Working Paper No. 126

A SIMULATION STUDY OF LABOR EFFICIENCY AND CENTRALIZED LABOR ASSIGNMENT CONTROL IN A PRODUCTION SYSTEM MODEL

by

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September, 1967

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This working paper should be regarded as preliminary in nature, and subject to change before publication in the open literature. It should not be quoted without prior consent of the author. Comments are cordially invited.

This work was principally supported by the Office of Naval Research under Task 047-003, and partially by the Western Management Science Institute under a grant from the Ford Foundation. Reproduction in whole or in part is permitted for any purpose of the United States Government.

A SIMULATION STUDY OF LABOR EFFICIENCY AND CENTRALIZED LABOR ASSIGNMENT CONTROL IN A PRODUCTION SYSTEM MODEL[1]

Rosser T. Nelson[2]

This paper reports a set of simulation experiments designed to study service systems in which labor interchange is possible among service stations. It is one of a series of studies in which the author has explored design and control aspects of labor and machine limited production (service) systems. The interrelationships among four experimental variables are investigated in terms of resulting system performance statistics. The variables are the job routing structure which describes the flow of work through the service facilities, the queue discipline, the efficiency of labor interchange, and the degree of centralized control exercised in labor assignment.

1. INTRODUCTION

Many production and other types of servicing systems may be characterized as queueing systems with both service facilities and labor as constraining resources. A job-shop production system with a mobile labor force is the particular example which motivated the work described here. Jobs undergo processing operations, each of which requires an appropriate machine or work bench and a laborer who can perform the necessary work. Numerous examples may be offered in other areas of society[3] such as a hospital with limited special equipment ans limited medical personnel, an educational program in which students require certain subject offerings and in which a limited number of qualified teachers must staff all requirements over a period of time, or a situation in which specific welfare requirements exist which must be satisfied by a limited number of semi-specialized social workers and limited material goods.

The simulation experiments reported here are based on a general model of labor and machine limited production systems which is described in [1]. Earlier experiments with specific versions of the general model are reported in [1] and [2]. This paper extends the earlier work to concentrate on two specific factors of system design and control; labor efficiency and the degree of centralized labor assignment control. We shall attempt, in the course of the paper, to describe how these two factors relate to a number of decision areas such as labor hiring and training policies, departmental structure of the system, aspects of physical location of facilities, and communications.

The specific model used in the experiments has two service centers and two laborers. Consequently, the results are of limited direct value. Other aims of the study are, (1) to present a procedural framework which may be equally useful for studying larger, more complex systems, and, (2) to provide basic results which may stimulate insights and initial hypotheses for testing in further experiments or in actual operating systems.

2. THE SIMULATION MODEL AND EXPERIMENTS

A set of simulation experiments was designed to study labor efficiency and centralized labor control in fairly simple labor and machine limited queueing networks.

The model employed may be described as follows: A service system consists of two service centers. Each service center has two service channels and a single queue. Customers arrive at the system according to a Poisson arrival process with mean arrival rate $\lambda = 1$. The basic service times (i.e., the service times for a laborer with maximum efficiency) at each service center are exponential with potential[4] mean service rate $\mu = 1.125$ per channel. The service system has only two laborers to handle the four service channels.

The actual average labor utilization as measured in the simulations ranged from 89 c/o upward. The measured values of average labor utilization for each experiment are reported on the data sheets in the Appendix.

Two extreme patterns of customer flow through the network are used in order to ascertain the effects of job routings. One flow pattern designates that each arriving customer requires a single service operation at service center 1 followed by a single service operation at service center 2. Henceforth, this will be referred to as the case of "series job routings." The other flow pattern employed generates customer service requirements by use of a Markov transition probability matrix which reflects an extreme job-shop routing structure with customers requiring different numbers of service operations:

		Service Center 1	Service Center 2	Exit from System
FROM	Entry Into System	0.5	0.5	0.0
	Service Center 1	0.0	0.5	0.5
	Service Center 2	0.5	0.0	0.5

(TO: Service Center 1, Service Center 2, Exit from System)

This will be referred to as the case of "job-shop job routings."

The labor efficiency factor is modelled by a labor efficiency matrix of the following form, where e_{ij} is the efficiency of laborer i at service center j, $0 \leq e_{ij} \leq 1$.

	Service Center 1	Service Center 2
Laborer 1	e_{11}	e_{12}
Laborer 2	e_{21}	e_{22}

The strict interpretation of labor efficiency rests on its operational use in the simulation model. If $e_{ij} = 0$, then laborer i cannot work at service center j. For $0 < e_{ij} \leq 1$, the service time required for laborer i to perform a service operation at service center j, is given by S/e_{ij} where S is the basic service time selected from the service time distribution for service center j. Thus, labor efficiency measures a laborer's relative speed of performance at a service center. The specific labor efficiency matrices used in the experiments are of the form $e_{11} = e_{22} = 1$, $e_{12} = e_{21} = \alpha$, where α is an experimental variable assigned the values $\alpha = 0$, .25, .5, .7, .9, and 1.0. Note that $\alpha = 0$ represents an ordinary two station series service system with no interchange of labor between the service centers (i.e., a two department system with one laborer and one service channel in each department) while $\alpha = 1.0$ represents a one department system with completely efficient interchange of labor between the service centers. Intermediate values of α represent various degrees of efficiency in labor interchanges between the service centers.

The method for assigning labor may be described in terms of two components; the service center selection procedure ℓ and the queue discipline q . The service center selection procedure determines which service center an available laborer is assigned to work at. The procedure which was used in all of the experiments may be described as follows. An available laborer is always assigned to the service center at which he is most efficient unless there is no work for him there and there is work at the other service center.[5] The queue discipline determines which of the available customers or jobs the laborer will work on once he has been assigned to a particular service center. Three common queue disciplines were employed for comparative purposes; first in service center, first-served (FCFS), first in system, first-served (FIFS), and shortest imminent operation time, first-served (SOT).

Closely related to the labor assignment procedure is an experimental parameter d, $0 \leq d \leq 1$, which measures the degree of centralized labor assignment control. The parameter d regulates the extent to which the service center selection procedure ℓ is allowed to operate in any experimental run. When a laborer completes a processing operation and there is more work available at the same service center, he becomes available for service center re-assignment by the service center selection procedure ℓ with probability d. With probability 1-d he continues to work at the service center he is at, without recourse to ℓ, employing the specified queue discipline q . Whenever the service center is emptied, the labor employed there becomes available for service center re-assignment by ℓ .

The parameter d was varied to model systems with different degrees of central control over labor assignments to service centers.

The values $d = 0$ (no central control), $d = .5$, and $d = 1$ (complete central control) were used. The practical interpretation of various values of d may be related to problems of communications and (or) penalties (e.g., time delays) associated with transfer of laborers between service centers.

Initial plans called for the simulation of the system for every combination of six values of the labor efficiency parameter α, three values of the degree of centralized labor assignment control parameter d, three different queue disciplines q, and the two types of job routings; series and job-shop. Of the 108 combinations, 12 were deemed unnecessary because variation in d is meaningless when $\alpha = 0$, i.e., when each laborer is constrained to one service center. An additional 18 experiments were eliminated during the computer runs because of the fact that the simulation results indicated that those particular parameter combinations led to unstable (over-loaded) systems. Thus, 78 runs were actually carried out[6], each consisting of the simulated processing of 32,000 jobs. The comparative nature of the study dictated a closely replicated workload input for each parameter set employed.

3. OBJECTIVE

Three of the four experimental variables represent control variables which may be adjusted to alter the performance of the system. The labor efficiency parameter α reflects the degree of flexibility of the labor force as determined by labor hiring and training programs and, in some instances, by the departmental organization of the system. The degree of centralized control of labor assignment parameter d is influenced by the physical location of service and control facilities as well as by communications procedures. The queue discipline q is, of course, a matter of direct choice. The fourth experimental variable, the job routing structure, is essentially fixed in any particular application by the particular processing requirements for incoming work. The series and job-shop routings employed here represent extreme cases, which were used to ascertain the influence of the job routing structure on the effectiveness of the control variables under study.

Manipulation of the control variables in any particular system will inflict costs. In addition, the degree of change which is feasible must be considered. The development of an appropriate cost model with feasibility constraints requires specification and attention to the details of a particular situation. This is not the purpose of this paper. Rather, the intent here is to study the effects and interactions of the experimental variables with respect to the time in system statistics for arriving jobs. The useful application of these results to any particular system will require that costs, feasibility constraints, and performance criteria be considered explicitly. Employed in this manner, the simulation results may provide useful information for guiding the development[7] of improved control procedures in a wide variety of situations.

4. RESULTS

Figure 1 is a summary presentation of the results of the simulation experiments. The left hand graphs are for the series job routings, the right hand graphs for the job-shop routings. The three levels of the degree of centralized labor assignment control parameter d are reflected in the vertical arrangement of the graphs; no central control in the top row, partial central control in the middle row, and complete central control in the bottom row. Each individual graph depicts the dependence of three representative job flow time or time in system statistics upon the queue discipline q and the labor efficiency parameter α. The three statistics[8] presented are the mean time in system $\bar{f}$ (measured on the abscissa), the standard deviation of the time in system σ_f (measured on the ordinate), and the second moment about the origin of the frequency distribution for time is system $(\bar{f})^2 + \sigma_f^2$ (the square of the vector distance from the origin which is measured along the circular arcs).

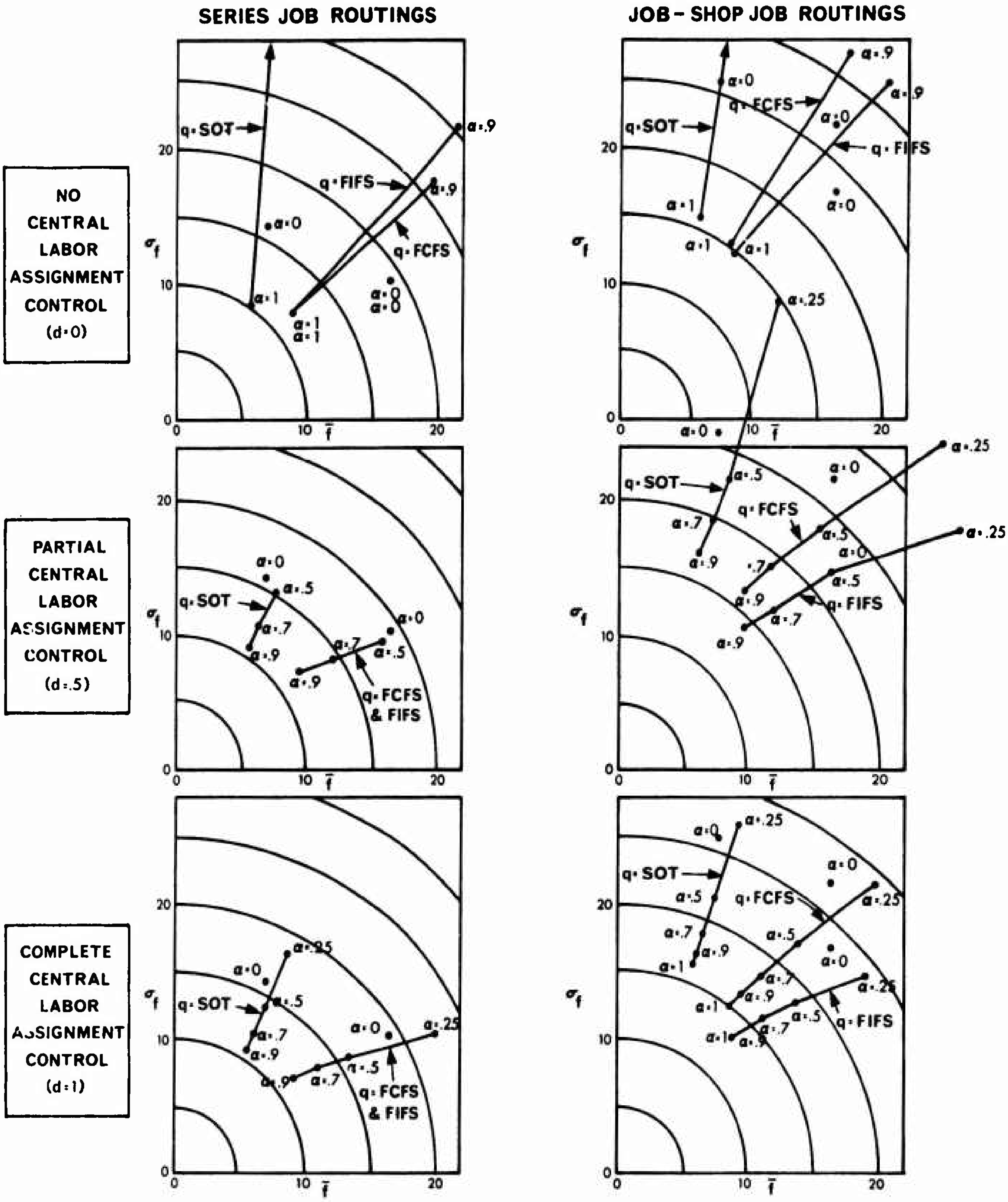

Figure 1. Summary Presentation of Time in System Statistics.

Although Figure 1 serves to completely summarize the experimental results, it will be useful for purposes of interpretation and discussion, to reduce the number of variables by concentrating on the best queue discipline q for each system and criterion statistic. Figure 2 represents the time in system statistics as functions of the control parameters α and d for the queue discipline which is best in each case. The top half of Figure 2 gives the results for series job routings, the bottom half for job-shop job routings. The three different time in system criterion statistics appear horizontally for each job routing type. The statistics are reported as ratios, i.e., as multiples of the best attained values. This procedure serves to make a comparison of the series and job-shop systems possible by eliminating the inherent differences in the absolute values of the statistics for the two systems. In each case the best attained value of the statistic is given to enable conversion to absolute values if desired. The best queue discipline, i.e., the queue discipline for which the results in Figure 2 apply, is also noted in each case.

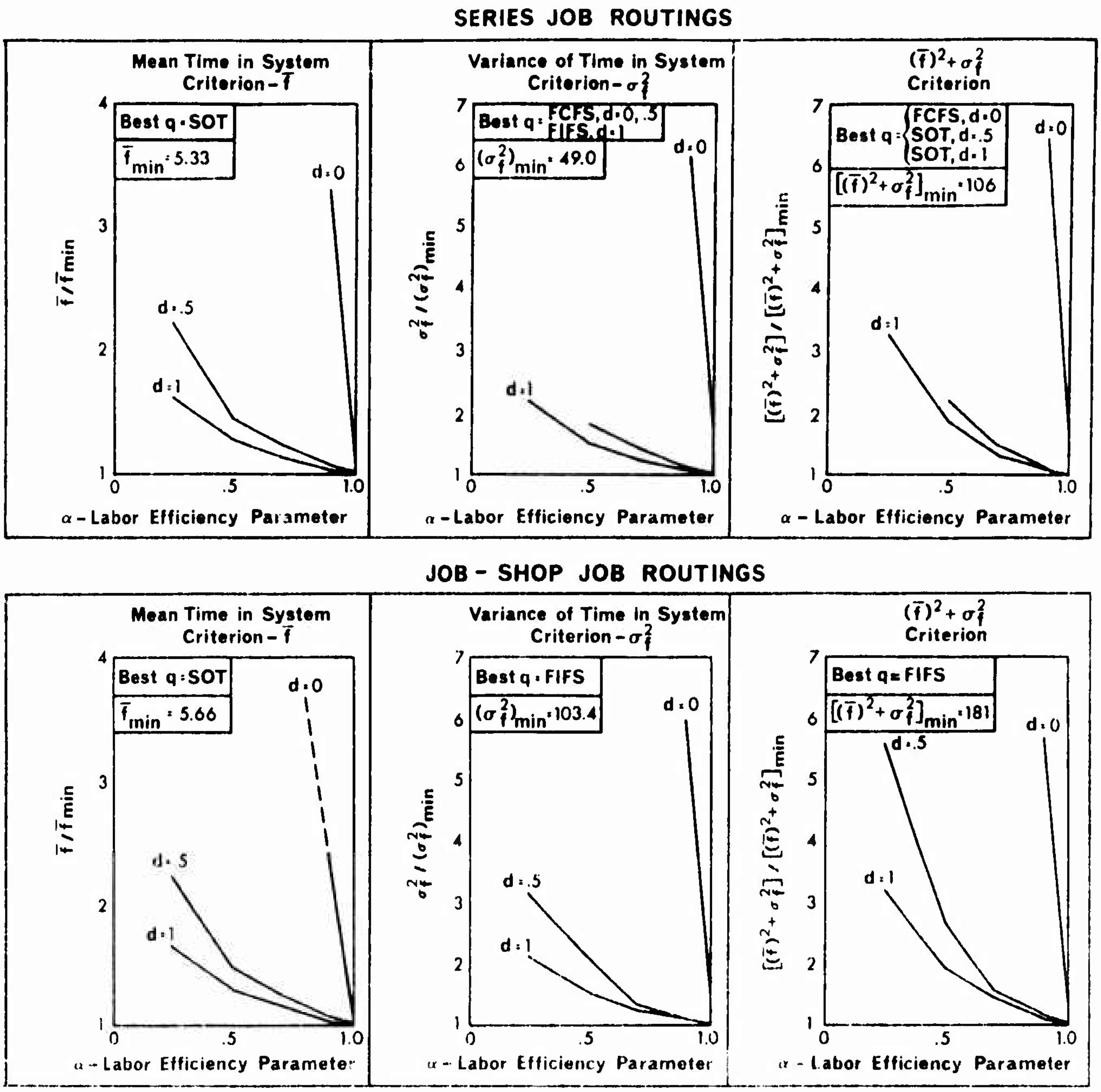

Figure 2. Time in System Statistics as Functions of the Control Parameters α and d, for the Best Queue Discipline q

QUEUE DISCIPLINES-DISCUSSION

Referring to Figure 2, we first note that the relative performance of the systems for different values of α and d (as measured by the statistical ratios) differs very little[9] between the series system and the job-shop system, when the best queue discipline q is employed. However, as we shall see below, the best q is not necessarily the same for the two types of routings, nor is it always independent of α and d . These observations indicate that the percentage improvements obtained in the time in system statistics by changes in the control parameters α, d, and q are approximately equal for the two extreme types of job routings.

A careful analysis of the best queue disciplines for the different systems and different criteria brings forth some new results not encountered in previous experiments. As the following discussion will serve to substantiate, there appear to be inter-actions between α, d, and the job routing structure which alter the relative performance of the queue disciplines. Previous work with a number of experimental systems [1,2] has shown the SOT queue discipline superior with respect to minimizing $\bar{f}$ and the FIFS queue discipline superior with respect to minimizing σ_f^2 for both series and job-shop routings. As figure 2 indicates the latter half of the pattern is violated in the current experiments for series job routings when $0 < \alpha < 1$ and $d \ll 1$. These happen to be parameter combinations not employed in any past work. Under these conditions of partially efficient interchange of labor combined with low levels of central control, the FCFS queue discipline minimized σ_f^2 for series job routings with the superiority of FCFS over FIFS increasing with decreasing central control. Of more import to problems of system design and control than the above phenomenon is the fact that all three queue disciplines deteriorate rapidly in performance with respect to both $\bar{f}$ and σ_f^2 (for both types of job routings) under these same conditions (see d=0 curves in Figure 2). The author is not able to explain the switch-over in the relative performance of FCFS and FIFS other than to say that the data indicates that it must be caused by an interaction of α, d, and job routing structure. The rapidly deteriorating performance of the various systems for low degrees of central control and $\alpha < 1$ is more readily explained and is the subject of the next section of the paper.

The best queue discipline for the third criterion employed $(\bar{f}^2 + \sigma_f^2)$ depends upon the job routing structure. For the series job routings, the best q is SOT[10] which also minimizes $\bar{f}$. For the job-shop job routings, the best q is FIFS which also minimizes σ_f^2. The explanation for this lies in the fact that the job-shop systems have a variable number of operations per job and the series systems do not. Since both systems have the same average number of operations per job, the variance of the time in system is a much larger contributor to the criterion $\bar{f}^2 + \sigma_f^2$ for job-shop systems. It is not surprising then that the SOT rule, which does well with respect to the $\bar{f}^2$ term, is best for the series systems while the FIFS rule, which reduces σ_f^2 is best for the job-shop systems.

DEGREE OF CENTRALIZED LABOR ASSIGNMENT CONTROL-DISCUSSION

Figures 1 and 2 show that the degree of central control of labor assignment d becomes progressively more important as the labor efficiency parameter α decreases from 1. The reason for this is that, under limited central control, one, or even both men, spend time working at the machine center where they are least efficient even when there is work that they could be doing at the machine center where they are most efficient. The output data from the simulation included the mean service time per job. This made it possible to calculate, for each system studied, the fraction of operations performed at the lower efficiency. The following equation was solved for x :

$$\bar{S}(\alpha) = (1-x)\left(\frac{2}{\mu}\right) + x\left(\frac{2}{\alpha\mu}\right) \qquad (\mu = \frac{9}{8} \text{ for all experiments})$$

where $\bar{S}(\alpha)$ = mean service time per job measured by simulation

α = labor efficiency parameter

x = fraction of work done at lower labor efficiency = α

$2/\mu$ = mean service time per job at labor efficiency = 1

$2/\alpha\mu$ = mean service time per job at labor efficiency = α

The values of x as functions of α, d, q, and the job routing structure are tabulated in Table 1.

α	q=FCFS			q=FIFS			q=SOT		
	d=1	d=.5	d=0	d=1	d=.5	d=0	d=1	d=.5	d=0
1.0	.50	.50	.50	.50	.50	.50	.50	.50	.50
.9	.17	.22	.54	.16	.22	.57	.14	.20	.75
.7	.13	.16	-	.13	.16	-	.11	.14	-
.5	.09	.11	-	.09	.11	-	.08	.10	-
.25	.04	.04	-	.04	.04	-	.04	.04	-
0	0	0	0	0	0	0	0	0	0

SERIES JOB ROUTINGS

α	q=FCFS			q=FIFS			q=SOT		
	d=1	d=.5	d=0	d=1	d=.5	d=0	d=1	d=.5	d=0
1.0	.50	.50	.50	.50	.50	.50	.50	.50	.50
.9	.20	.20	.54	.16	.20	.56	.15	.20	.68
.7	.15	.16	-	.14	.16	-	.12	.14	-
.5	.10	.11	-	.09	.11	-	.08	.10	-
.25	.04	.04	-	.04	.04	-	.04	.04	-
0	0	0	0	0	0	0	0	0	0

JOB-SHOP JOB ROUTINGS

Table 1. Fraction of Operations Done by Less Efficient Labor.

With the exception of the cases $\alpha=0$ (where the laborers are fixed and d is irrelevant) and $\alpha=1$ (where the men are equally efficient and each perform half of the operations), Table 1 indicates that the fraction of operations performed by less efficient labor increases as d decreases. This is because the mis-assignments of labor tend to extend over longer periods of time with less central control. Table 1 also shows that the fraction of operations done by the less efficient labor decreases as the labor efficiency parameter α decreases for large values of d , but that the opposite is true for small values of d . In fact, for d=0, mis-assignments of labor are more numerous than correct assignments. This would seem to be attributable to the fact that the least efficient man takes longer to perform any given operation at a machine center and, therefore, he spends more time at that machine center when there is no central control operating to return him to the machine center where he is more efficient. Even for large values of d where the less efficient labor performed less operations with decreasing α , this was dominated by the increasing service time per operation performed, so that the resulting service times and waiting times increase as the labor efficiency parameter α decreases. These observations serve to explain the widely divergent behavior of the curves in Figure 2, particularly for low levels of central control of labor assignment.

LABOR EFFICIENCY-DISCUSSION

From Figure 2 one can ascertain the efficiency of labor interchange α for the two department system which makes it equivalent in performance to the one department system ($\alpha=0$) for each of the performance criteria and for each value of d . These break-even labor efficiency values appear in Table 2. The best q discipline, as denoted in Figure 2, is assumed in each case.

Criterion	Series Job Routings d=1	Series Job Routings d=.5	Series Job Routings d=0	Job-Shop Job Routings d=1	Job-Shop Job Routings d=.5	Job-Shop Job Routings d=0
$\bar{f}$	.47	.63	.99	.44	.58	.98
σ_f^2	.25	.43	.99	.15	.35	.97
$(\bar{f})^2 + \sigma_f^2$	.40	.48	.98	.27	.47	.96

Table 2. Break-Even Efficiencies of Labor Interchange for Three Performance Criteria.

Table 2 brings forth the fact that the advantages of the alternative departmental arrangements is closely tied to the degree of centralized control of labor assignment. With d=0, the two department system is best for all three criteria, unless the efficiency of labor interchange possible with one department is virtually complete ($\alpha \approx 1$). With greater central control, the value of α necessary to favor the one department system falls off rapidly. One other pattern relevant to system design and control is evident from Table 2; the variance criterion σ_f^2 favors the one department system under the greatest range of values of α and d while the mean time in system criterion $\bar{f}$ similarly favors the two department system. Table 2 may provide a useful guide for optimal departmental arrangement if even crude estimates of efficiency of labor interchange are attainable. However, it is important to remember the limited experimental conditions (Sec. 2) for which the particular entries in the table were obtained and, to consider the costs associated with the alternatives available. Cost considerations are discussed in the following section.

The two department system with fixed labor force can be compared with the one department system with flexible labor force for the various values of α and d in another way. Instead of viewing the mean arrival rate of jobs into the system as fixed and comparing the alternative system designs on the basis of the resulting time in system statistics as was done above, one can think of the mean arrival rate as variable and ask what ratio of mean arrival rates in the two systems leads to equal values of the time in system statistics. This point of view is related to the notion that improvements in system performance might be used to increase the workload processed rather than to reduce the time in system statistics. For the series job routings and FCFS queue discipline, these ratios were computed by using queueing theoretical results for the two department system and the simulation results for the one department systems. The results of the computations are summarized in Table 3.

	Criterion = $\bar{f}$			Criterion = σ_f^2			Criterion = $(\bar{f})^2 + \sigma_f^2$		
α	d=1	d=.5	d=0	d=1	d=.5	d=0	d=1	d=.5	d=0
.9	.91	.91	1.02	.93	.93	1.04	.91	.92	1.03
.7	.94	.96	-	.95	.96	-	.94	.96	-
.5	.98	1.00	-	.96	.98	-	.97	.99	-
.25	1.03	1.05	-	1.00	1.03	-	1.02	1.04	-
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 3. Ratio of Mean Arrival Rate in Fixed Labor System to Mean Arrival Rate in Flexible Labor System Which Leads to Same Value of Indicated Time in System Statistic (Series Job Routings, q=FCFS).

As an example of the interpretation of Table 3, a one department series system with two machine centers, a FCFS queue discipline, an efficiency of labor interchange α=.9, and a degree of central control of labor assignment d=.5, can handle a 10% larger workload [1.00-91/.91] than the corresponding two department system using FCFS and fixed labor of efficiency α=1, with no resulting increase in mean time in system $\bar{f}$.

COST CONSIDERATIONS - DISCUSSION

Consistent with what was said in the statement of objectives for this study, we shall not attempt to develop a detailed cost model to be used in conjunction with the simulation results because such an undertaking would "require specification and attention to the details of a particular situation." Rather, we shall merely indicate, by way of a hypothetical example, how the simulation results obtained here (or similar results derived explicitly for the purpose at hand) might be employed, in conjunction with cost data, to experimentally resolve systems design and control problems.

We denote a control action by a control vector (α,d) which specified the labor efficiency parameter $0 \leq \alpha \leq 1$ and the degree of central control of labor assignment $0 \leq d \leq 1$. We shall say that the control vector (0,0) describes the two department system. We shall assume that the following cost elements[11] are relevant in considering transition to a two department system with a control action (α,d), where $0 < \alpha \leq 1$, $0 \leq d \leq 1$:

$C_1(\alpha)$ - incremental cost of achieving a labor efficiency of interchange of level α.(e.g., incremental labor costs or training costs) $[C_1(0) = 0]$

$C_2(d)$ - incremental cost of achieving centralized labor assignment control of degree d. (e.g., communications and physical layout costs) $[C_2(0) = 0]$

C_3 - cost of opening service channels to make labor interchange feasible. (e.g., equipment costs) $[C_3(0,0) = 0, C_3(\alpha,d) = C_3 \text{ for } \alpha \neq 0]$

$T(\alpha,d)$ - costs attributable to time in system statistics when operating with control action (α,d). (e.g., in-process inventory costs, customer goodwill costs). $[T(0,0) = T_0]$

The incremental gain from introducing the control action (α,d) is then given by:

$$G(\alpha,d) = T_0 - T(\alpha,d) - C_1(\alpha) - C_2(d) - C_3 \quad [G(0,0) = 0]$$

The problem of choosing the control action (α,d) which maximizes $G(\alpha,d)$ is dependent upon the simulation results through the cost elements T_0 and $T(\alpha,d)$, because determination of these costs[12] requires the relationship of the system flow statistics to α and d, as given in Figure 2.

APPENDIX

The appended data sheets give detailed results for the job-shop experiments[13] which may be of interest to a limited number of readers. The notation employed on the data sheet is identical to that used in the body of the report. The fractiles of the density functions of time in system are included in addition to the numerical values for statistics which appear only in graphical form in the report itself.

JOB-SHOP ROUTINGS

d = 1.0	α = 1.0			α = .9			α = .7			α	
	FCFS	FIFS	SOT	FCFS	FIFS	SOT	FCFS	FIFS	SOT	FCFS	
AVG. LABOR UTILIZATION	.8869	.8869	.8869	.9025	.9024	.9003	.9360	.9358	.9300	.9694	
$\bar{F}$	8.76	8.83	5.66	9.37	9.47	5.89	11.13	11.22	6.53	13.88	
σ^2_F	159.0	103.4	242.3	171.6	109.8	261.3	216.5	131.4	320.71	293.1	
FRACTILES											
.20	1.61	1.79	0.98	1.79	2.01	1.02	2.37	2.75	1.10	3.35	
.40	3.55	3.96	1.96	3.87	4.47	2.05	4.92	5.62	2.30	6.57	
.60	6.54	7.51	3.61	7.17	8.25	3.71	8.82	10.25	[illegible]	11.37	
.80	12.82	13.79	6.89	13.75	14.94	7.12	16.41	17.54	7.79	20.45	
.90	[illegible]	20.70	11.60	21.75	21.92	[illegible]	25.52	[illegible]	13.17	31.28	
.95	[illegible]	27.63	18.46	31.45	29.03	18.96	36.22	[illegible]	21.04	43.08	
.99	[illegible]	53.81	51.51	60.94	55.21	54.59	58.41	[illegible]	61.64	79.79	
.999	124.17	74.59	169.50	127.63	74.97	[illegible]	140.63	[illegible]	207.26	[illegible]	
1.000	288.00	84.00	870.00	300.00	84.00	876.00	328.00	[illegible]	366.00	372.00	
$\sigma^2_F + (\bar{F})^2$	235.7	181.4	274.3	259.4	199.5	296.[illegible]	340.[illegible]	257.2	363.4	485.8	3

A.

JOB-SHOP ROUTINGS

d = 0.5	α = 1.0			α = .9			α = .7			α	
	FCFS	FIFS	SOT	FCFS	FIFS	SOT	FCFS	FIFS	SOT	FCFS	
AVG. LABOR UTILIZATION		.8870	.8870	.9057	.9058	.9036	.9450	[illegible]	.9382	[illegible]	
$\bar{F}$		8.85	7.74	[illegible]	9.67	6.06	[illegible]	12.03	7.05	15.35	
σ^2_F		103.6	234.5	[illegible]	111.9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
FRACTILES	NOT										
.20	RUN	1.80	1.00	[illegible]	[illegible]	1.04	[illegible]	[illegible]	[illegible]	4.02	
.40		3.98	[illegible]	[illegible]	4.52	2.13	5.42	[illegible]	2.46	7.66	
.60	SEE	7.53	3.68	7.40	[illegible]	[illegible]	[illegible]	11.27	4.31	13.00	
.80	d = 0	13.83	7.07	14.09	15.30	[illegible]	17.67	[illegible]	[illegible]	22.74	
.90	AND	20.66	[illegible]	22.23	22.35	12.52	27.11	[illegible]	14.57	33.80	
.95	d = 1	27.63	[illegible]	[illegible]	29.52	[illegible]	38.15	[illegible]	[illegible]	45.90	
.99		53.49	51.01	61.46	55.00	54.31	70.31	[illegible]	[illegible]	[illegible]	
.999		74.45	166.51	128.51	75.73	[illegible]	144.34	[illegible]	234.51	166.17	
1.000		84.00	866.00	300.00	84.00	882.00	328.00	[illegible]	876.00	374.00	1
$\sigma^2_F + (\bar{F})^2$		181.9	267.4	267.5	205.4	294.2	371.8	283.7	386.9	553.6	4

JOB-SHOP ROUTINGS

α = .7			α = .5			α = .25			α = 0		
FCFS	FIFS	SOT	FCFS	FIFS	SOT	FCFS	FIFS	SOT	FCFS	FIFS	SOT
.9360	.9358	.9300	.9694	.9697	.9601	.9958	.9956	.9899	.8868	.8868	.8868
11.13	11.22	6.53	13.88	13.73	7.37	19.79	19.01	9.32	16.85	16.82	7.69
216.5	131.4	320.71	293.[illegible]	160.3	419.8	460.6	219.3	668.9	470.62	283.3	626.5
2.37	2.75	1.10	3.35	3.95	1.22	5.73	7.35	1.35	3.45	4.11	1.146
4.92	5.82	2.30	6.57	7.98	2.61	10.64	12.98	2.95	7.61	9.24	2.443
8.82	10.25	3.39	11.37	13.03	4.51	17.26	18.99	5.33	13.65	15.51	4.322
16.41	17.54	7.79	20.45	21.11	8.73	29.18	27.38	10.89	24.79	25.91	8.405
25.52	24.[illegible]	13.17	31.28	29.03	14.86	42.4[illegible]	36.22	19.24	39.20	35.36	14.625
36.22	32.[illegible]	21.04	43.08	37.30	23.63	57.18	46.[illegible]	31.[illegible]	54.08	50.66	24.521
68.41	53.[illegible]	51.64	79.79	55.1[illegible]	57.82	102.72	77.74	39.06	104.55	83.82	75.760
140.63	79.64	207.26	164.51	82.94	268.51	204.26	93.[illegible]	372.51	212.17	97.83	385.256
328.00	48.00	388.00	372.00	92.[illegible]	214.00	434.00	110.00	272.[illegible]	440.00	110.00	974.000
340.4	257.2	363.4	465.8	346.8	474.1	652.2	580.7	755.[illegible]	754.5	566.2	685.6

B.

JOB-SHOP ROUTINGS

α = .7			α = .5			α = .25			α = 0		
FCFS	FIFS	SOT	FCFS	FIFS	SOT	FCFS	FIFS	SOT	FCFS	FIFS	SOT
.9450	[illegible]	.9382	.9788	.9803	.9717	.9986	.9982	.9964	.8868	.8868	.8868
11.91	12.03	7.05	15.35	16.38	8.35	24.77	26.24	12.54	16.85	16.82	7.69
230.0	[illegible]	337.2	318.0	216.2	460.2	599.4	327.0	1218.0	470.6	283.3	626.5
2.65	3.06	1.15	4.02	5.06	1.28	7.83	11.18	1.44	3.45	4.11	1.15
5.42	5.47	2.46	7.66	8.94	2.80	14.07	18.94	3.23	7.61	9.24	2.44
9.58	11.27	4.31	13.00	15.85	5.05	22.46	26.78	6.08	13.65	15.51	4.32
17.67	1[illegible].43	8.52	22.74	24.74	9.98	36.59	38.37	14.09	24.79	25.91	8.41
27.11	26.71	14.57	33.30	33.17	17.29	52.12	49.64	27.16	39.20	35.36	14.63
38.15	33.49	23.50	45.90	42.54	28.19	69.41	61.27	46.69	54.08	50.66	24.52
70.31	59.55	65.51	83.72	79.04	79.26	118.89	88.46	125.26	104.55	83.82	75.76
44.34	81.43	234.51	168.17	94.96	262.51	218.26	110.61	476.51	212.17	97.83	385.26
28.00	92.00	876.00	374.00	106.00	892.00	440.00	120.--	1094.00	440.--	110.--	974.00
71.8	283.7	386.9	553.6	484.5	529.9	1212.9	1015.5	1375.3	754.5	566.2	685.6

JOB-SHOP ROUTINGS

d = 0	α = 1.0			α = .9			α = .7			α
	FCFS	FIFS	SOT	FCFS	FIFS	SOT	FCFS	FIFS	SOT	FCFS
AVG. LABOR UTILIZATION	.8872	.8872	.8873	.9394	.9416	.9539				
$\bar{F}$	8.76	8.78	6.01	17.63	20.44	13.61				
σ^2_F	166.2	148.4	223.5	726.7	614.0	4652.4				
FRACTILES										
.20	1.57	1.69	1.01	2.64	3.09	1.24				
.40	3.45	3.69	2.05	6.05	7.63	2.72	NOT RUN - OVE			
.60	6.36	6.95	3.81	12.13	15.73	5.02				
.80	12.65	13.33	7.62	25.69	34.77	10.68				
.90	20.64	20.67	12.81	42.74	55.06	20.45				
.95	30.55	29.03	20.62	63.26	69.00	39.03				
.99	61.79	50.54	51.35	128.51	100.56	175.56				
.999	123.50	133.26	151.51	268.26	218.51	1198.51				
1.000	294.00	366.00	768.00	522.00	368.00	2030.00				
$\sigma^2_F + (\bar{F})^2$	242.9	225.5	259.6	1037.5	1031.8	4837.6				

A.

JOB-SHOP ROUTINGS

	$\alpha = .7$			$\alpha = .5$			$\alpha = .25$			$\alpha = 0$		
DT	FCFS	FIFS	SOT	FCFS	FIFS	SOT	FCFS	FIFS	SOT	FCFS	FIFS	SOT
99										.8868	.8868	.8868
51										16.85	16.82	7.69
4										470.62	283.3	626.5
4										3.45	4.11	1.15
72	NOT RUN - OVERLOADED SYSTEMS									7.61	9.24	2.44
22										13.65	15.51	4.32
58										24.79	25.91	8.41
5										39.20	35.36	14.63
3										54.08	50.66	24.52
6										104.55	83.82	75.76
1										212.17	97.83	385.26
0										440.--	110.--	974.--
										754.5	566.2	685.6

B.

REFERENCES

[1] Nelson, Rosser T., "Labor and Machine Limited Production Systems," Management Science, Vol. 13, No. 9, May, 1967.

[2] Nelson, Rosser T., "Dual Resource Constrained Series Service Systems," Western Management Science Institute Working Paper No. 113, Graduate School of Business Administration, University of California, Los Angeles, February, 1967.

FOOTNOTES

1. This work was supported by the Office of Naval Research under Contract No. 233 (73), Task No. 047-003 and by the Western Management Science Institute under a grant from the Ford Foundation. Computational facilities were provided by the Western Data Processing Center, University of California, Los Angeles.

2. Graduate School of Business Administration and Western Management Science Institute.

3. Hopefully, the use of a production model, and the associated terminology, will not discourage the reader from drawing analogies to other areas of application.

4. The term "potential mean service rate" refers to the mean service rate of a service channel when a completely efficient laborer is working at that channel.

5. The laborer who is initially assigned to a processing operation is required to complete that operation. Hence, there will be times when less efficient labor is being employed while more efficient labor is idle or also employed where it is less efficient. This assumption is intended to reflect prohibitive switch-over costs during individual processing operations.

6. Computations were performed on the IBM 7094 computer at the Western Data Processing Center, UCLA.

7. "guiding the development" - because any extension beyond the system used in the experiments is, in essence, inductive hypothesis testing.

8. A discussion of the reasons underlying the choice of these three statistics for summarizing the frequency distribution of time in system appears in [2].

9. The only difference of note occurs for the statistics involving σ_f^2 when d=.5.

10. Except for d=0, which is the exceptional case described above.

11. We assume all cost elements converted to a common time rate basis.

12. Some specific cost models for $T(\alpha,d)$ related to the system flow statistics are described in [2].

13. The corresponding data for the series systems is available from the author.

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1 ORIGINATING ACTIVITY (Corporate author) Western Management Science Institute	2a REPORT SECURITY CLASSIFICATION Unclassified 2b GROUP

3 REPORT TITLE

A Simulation Study of Labor Efficiency and Centralized Labor Assignment Control in a Production System Model

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

Working Paper

5 AUTHOR(S) (Last name, first name, initial)

Nelson, Rosser T.

6 REPORT DATE September, 1967	7a TOTAL NO OF PAGES 25	7b NO OF REFS 2

8a CONTRACT OR GRANT NO Task 047-003 b PROJECT NO c d	9a ORIGINATOR'S REPORT NUMBER(S) Working Paper No. 126 9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

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11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY

13 ABSTRACT

This paper reports a set of simulation experiments designed to study service systems in which labor interchange is possible among service stations. It is one of a series of studies in which the author has explored design and control aspects of labor and machine limited production (service) systems. The interrelationships among four experimental variables are investigated in terms of resulting system performance statistics. The variables are the job routing structure which describes the flow of work through the service facilities, the queue discipline, the efficiency of labor interchange, and the degree of centralized control exercised in labor assignment.

DD FORM 1 JAN 64 1473 0101-807-6800

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