processing time variation	1) Low Variation (LV), 2) High Variation (HV)										
B: Operating policy	No.	1	2	3	4	5	6	7	8	9	10
	Symbol	LNQ FISF	LNQ FIQF	LNQ SPTF	LNQ EDDF	LNQ LNOF	AQW FISF	AQW FIQF	AQW SPTF	AQW EDDF	AQW LNOF
		11	12	13	14	15	16	17	18	19	20
		FIS FISF	FIS FIQF	FIS SPTF	FIS EDDF	FIS LNOF	FIQ FISF	FIQ FIQF	FIQ SPTF	FIQ EDDF	FIQ LNOF
		21	22	23	24	25	26	27	28	29	30
		SPT FISF	SPT FIQF	SPT SPTF	SPT EDDF	SPT LNOF	EDD FISF	EDD FIQF	EDD SPTF	EDD EDDF	EDD LNOF
		31	32	33	34	35					
		LNO FISF	LNO FIQF	LNO SPTF	LNO EDDF	LNO LNOF					

The auxiliary experiment used the sequencing rule and the worker assignment rule for each of the 35 operating policies, under each of the two levels of the processing time variation. It was conducted as a two-factor factorial design with two factors: factor (C) represented the sequencing rule with 5 levels, and factor (D) represented the worker assignment rule with 7 levels, under each of the two levels of factor (A) of the primary experiment.

to eliminate the effect of the transient period of system warm-up, a test run of the simulation model was made under the $\begin{Bmatrix}\text{LNQ}\\ \text{FISF}\end{Bmatrix}$ operating policy and low variation of processing time (LV). Average queue length, mean flow time and utilization level reached steady state after 6000 time units. Therefore, a run length of 15000 time units was established, and statistical data were collected during the last 9000 time units of the run length. Five runs were made for each of the 70 experimental factor combinations, thus a total of 350 simulation runs were made. Previous research indicated that at least three runs should be made to determine the variability of the simulation output analysis [18]. The simulation model was run on a 386DX-25Mz PC with math-coprocessor using the PC version 2.1 of SLAM II [15]. Analysis of variance procedure (ANOVA), Tukey's multiple comparison test [11], bar charts and graphs were used to analyze the data collected from the simulation runs.

EXPERIMENTAL RESULTS AND ANALYSIS

The means and standard deviations of the observed values from the simulation runs for the performance measures under each of the 35 operating policies are displayed in Table (2). Table (3) shows the results obtained from the ANOVA procedure for the experimental factors of both the primary and auxiliary experiments. Since the ANOVA results were significant, Tukey's range multiple comparison tests were performed at the 0.05 significance level to rank and
reveal where significant differences in performance among operating policies, sequencing rules, and worker assignment rules occurred. Table (4) presents the ranking and grouping of the operating policies in terms of each of the performance measures. The horizontal lines drawn under policy and rule numbers indicate groups with no significant differences. The operating policies, sequencing rules, and worker assignment rules are rank ordered according to their sample means from left to right, best to worst.

the ANOVA results indicate that operating policies and processing time variation; factors (A) and (B), have significant impact on the performance of the job shop, in terms of mean flow time, maximum tardiness, average inprocess jobs, total worker transfers, and number of late jobs. Their interaction is also highly significant in terms of T_{max} and TWT performance measures, while it is less and less significant in terms of N_L, $\bar{F}$and $\bar{N}_s$, respectively. Furthermore, the processing time variation effect has the most significant effect on shop performance. Moreover, the sequencing rule factor (C) has shown significant effect on all shop performance measures and at both levels of the processing time variation factor. On the other hand, factor (D); the worker assignment rule, has shown significant impact on T_{max}, TWT, and N_L measures at LV level. While at the HV level of the processing time variation factor it has shown significant effects only on TWT, and N_L measures. It is worth noting that the interaction effect between the sequencing rule factor and the worker assignment rule factor is primarily influenced by the sequencing rule factor.

Figures (4) through (8) present bar charts showing performance measure mean values at low and high variation of processing time factor for all operating policies. In terms of mean flow time, operating policy #3 $\begin{Bmatrix}\text{LNQ}\\ \text{SPTE}\end{Bmatrix}$ was superior to all other policies, while operating policies #5 $\begin{Bmatrix}\text{LNQ}\\ \text{LNOF}\end{Bmatrix}$ and #15 $\begin{Bmatrix}\text{FIS}\\ \text{LNOF}\end{Bmatrix}$ were the worst under LV and HV levels of processing time variation, respectively. Maximum tardiness was optimized by policy #4 $\begin{Bmatrix}\text{LNQ}\\ \text{EDDF}\end{Bmatrix}$.

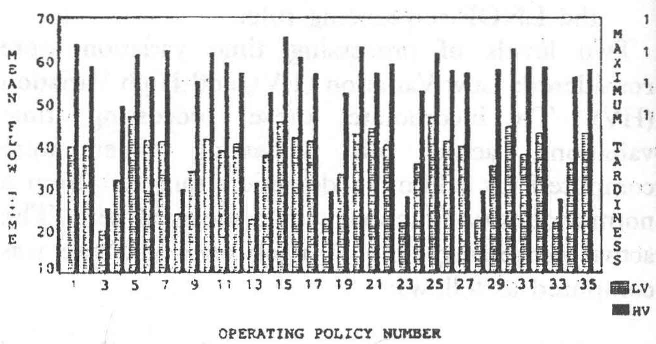

Figure 4. A bar chart for mean flow time under LV and HV of processing time.

Average inprocess jobs performance measure was minimized by policy #3 $\begin{Bmatrix}\text{LNQ}\\ \text{SPTF}\end{Bmatrix}$ for all experimental conditions. In terms of total worker transfers, operating policy #10 $\begin{Bmatrix}\text{AQW}\\ \text{LNOF}\end{Bmatrix}$ produced the minimum value, while the number of late jobs performance measure achieved its lowest value with operating policy #3 $\begin{Bmatrix}\text{LNQ}\\ \text{SPTE}\end{Bmatrix}$ under both levels of the processing time variation factor.

Operating Policy Number, Symbol	Statistics	Low Variation (LV) $\bar{F}$	LV T_{max}	LV $\bar{N}_S$	LV TWT	LV N_L	High Variation (HV) $\bar{F}$	HV T_{max}	HV $\bar{N}_S$	HV TWT	HV N_L
1: LNQ	Mean	39.86	108.06	11.69	5994	3466	63.88	148.80	19.80	5934	4074
FISF	Std Dev	5.85	25.88	3.38	61	196	4.46	38.21	7.51	21	243
2: LNQ	Mean	40.04	124.20	12.11	6068	3492	58.72	177.60	17.70	6046	3990
FQSF	Std Dev	5.82	24.65	3.83	52	254	8.56	50.91	6.96	73	126
3: LNQ	Mean	19.88	505.20	4.97	5944	1356	25.36	1102.40	6.73	5892	1700
SPTF	Std Dev	1.53	241.43	1.09	55	91	2.29	441.49	2.19	33	54
4: LNQ	Mean	31.86	75.56	8.90	5948	2974	49.46	127.72	14.07	5948	3776
EDDF	Std Dev	4.53	28.65	2.30	26	225	10.53	53.01	3.24	51	139
5: LNQ	Mean	46.82	634.80	14.72	6288	2582	61.46	740.60	18.50	6274	2846
LNOF	Std Dev	6.26	176.08	4.92	94	100	10.25	238.57	4.38	83	114
6: AQW	Mean	41.16	168.40	11.60	3340	3416	56.24	219.00	17.38	2716	3962
FISF	Std Dev	6.46	75.13	3.06	206	202	7.19	63.16	6.72	253	137
7: AQW	Mean	40.92	331.00	12.12	3296	3704	62.46	254.60	19.70	2680	3980
FIQF	Std Dev	7.18	359.19	3.25	197	555	11.87	73.91	7.09	253	213
8: AQW	Mean	23.72	520.60	6.39	3574	2210	29.64	1180.40	8.33	3226	2636
SPTF	Std Dev	1.56	253.53	1.85	188	233	2.58	666.39	2.66	151	169
9: AQW	Mean	33.82	116.90	9.21	3550	3086	55.14	200.00	16.92	2682	3860
EDDF	Std Dev	4.39	29.27	2.84	138	203	9.90	77.17	7.26	138	215
10: AQW	Mean	41.32	331.40	12.23	3252	3162	61.94	484.00	18.82	2660	3698
LNOF	Std Dev	7.91	139.90	2.63	264	161	16.29	296.35	4.66	220	195
11: FIS	Mean	38.86	128.70	10.86	5140	3314	59.52	195.20	19.06	4809	3826
FISF	Std Dev	6.01	44.35	2.41	85	128	6.76	54.92	4.32	101	148
12: FIS	Mean	40.32	147.40	12.41	5040	3328	57.12	213.00	17.42	4666	3780
FIQF	Std Dev	4.35	47.99	2.47	64	170	8.94	97.99	7.46	192	151
13: FIS	Mean	22.44	618.00	7.04	5096	1622	31.12	1112.40	8.64	4936	2050
SPTF	Std Dev	3.18	488.45	4.22	66	115	3.61	575.29	2.94	90	107
14: FIS	Mean	37.70	126.52	10.77	5106	3012	52.50	174.40	15.84	4818	3550
EDDF	Std Dev	6.40	32.74	4.46	81	224	9.86	56.69	5.32	67	323
15: FIS	Mean	45.48	694.60	14.14	4948	2626	65.48	893.60	20.38	4746	3038
LNOF	Std Dev	4.17	84.28	4.21	75	29	12.55	256.13	10.07	86	128
16: FIQ	Mean	41.86	120.50	12.46	5124	3414	60.96	201.80	18.52	4960	3822
FISF	Std Dev	5.24	43.82	3.85	56	196	9.96	46.62	5.87	51	209
17: FIQ	Mean	41.08	478.00	11.63	5054	3356	56.88	188.00	16.90	4962	3800
FIQF	Std Dev	7.43	425.64	3.13	64	116	5.41	49.66	4.43	35	164
18: FIQ	Mean	22.48	607.80	5.77	5064	1654	29.10	144.51	8.36	4922	1958
SPTF	Std Dev	1.61	1451.60	1.45	74	79	4.01	665.87	3.50	39	48
19: FIQ	Mean	33.04	705.00	9.59	5112	2958	52.28	155.20	16.67	4972	3648
EDDF	Std Dev	4.35	568.79	1.71	43	147	7.11	49.11	6.13	55	235
20: FIQ	Mean	42.62	819.80	12.62	4980	2634	63.30	1092.20	19.86	4784	3008
LNOF	Std Dev	4.79	253.46	2.92	67	55	7.79	483.09	8.15	39	158
21: SPT	Mean	43.94	139.00	13.30	5122	3426	57.02	161.80	17.68	4976	3826
FISF	Std Dev	4.63	34.56	5.35	64	185	8.10	39.49	5.42	40	201
22: SPT	Mean	40.02	312.20	11.60	5156	3310	59.14	174.80	17.44	4926	3792
FIQF	Std Dev	5.03	355.33	2.63	132	146	7.17	46.39	5.30	35	228
23: SPT	Mean	21.72	574.20	5.55	5176	1566	27.94	664.20	7.81	5026	1950
SPTF	Std Dev	1.40	149.10	1.40	57	47	3.19	378.84	2.08	39	121
24: SPT	Mean	35.58	105.62	10.02	5162	2998	52.86	173.80	15.24	5024	3554
EDDF	Std Dev	5.19	32.63	2.65	63	263	11.55	63.82	3.78	81	207
25: SPT	Mean	46.64	499.20	13.61	5008	2656	61.70	980.80	20.10	4884	2918
LNOF	Std Dev	3.42	274.96	4.92	64	150	9.79	393.81	6.72	51	130
26: EDD	Mean	40.94	289.40	12.18	4920	3378	57.64	173.00	17.14	4696	3806
FISF	Std Dev	3.04	355.23	3.71	68	163	7.11	59.92	6.55	73	122
27: EDD	Mean	39.58	125.40	11.72	4902	3354	56.96	202.80	17.00	4698	3826
FIQF	Std Dev	4.83	37.62	3.32	55	163	9.38	63.74	3.54	118	124
28: EDD	Mean	22.22	549.00	5.56	5076	1640	29.22	403.60	8.17	4998	1976
SPTF	Std Dev	2.01	163.42	1.30	93	114	3.43	348.77	2.30	53	118
29: EDD	Mean	34.94	115.26	10.15	5134	3004	57.92	202.00	18.04	4864	3704
EDDF	Std Dev	5.18	40.28	3.19	21	101	8.29	42.14	4.77	68	224
30: EDD	Mean	44.32	691.80	12.82	4840	2716	62.76	1254.80	21.06	4674	3090
LNOF	Std Dev	7.41	247.35	2.68	35	94	9.18	416.35	9.33	65	84
31: LNO	Mean	37.92	109.68	10.59	5204	3260	58.54	168.80	17.66	4994	3830
FISF	Std Dev	5.44	38.54	2.07	83	214	6.64	22.06	7.08	86	199
32: LNO	Mean	42.70	144.20	12.42	5078	3388	58.54	176.00	17.30	5016	3792
FIQF	Std Dev	5.38	24.99	3.17	64	201	8.28	38.52	6.17	56	204
33: LNO	Mean	21.80	619.60	5.70	5128	1592	27.44	1025.20	7.24	5050	1914
SPTF	Std Dev	1.05	199.19	1.50	44	55	3.65	517.74	1.33	81	87
34: LNO	Mean	35.90	114.42	10.23	5104	2964	56.20	170.10	16.32	5060	3570
EDDF	Std Dev	6.25	37.87	2.72	51	230	10.36	67.41	6.98	64	163
35: LNO	Mean	42.76	766.00	12.59	5062	2620	58.02	874.60	17.70	4884	2908
LNOF	Std Dev	7.11	328.10	2.61	66	160	11.58	-299.36	5.49	78	127

Std Dev: Standard Deviation.

Table 2: Means and standard deviations of observed values for the performance measures.

Table 3. Anova results.

Factors / Primary experiment		$\bar{F}$	T_{max}	$\bar{N}_S$	TWT	N_L
A	F value	448.9	22.9	115.6	401.5	578.8
	Sig.of F	** .000	** .000	** .000	** .000	** .000
B	F value	21.2	15.2	5.6	659.9	150.4
	Sig.of F	** .000	** .000	** .000	** .000	** .000
A*B	F value	1.5	2.8	0.5	9.0	1.5
	Sig. of F	* .049	** .000	.995	** .000	* .042

Legend

A : processing time variation
B : operating policy
A*B : interaction of A & B
C : sequencing rule
D : worker assignment rule
C*D : interaction of C & D
α : significance level
* significant beyond α=0.05
** significant beyond α=0.01

Auxiliary experiment		Low Variation (LV)					High Variation (HV)				
		$\bar{F}$	T_{max}	$\bar{N}_S$	TWT	N_L	$\bar{F}$	T_{max}	$\bar{N}_S$	TWT	N_L
C	F value	103.0	35.5	30.2	7.1	508.8	89.5	74.9	22.5	13.9	723.4
	Sig. of F	** .000	** .000	** .000	** .000	** .000	** .000	** .000	** .000	** .000	** .000
D	F value	0.4	3.8	0.2	1571.7	11.0	0.1	1.2	0.2	2123.1	18.5
	Sig. of F	.894	** .002	.977	** .000	** .000	.990	.305	.989	** .000	** .000
C*D	F value	0.6	1.6	0.3	5.2	2.0	0.4	2.5	0.2	7.2	3.8
	Sig. of F	.913	* .036	.888	** .000	** .006	.991	** .000	1.00	** .000	** .000

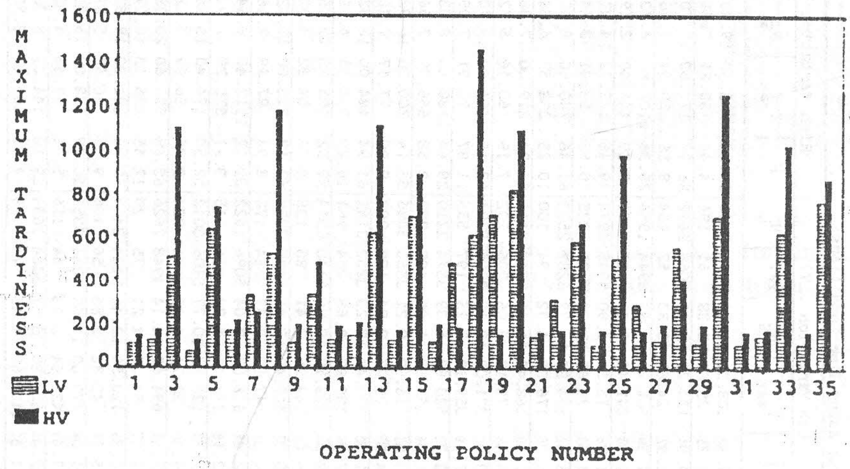

Figure 5. A bar chart for maximum tardiness under LV and HV of processing time.

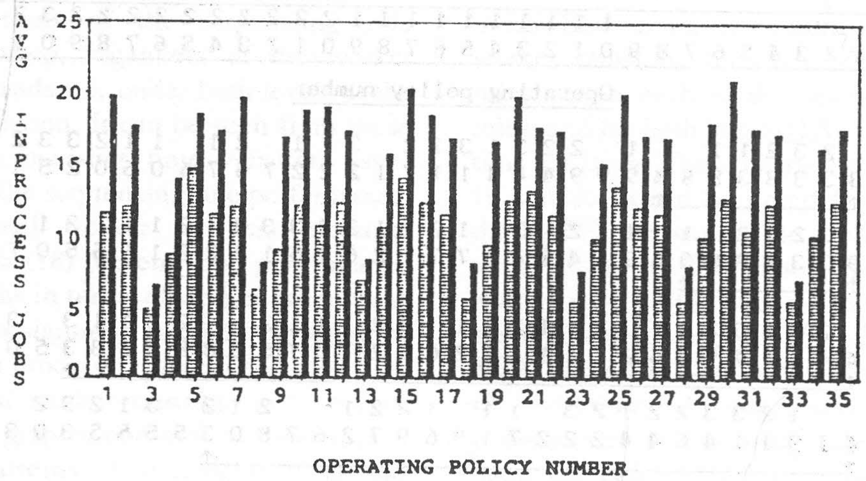

Figure 6. A bar chart for average inprocess jobs under LV and HV of processing time.

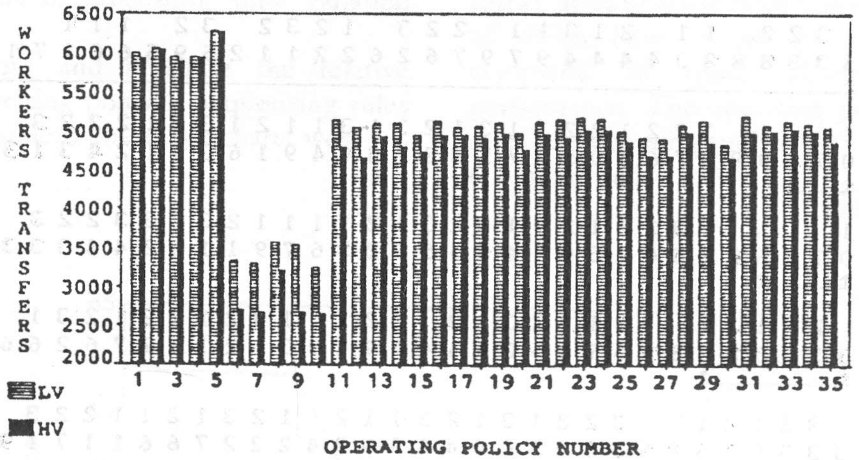

Figure 7. A bar chart for workers transfers under LV and HV of processing time.

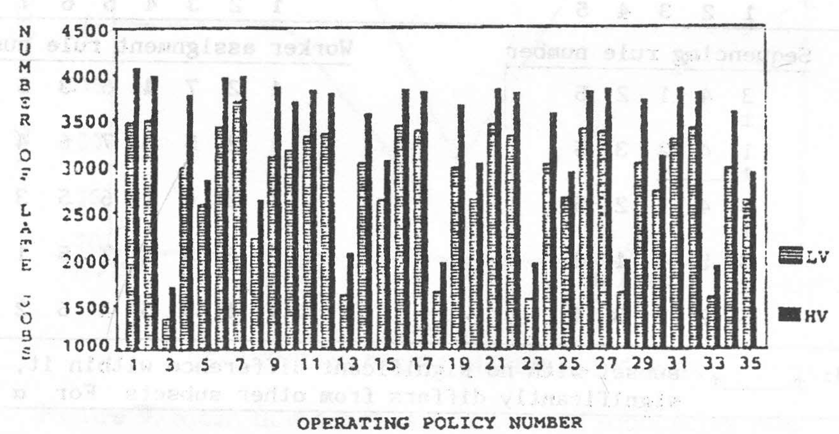

Figure 8. A bar chart for number of late jobs under LV and HV of processing time.

Rank:		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
		Operating policy number																																		
$\bar{F}$	LV	3	23	33	28	13	18	8	4	19	9	29	24	34	14	31	11	27	1	22	2	12	7	26	17	6	10	16	20	32	35	21	30	15	25	5
		↑							↑																											
	HV	3	33	23	18	28	8	13	4	19	14	24	9	34	6	17	27	21	12	26	29	35	31	32	2	22	11	16	5	25	10	7	30	20	1	15
		↑						↑																												
T_{max}	LV	4	24	1	31	34	29	9	16	2	27	14	11	21	32	12	6	26	22	7	10	17	25	3	8	28	23	18	13	33	5	30	15	19	35	20
		↑																												↑						
	HV	4	1	19	21	31	34	26	24	14	22	32	2	17	11	9	16	29	27	12	6	7	28	10	23	5	35	15	25	33	20	3	13	8	30	18
		↑																							↑											
$\bar{N}_S$	LV	3	23	28	33	18	8	13	4	9	19	24	29	34	31	14	11	22	6	17	1	27	2	7	26	10	12	32	16	35	20	30	21	25	15	5
		↑																													↑					
	HV	3	33	23	28	8	18	13	4	24	14	34	19	17	9	27	26	32	6	12	22	31	21	2	35	29	5	16	10	11	7	1	20	25	15	30
		↑																																↑	
TWT	LV	10	7	6	9	8	30	27	26	15	20	25	12	17	35	18	28	32	13	34	14	19	21	16	33	29	11	22	24	23	31	3	4	1	2	5
		↑		↑																																
	HV	10	7	9	6	8	12	30	26	27	15	20	11	14	29	25	35	18	22	13	16	17	19	21	31	28	32	34	24	23	33	3	1	4	2	5
		↑			↑																															
N_L	LV	3	23	33	13	28	18	8	5	35	15	20	25	30	19	34	4	24	29	14	9	10	31	22	11	12	27	17	26	32	16	6	21	1	2	7
		↑					↑																													
	HV	3	33	23	18	28	13	8	5	35	25	20	15	30	14	24	34	19	10	29	4	12	22	32	17	26	16	11	21	27	31	9	6	7	2	1
		↑					↑																													

Processing time variation: Low variation (LV)

Rank:	1	2	3	4	5		1	2	3	4	5	6	7
	Sequencing rule number						**Worker assignment rule number**						
$\bar{F}$	3	4	1	2	5		1	2	7	4	6	3	5
	↑												
T_{max}	1	4	2	3	5		1	2	5	3	7	6	4
	↑		↑										
$\bar{N}_S$	3	4	1	2	5		7	2	4	1	6	5	3
	↑												
TWT	3	5	4	1	2		2	6	3	4	7	5	1
	↑						↑						
N_L	5	2	1	3	4		7	1	3	5	4	6	2

Legend: ↑———↑ subset with no significant difference within it, but significantly differs from other subsets. For $\alpha = 0.05$

Table 4: Tukey's range test results for ranking and grouping of operating policies, sequencing rules, and worker assignment rules.

Figures (9) through (13) show the performance measures as functions of the sequencing rule employed in the shop, regardless of the worker assignment rule considered, under both levels of the processing time variation. It can be seen from these figures that high processing time variation has a negative impact on the sequencing rule performance, except for the total worker transfers measure. Figures (14) through (18) present shop performance measures as functions in terms of worker assignment rule. Again, worker assignment rule was worsened by the high variation in processing time for all measures except for the total worker transfers performance measure. From the graphs, one may observe that the performance patterns of sequencing rules and worker assignment rules, in terms of all shop measures are consistent for both low variation and high variation levels of processing time variation factor.

To further explore and illustrate the relative performance of operating policies; sequencing rules within worker assignment rules, bar charts were constructed for selected performance measures; mean flow time, maximum tardiness, and total worker transfers, for each of the five sequencing rules within each of the seven worker assignment rules, and for both levels (LV, HV) of the processing time variation. These charts are presented in Figures 19 and 20. It can be noted from these figures that the SPTF rule within the LNQ rule is the best in terms of mean flow time, while the EDDF rule within the LNQ rule is the best in terms of maximum tardiness, and the LNOF rule within the AQW rule is the best for total worker transfers under all experimental conditions. Considering the performance of operating policies with matching rules, i.e. policies that incorporate the same basic rule principle for both sequencing jobs for processing and assigning workers to workcenters (counterpart rules), none of these rules was ranked first. But some of which have shown no significant difference compared to those observed with superior performance. The operating policies with matching rules are operating policies #11, #17, #23, #29, and operating policy #35.

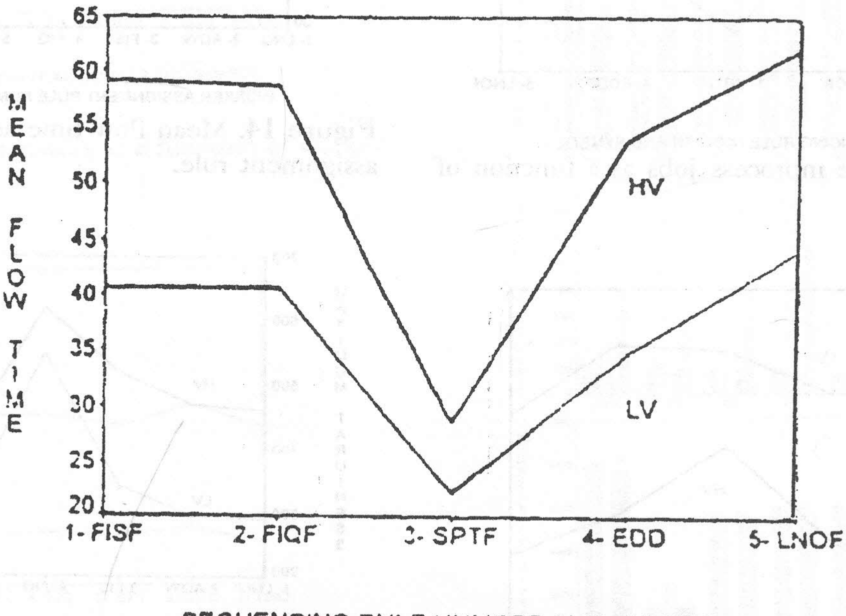

Figure 9. Mean flow times as a function of sequencing rule.

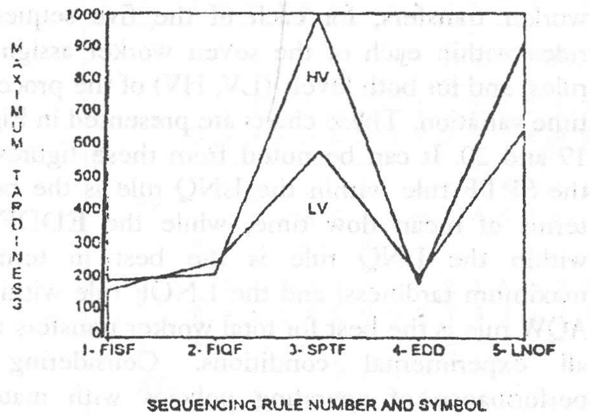

Figure 10. Maximum tardiness as a function of sequencing rules.

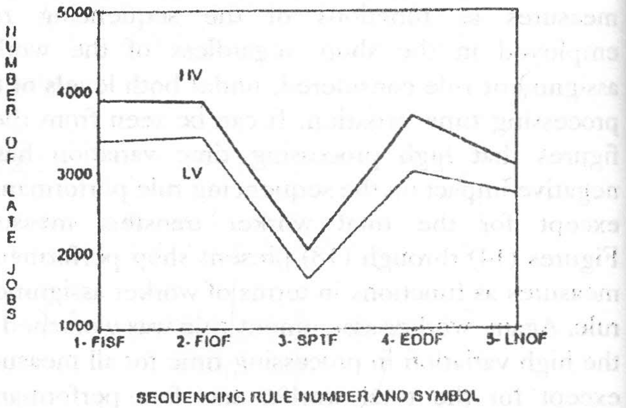

Figure 13. Number if late jobs as a function of sequencing rule.

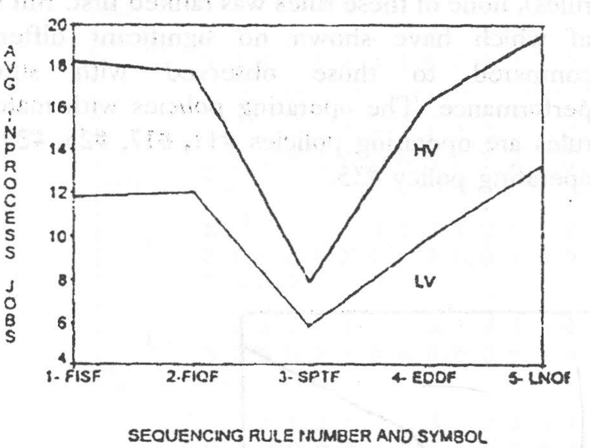

Figure 11. Average inprocess jobs as a function of sequencing rules.

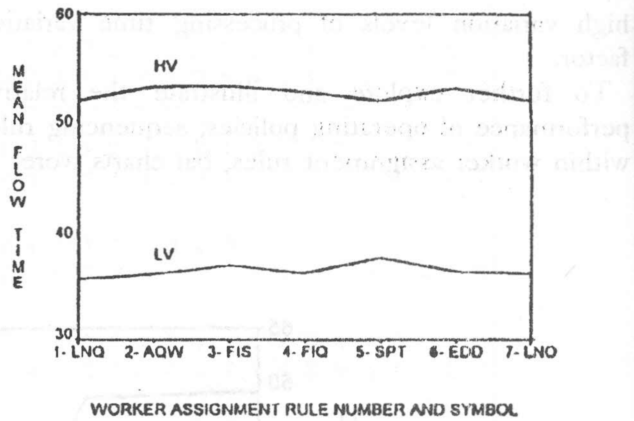

Figure 14. Mean flow time as a function of worker assignment rule.

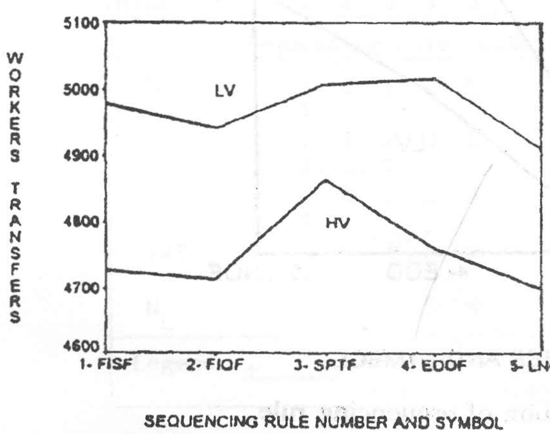

Figure 12. Workers transfers as a function of sequencing rules.

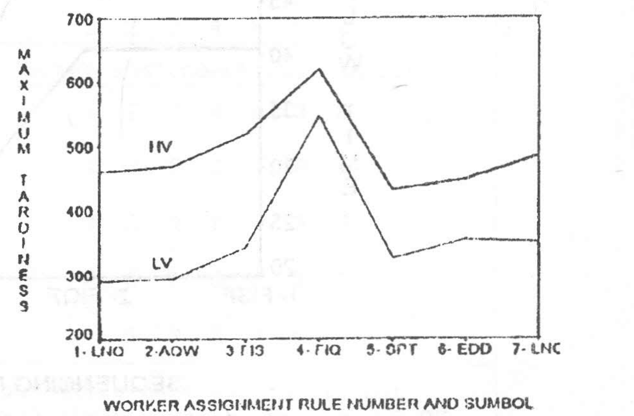

Figure 15. Maximum tardiness as a function of worker assignment rule.

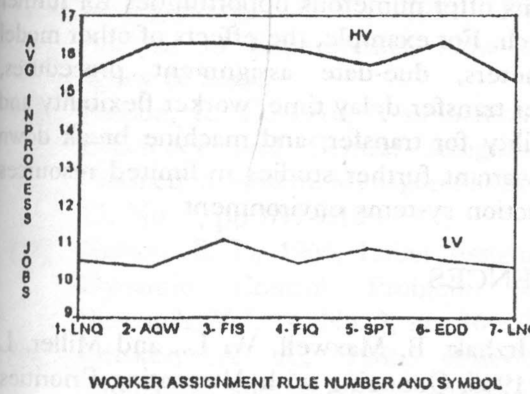

Figure 16. Average inprocess jobs as a function of worker assignment rule.

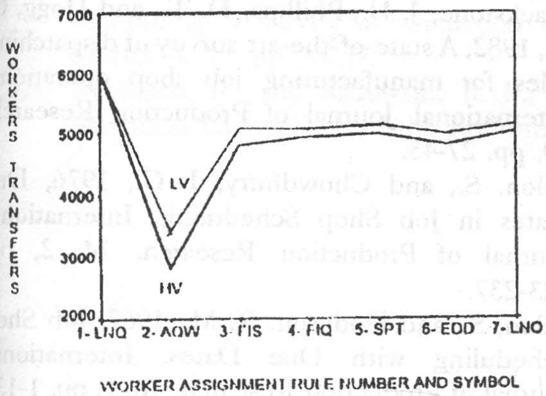

Figure 17. Workers transfers as a function of worker assignment rule.

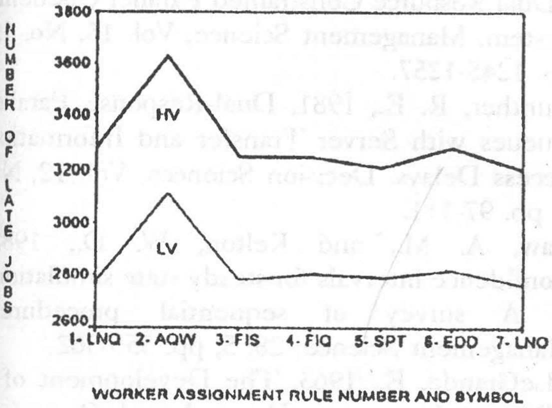

Figure 18. Number of late jobs as a function of worker assignment rule.

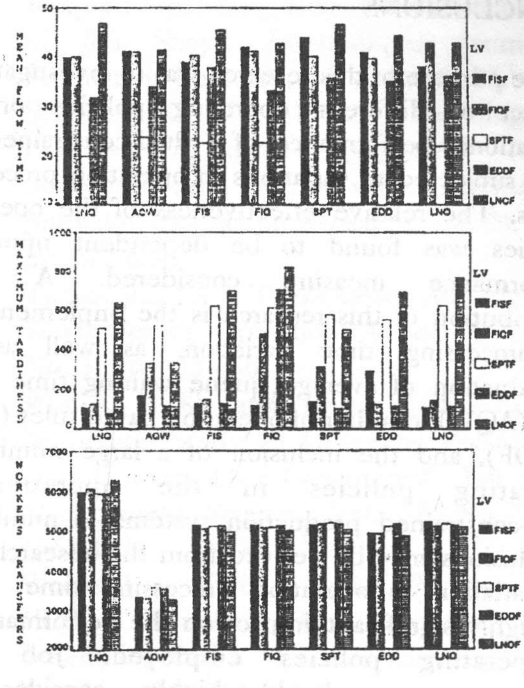

Figure 19. Bar charts for selected performance measures under the LV level of processing time.

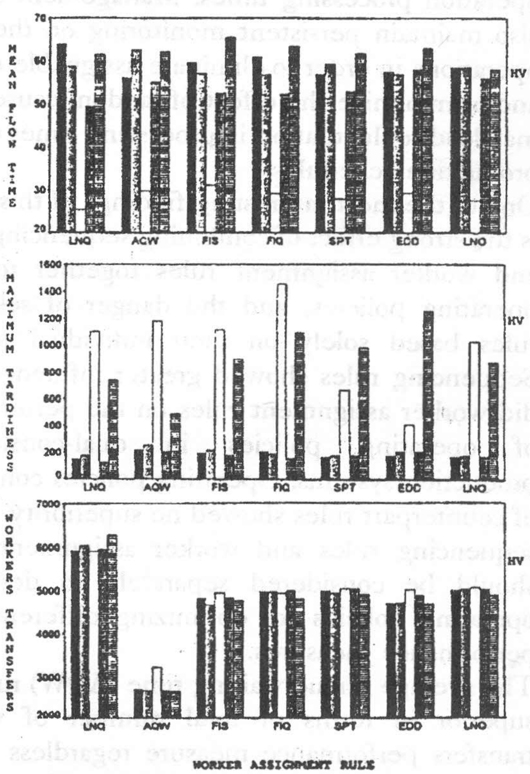

Figure 20. Bar charts for selected performance measures under the LV level of processing time.

CONCLUSIONS

The purpose of this research was to investigate the impact of different operating policies on the operational performance of a dual-constrained job shop subjected to variations in operation processing times. The relative effectiveness of the operating policies was found to be dependent upon the performance measure considered. A major contribution of this research is the implementation of processing time variation, as well as the introduction of average queue waiting time based rule (AQW), number of operation based rules (LNO, LNOF), and the inclusion of a large number of operating policies in the operation of dual-constrained production systems. A number of conclusions may be derived from this research:

1- Variation in operation processing times has a highly significant impact on the performance of operating policies employed. Job shop management should highly consider the establishment of expected operation processing times which do not largely deviate from actual operation processing times. Management should also maintain persistent monitoring on the shop operations in order to eliminate assignable causes and/or minimize the effect of random causes that may lead to fluctuation in processing times during production schedules.
2- One of the most interesting findings of this study is the strong effect of combining sequencing rules and worker assignment rules together to form operating policies, and the danger of selecting rules based solely on their individual impact. Sequencing rules showed greater influence than did worker assignment rules on the performance of operating policies in dual-constrained production systems. Operating policies consisting of counterpart rules showed no superiority. Thus, sequencing rules and worker assignment rules should be considered separately in designing operating policies for optimizing different shop performance measures.
3- The average queue waiting time (AQW) rule was superior in terms of total number of worker transfers performance measure regardless of the sequencing rule combined with.

Finally, Dual-constrained job shop production systems offer numerous opportunities for further research. For example, the effects of other model parameters, due-date assignment procedures, worker transfer delay time, worker flexibility and eligibility for transfer, and machine break down may warrant further studies in limited resources production systems environment.

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