A LARGE SCALE JOB-SHOP SIMULATION BASED ON ACTUAL OPERATING DATA

Harold J. Steudel

ABSTRACT

This paper describes a simulation study of a large job-shop based on actual operating data and procedures. The simulation model is used to investigate and solve problems of shop floor congestion and poor lead times. Statistically design experiments are used to evaluate the effect of material handling support and job input rates on various common measures of shop performance. A predictive model for mean job flow time is also developed using multiple regression. This analysis provides the basis for several layout changes which reduce material handling and shop floor congestion. The results of the study also show the need for formalized work center loading and scheduling procedures based on the finite capacity of the work centers.

INTRODUCTION

Digital computer simulation is a common approach to analyze the complex relationships present in manufacturing job-shop systems. Past research has focused on the effects of priority dispatching rules (1,2), the joint effects of labor and machine constraints (4,5,6), the influence of due date assignment rules (3), and most recently the impact of due date assignment rules on various measures of shop performance (7). These studies, however, considered only hypothetical job-shops. The size of the networks of work centers were relatively small (approx. 8-12), and arrival times, routings, and service times were stochastically determined from theoretical distributions. Although hypothetical job-shop models provide a relative measure of the effects of decision rules, they are not realistic enough to characterize and subsequently analyze the effect of changes on an actual job-shop. Furthermore, several tactical problems are not encountered in hypothetical models which require substantial attention for simulations based on sampled operating data.

In this paper the experience and results of developing a digital simulation model for a large job-shop (approx. 67,500 sq. ft.) dedicated to the manufacture of control cabinets are presented. The model is structured and based entirely on actual operating policies and sampled operating data.

The major objective of this study is to investigate possible causes and solutions for the excessive amounts of congestion and poor job lead times being experienced. Specifically, the model is used with experimentally designed test procedures to evaluate the effects of changes in the rate of orders released and the amount of material handling support provided for the shop. Criteria used to measure shop performance are total queue size, mean flow time, percentage of jobs late, number of jobs and operations completed, and the amount of time machines wait for material handlers. Multiple regression analysis is then used to develop a predictive model for mean job flow time based on the amount of time machine operators wait for material handling equipment (a function of material handling support levels) and the overall level of work (and congestion) in the shop.

PHYSICAL SYSTEM

The job-shop network consists of six related departments primarily concerned with shearing, punch pressing, welding, machining, painting and assembly of control cabinet components. There are 64 work centers in the shop. Each work center contains one or more identical machines. In total there are 108 machines which are available for work during one or two 8-hour shifts. The entire shop is under one roof of approximate dimensions of 150 feet by 450 feet.

The 108 machines are operated by 58 men on the first shift and 16 men on the second shift. Every man is a member of one of ten labor pools. A labor pool is responsible for a fixed set of machines in a single department. Labor pool efficiencies are not identical, but are known based on measured performance.

Specific job assignments for each labor pool member are made by the department foreman at the start of each shift. Re-assignment to a different job (and possibly a different machine) can occur during a shift only after completion of an initially assigned job. Inter-labor pool man transfers are permitted only if the two labor pools are in the same department. The basis for all job assignments is the job due date specified on the operation sheet.

Each operation of the job also has an allowed processing time assigned to it. This time is equal to 2 days plus the standard job cycle time (specified on the operation sheet) measured in 8 hour days. All values are "rounded up" to the nearest day. For example, if the job cycle time is 12 hours, then 2 days + 12 / 8 = 3.5 → 4 days would be allowed to complete this operation. Accordingly, every completed operation can be graded as being either early, on-time, or late. Thus, this statistic serves as a performance measure for monitoring the shop.

Between each processing operation, the in-process materials are stored in either pallet racks, tote pan racks or floor stacking areas. Material movements between machine and storage facilities is accomplished via fork lift trucks, overhead tram-rail cranes, hand trucks or push carts. All material movement is along a "highway type" system of aisles.

The majority of in-process materials is stored on pallets and accordingly handled by means of fork-lift trucks. Typically after a machine operator finishes a pallet load of work, he must flag down a truck to: (1) remove the pallet load of completed material and place it in an appropriate storage location, and (2) find the storage location of the next load of material (same job or next job) and deliver it to the machine. Although six work centers do have a surge area for material to be delivered during the work cycle, the entire shop is quite dependent on the service provided by the two trucks on first shift, and the one truck on second shift. In effect, the trucks are the servers to the men/machines, and the men/machines are the servers to the jobs flowing through the shop. Thus, the simulation model can be viewed as two interdependent multiple server queueing networks.

SIMULATION MODEL

The components of the simulation model are the work centers, labor pools, storage facilities, aisles, and the operating data base of the work to be processed. Each of the components is defined by the following specifications.

Workcenters are defined by specifying the,

1. identification number
2. X-Y coordinate from the grid layout
3. material transfer point
4. department number
5. labor pool number
6. number of identical machines in the work center
7. surge storage capacity (if any)
8. number of shifts worked per day

Labor pools are defined by specifying the,

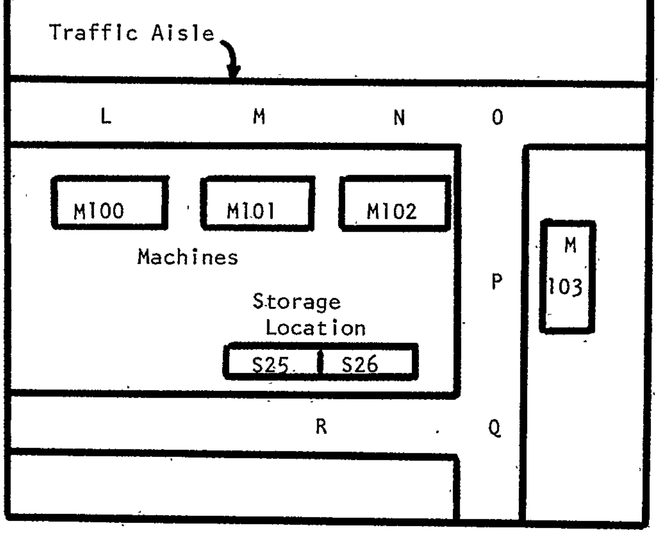
1. labor pool number
2. department number
3. set of work centers covered
4. number of men on first and second shift
5. labor pool efficiency number (i.e., how many standard hours of work can be done in one actual hour).

Storage facilities are defined specifying the,

1. identification number
2. X-Y coordinate
3. material transfer point
4. capacity of the storage unit
5. the type of load stored (pallet, box, etc.)

The location of aisles are specified by means of a series of transfer points whose X-Y coordinates are known. All material movement among machines and storage areas is along aisles via these linked transfer points. For example, Figure 1 shows the series of connected transfer points (L-M-N-O-P-Q-R) which define the aisle movement of material from machine M100 to storage location S25. Thus, knowing the X-Y location of every work center, storage area and transfer point, the shortest path-distance can be determined. Furthermore, knowing the mode of transport, the corresponding transport time can be calculated.

FIGURE 1



The data base consists of 200 randomly sampled jobs (operation sheets) from a two month period of actual operation. Each operation sheet specifies the,

1. job identification number
2. routing sequence
3. in-process storage locations
4. machine cycle times including handling
5. type and number of loads (pallet, box, etc.) of each operation
6. number of men required at each operation.

Jobs are randomly selected from the data base at the average rate of 68 jobs per day for the simulation. All work enters the shop on first shift.

The simulation logic is written as a variable time increment model and is coded into 930 records of FØRTRAN IV. The program structure consists of a main program and five subroutines. Core requirements are 64 K. For a simulation run of 130 days, the CPU time requirements (including compilation) are approximately 11 minutes on a Univac 1110, and 20 minutes on a Xerox Sigma 9. (FØRTRAN BATCH COMPILERS)

TACTICAL PROBLEMS

Conducting a large scale simulation study using sampled operating data poses several interesting tactical problems, about which little theoretical or empirical work has been published. One problem is the determination of the run length to obtain an equilibrium or steady state (assuming one exists). Another problem is calibrating or "fine tuning" the simulator to realistically characterize and mimmic the behavior of the sampled system. In this section these problems are discussed as well as some simple solutions.

Equilibrium Conditions

In simulating relatively small hypothetical job-shops, where arrivals, routings, and job service times are stochastically determined, it is a simple matter to select mean interarrival and service times to provide a desired level of labor utilization. (90% for example). A equilibrium or steady state will be reached and detected quite quickly. Obtaining equilibrium in simulations of large networks based on sampled operating data, however, presents more of a problem. For one, large networks of queues stabilize less readily than small networks, even if hypothetical arrival and service rates can be selected. The major problem in simulating from a data base of sampled shop data however, is due to the existence of the occasional large job. In this study, for example, the average operation processing time was around 1 hour for the 920 operations (200 jobs). Nevertheless, several operations had processing times in the range from 30 hours to 80 hours. Two operations required around 180 hours. Processing these large jobs tends to cause congestion in terms of the amount of in-process inventory in storage, as well as bottlenecks in the overall work flow. Since it is difficult to process work around these large jobs, the shop tends to get "plugged up". Furthermore, many of the job-shop queues never appear to become stable, at least as viewed in the short term. Consequently, the equilibrium state is difficult to detect in a statistic as dynamic as queue levels.

After some experimentation, the statistic "percentage of operations late" was selected as the criterion for detecting equilibrium. This statistic tended to smooth out the large job spikes. Also, the statistic was measured by and consequently familiar to shop personnel. The simulation program was accordingly run under "normal conditions", and this statistic was determined for the six departments at the end of 70, 90, 110 and 130 days as shown below:

% of Operations Late

Departments	Day Number			
	70	90	110	130
D/M	10.0	10.0	9.9	9.4
E/K	14.5	19.6	21.9	22.8
N	19.1	15.8	14.3	14.7
P	17.1	14.5	13.8	16.2

These values indicate that after 70 days of running (starting from empty), the system reaches an acceptable state of equilibrium. Thus no sampling was done until the completion of day number 70.

One minor adjustment was necessary to reach an equilibrium state. Since on the average 68 jobs entered the shop each day, each job in the data base of 200 jobs was selected approximately once every 2.94 days. Since experience indicated that this frequency was too high for the two large jobs of 180 hours, the program was modified such that these jobs would be selected less frequently, or approximately once every 10 days.

Calibration

Using actual data for a simulation study requires more effort than the use of hypothetical data. That effort is justified only if the simulation can be calibrated to realistically depict the performance characteristics of the system which was sampled. This problem is essentially one of "fine tuning" the model.

In this study the data base was collected by sampling work over a two months period of time during which statistics were available to describe the work load, labor, and shop performance conditions. The simulation was accordingly set up and run with a similar job input rate, labor and labor efficiency conditions, and work center status. To calibrate the simulator, the statistic "percentage of operations late" was again chosen as the best overall measure of shop performance. The simulator was then "fine tuned" by adjusting the ten labor pool efficiency factors slightly from the expected values. This adjustment facilitated the processing of the appropriate amount of work (std. hours) in the period of run time hours. In effect, this adjustment procedure provided a correction factor to allow for the inevitable discrepancies in work load between the relatively small sample of jobs and the amount of work actually done during the two month sampling period. It was found, however, that adjustments from expected levels of around $\pm 10\%$ would bring the percentage of operations late to within around $\pm 3\%$ of target values. In retrospect, adjusting the labor pool efficiency factors worked quite well as a "fine tuner."

EXPERIMENTAL DESIGN

A two level factorial design with full replication was used to experiment with the simulation model. This approach provides estimates of the main effects and interactions between the independent (control) variables on various dependent (response) variables. Replication provides an estimate of the variability of the system responses, and thus allows the analyst to evaluate the statistical significance of the results.

A major interest of the study was to investigate the problems of job lateness and shop congestion. These response variables were expected to be related to the level of workload demand on the shop, and the level of material handling support provided by the forklift trucks. Accordingly the following independent variables were chosen:

X_1 = Number of forklift trucks available on first shift

X_2 = Mean rate of job arrivals to the shop;

The following low and high levels were then selected for each variable.

Variable	Low Level	High Level
X_1	2 Trucks	3 Trucks
X_2	68 $\frac{\text{Arrivals}}{\text{day}}$	72 $\frac{\text{Arrivals}}{\text{day}}$

The experiment thus consisted of the four runs (and four replication runs) shown in Figure 2.

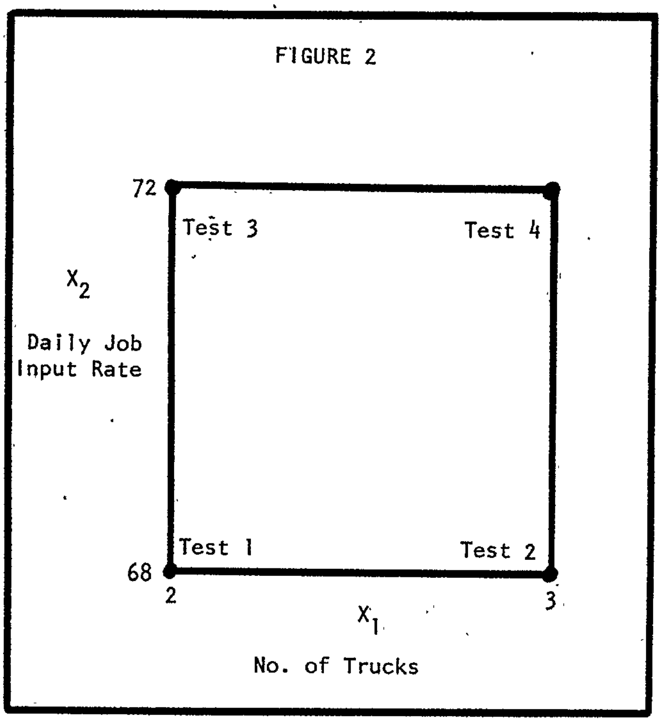


FIGURE 2

The next step of the analysis involved recording values for the following response variables at the end of the 60 day run (day 71 thru day 130) for each of the four test conditions and their replications.

$Y_{1,j}$ = Number of jobs completed

$Y_{2,j}$ = Number of job operations completed

$Y_{3,j}$ = Machine idle time due to wait for truck

$Y_{4,j}$ = Truck idle time

$Y_{5,j};Y_{6,j};Y_{7,j};Y_{8,j}$ = Percent of operations late in departments D/M, E/K, N, and P. where $j = 1,2....4$.

The average main effects of variable X_1 and X_2 denoted as E_1 and E_2, and the interaction effect (E_{12}) can then be calculated for each of the eight response variables ($Y_1, Y_2 ... Y_8$) using the following equations.

$$E_{i,1} = 1/2\ (\overline{Y}_{i,2} + \overline{Y}_{i,4} - \overline{Y}_{i,1} - \overline{Y}_{i,3}) \quad (1)$$

$$E_{i,2} = 1/2\ (\overline{Y}_{i,3} + \overline{Y}_{i,4} - \overline{Y}_{i,1} - \overline{Y}_{i,2}) \quad (2)$$

$$E_{i,12} = 1/2\ (\overline{Y}_{i,1} + \overline{Y}_{i,4} - \overline{Y}_{i,2} - \overline{Y}_{i,3}) \quad (3)$$

where $\overline{Y}_{i,j}$ is the mean of the original and the replicated value of response $i (i = 1,2....8)$ for test no. $j (j = 1,2....4)$.

It should be noted that the calculation of the average main and interaction effects is equivalent to fitting the following regression model for each of the eight response variables.

$$\overline{Y}_i = \hat{\alpha}_i + \hat{\beta}_i X_1 + \hat{\partial}_i X_2 + \hat{\theta}_i X_1 X_2 \quad (4)$$

where $\hat{\alpha}_i = 1/4\ (\overline{Y}_{i,1} + \overline{Y}_{i,2} + \overline{Y}_{i,3} + \overline{Y}_{i,4})$
$\hat{\beta}_i = E_{i,1}/2$
$\hat{\partial}_i = E_{i,2}/2$
$\hat{\theta}_i = E_{i,12}/2$

The statistical significance of each main and interaction effect can be assessed by calculation of the 95% confidence interval given by:

$$\text{STATISTIC} \pm t_4(.025) \sqrt{Sp^2/2} \quad (5)$$

where Sp^2 is the pooled (average) variance of S_1^2, S_2^2, S_3^2 and S_4^2 which are estimated from the four replicates of tests 1 thru 4 respectively.

EXPERIMENTAL RESULTS

The values of the eight response variables recorded from the four simulation test runs and their replicates are provided in Table 1. The mean responses and the values of the main effects and the interaction effects are shown in Table 2. Also listed is the plus or minus increment of the 95% confidence interval for each statistic. The following sections first summarize the above results for each of the independent variables, and then discuss the results of a regression model obtained for estimating mean job thru put time.

Number of Trucks

The average effect of increasing the number of forklift trucks from two to three on first shift is an increase of 151 jobs completed in 60 days. This is due largely to the average decrease of 1226 hours spent waiting for forklift trucks. Total truck idle time, although, increases by 371 hours. The effects of an additional truck on the number of operations completed, and the percentage of those operations which were late, however, are not significant. Department N is an exception.

Additional insight can be gained by considering how the time not spent waiting for trucks would be utilized. Considering the present input rate of 68 jobs per day only, the addition of one truck on first shift would decrease the average waiting time for trucks by 1077 hours in 60 days. This "savings in time" would result in an additional 620 hours of productive work being completed. The remainder of the savings (457 hours) would be consumed as an increase in idle time for the men. Likewise, this change only reduces the percentage of late operations from around 19% to 16%. These results indicate that the addition of one truck is only marginally justifiable (8 hour/day/truck X 60 days = 480 hours invested vs. 620 hours saved). Any further addition of material handling support would mainly increase truck idle time, and would result in little or no improvement in productive output. The inefficiences remaining in the shop are a consequence of the lack of better workload balance. This type of improvement can only be affected by better order releasing and workload scheduling procedures.

TABLE 1

Test No	No. of Job Arrivals	No. of Jobs Completed	No. of Operations Completed	Wait for Trucks (HRS)	Truck Idle (HRS)	% of Operations Late (Department) D/M	E/K	N	P
1	4117	3933	12,496	1611	347	9.4	22.8	14.7	16.2
2	4117	3987	12,658	736	724	6.9	23.2	12.3	16.6
3	4388	3893	12,812	2124	298	11.9	25.7	15.4	16.9
4	4388	4174	13,164	813	663	9.5	26.3	14.0	21.5
1R	4191	3829	12,587	2008	303	11.4	39.1	14.5	22.2
2R	4191	3968	12,924	731	677	11.3	33.2	9.9	15.2
3R	4464	3909	13,152	2309	277	12.7	42.1	16.8	27.3
4R	4464	4048	13,390	868	644	13.4	16.8	14.6	31.0

TABLE 2

		Mean	E_1	E_2	E_1E_2	95% C.I.
No. of Jobs Completed		3,967	151	74	54	$\pm$ 115
No. of Operations Completed		12,898	272	463	23	$\pm$ 344
Wait for Trucks		1,400	-1226	257	-150	$\pm$ 306
Truck Idle		492	371	-42	-5	$\pm$ 49
% of Operations Late:	D/M	10.8	-1.1	2.2	0.2	$\pm$ 4.3
	E/K	30.7	-3.5	2.2	-0.8	$\pm$ 18.1
	N	14.0	-2.7	2.4	0.8	$\pm$ 2.0
	P	20.9	0.5	6.6	3.8	$\pm$ 10.6

Input Rate

The average effect of increasing the number of jobs from an average of 68 jobs per day to 72 jobs per day is an increase of 463 operations completed. All the other effects (except department N) are non-significant. Thus slight variations in the average input rate will not have profound effects on the performance of the shop. It is also seen in Table 2 that the two factor interaction effects are not statistically significant.

Thru-put Estimation

A second phase of the analysis was to develop a regression model to estimate the mean job flow time (thru-put). Accordingly, after the equilibrium period of 70 days, each run was sampled at 480 hour (20 day) intervals to obtain values of the statistics.

T = Average Job Thru-put Time
Z_1 = Total Waiting Time per day of machines and men for trucks
Z_2 = Total Number of Hours of In-Process Work in queue prior to the 64 work centers

This procedure provided data with which to estimate the parameters of the predictive model.

$$T = \hat{\beta}_0 + \hat{\beta}_1 Z_1 + \hat{\beta}_2 Z_2$$

as follows: $\hat{\beta}_0 = -2.08$
$\hat{\beta}_1 = 1.077$
$\hat{\beta}_2 = 0.084$

The coefficient of determination (R^2) of the fitted model was .974, indicating that 97.4% of the total variability in the data is accounted for by the model. The model is valid for Z_2 greater than 1000 hours.

This predictive model is quite interesting since it describes the extent to which mean job thru-put time increases as the total amount of work in the shop increases, and the amount of material handling support decreases. (i.e., greater wait-for-truck times). It provides a quantitiative characterization of the response of the total system which is useful both for establishing a level of performance, and for predicting job times in scheduling functions.

CONCLUSIONS

The information and knowledge gained from the simulation model was well worth the time and costs invested. The model provided considerable insight to the present behavior characteristics of the overall shop system, as well as useful statistics on traffic patterns, material handling activities, storage requirements, etc. This information facilitated several layout changes including the formation of two centralized storage rack areas, the addition and layout of a new press brake, and several other machine location moves to lessen localized congestion and reduce material handling.

More importantly, however, the simulation model provided a means to access the performance of the shop in light of the variability of the workload mix which is processed. By changing only the "seed" of the random number generator, thereby providing a different mix of job entries into the shop, the simulation replicates show surprisingly large changes in commonly measured shop responses. The level of certain queues, for example, show a variation as large as 100 jobs from the original run to the replication run. The percentage of operations late in departments E/K (Table 1) also exhibited a variation from an average of 24.5% late to 36.8% late. These large amounts of variation are simply an indication of how differently the same shop would respond to a different input mix of jobs (from the same population of jobs) if no attempt is made to release work in a manner which provides good workload balance among the work centers. In effect large variability in shop conditions and performance is an inevitable consequence of releasing work according to due dates without regard to shop capacities. Undoubtedly, these types of large inherent variability are what make large job-shops difficult to control. Thus the results of the simulation study strongly indicate the need for a better system for work center loading and scheduling work in the shop.

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