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A SIMULATION APPROACH TO DESIGN A MOTOREDUCER ASSEMBLY AND TESTING FACILITY

Harold J. Steudel
Associate Professor of Management
Marquette University
Milwaukee, Wisconsin

ABSTRACT

This paper describes the application of a digital computer simulation model to design a large facility for assembling and testing approximately 30,000 motoreducers a year. The simulation model is designed and calibrated entirely on actual operating data, and used in conjunction with statistically designed experiments to evaluate the effects of various controllable factors on the size and configuration of the department level facility. The paper shows that a relatively simple and straightforward simulation model can provide quite insightful and valuable results, yet still be well within the capabilities and budget of the "ordinary practitioner" of management science in facilities planning.

INTRODUCTION

Today's facilities planner has very few analytical tools and procedures available to apply in designing detail layouts of departmental facilities at a work station level. The well known computer models like CRAFT (1), CORELAP (3) or COFAD(4) can provide useful assistance in designing plant layouts where the primary interest is determining the relative location of various machines and/or departments. Likewise SIMSHOP (5,6) the relatively new job-shop simulation model, is appropriate primarily for designing large scale job-shop systems in which the emphasis is on integrating layout configurations, material handling systems, and work force scheduling procedures. All of these computerized layout models are too broad in scope, however, to provide a useful tool for designing a detailed layout at a work station level. Consequently detailed work station layouts usually are designed by manually repositioning templates on a grid sheet until a "good" layout is determined. A major drawback of such intuitive design procedures is the lack of flexibility to generate and accurately evaluate alternative designs. A need clearly exists to provide the facilities planner with a more powerful analytic tool. Computer simulation not only fills this need, but is clearly part of the new technology coming in the area of computer-aided layout (7).

This paper presents an application of computer simulation to design a large facility for assembling and subsequent testing of motoreducer units comprised of numerous shafts, gears, bearings, etc. enclosed in a steel housing. The simulation model is designed and calibrated entirely on actual operating data and procedures for seven different types (families) of motoreducers encompassing several hundred different variations of size and gear reduction. Statistically designed experiments are run with the model to evaluate the effects of alternative testing procedures, company growth, and work force levels on the design requirements of the assembly and test facility. The simulation model and experimental design procedure together provide a realistic and valuable tool to determine the size and configuration of the new facility in terms of assembly stations, conveyors, access aisles, surge areas, test plates, supporting equipment, and interfaces with existing facilities. In addition to presenting this specific application, the paper will provide a methodological framework for applying statistically designed and evaluated simulation experiments for designing facilities in a manufacturing environment.

PHYSICAL SYSTEM

The assembly and test facility is an integral part of the total production facilities for a company specializing in mechanical power transmission equipment with annual sales in excess of $250 million. The compa manufactures

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and assembles seven types of motoreducer units with a volume of 30,000 motoreducers a year on a two shift basis. As a result of new product lines, product growth, method changes, etc., the existing assembly and test facility has become obsolete, thus dictating the design of a new layout for this area.

The basic physical relationships of the assembly and test facility, as determined from existing conditions, is given in Figure 1. Nine separate assembly stations feed a total of 58 different units into two test plates areas, each of which has three separate spindles, thereby providing the capability to spin test more than one unit at a time. Each assembly station and test plate spindle is a separate entity, capable of handling only the type/size of units shown.

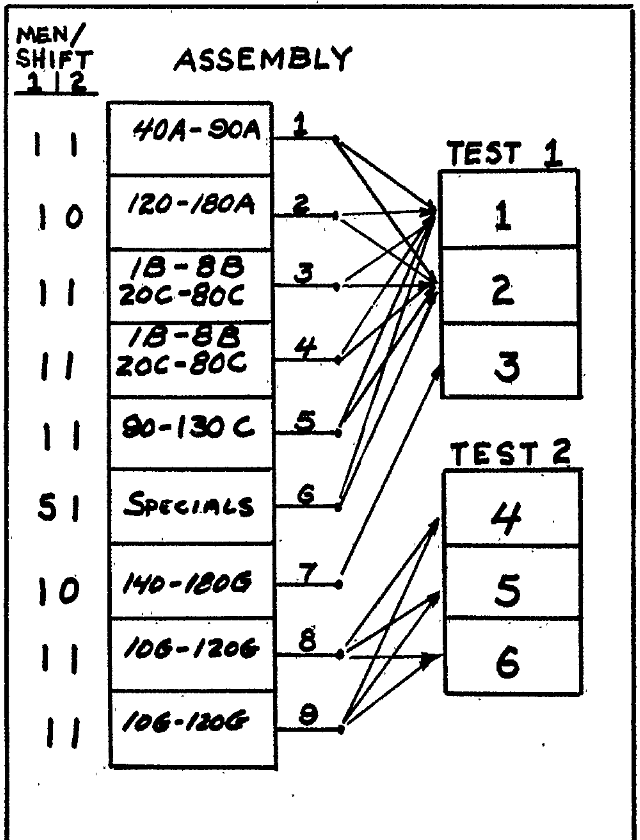


FIGURE 1 Layout Configuration

Figure 1 also shows the current number of assembly and test plate operators on each shift during the Monday thru Friday workweek. On second shift, only one testing operator is present, jockeying between the two test plates as dictated by the size of the queues. A test plate operator may also work on a Saturday in order to eliminate any "backlog queue" existing at the end of the week. Assembly, however, never operates on Saturdays. Consequently, Monday morning represents a zero queue regeneration point for the testing area.

Motoreducer units are assembled according to customer orders, ideally requiring a lead time from order receipt to shipment of less than 72 hours. Each of the 58 type/size of units has the option of being available in a single, double, triple, and occasionally quadruple reduction. Some units also have special bevel gear right angle input drives. The results of these variations, in addition to optional equipment, is that hundreds of different units are assembled and the most frequent order size is one. The occasional occurence of a batch arrival is viewed as being non-significant.

SIMULATION MODEL

The simulation model was designed with emphasis on keeping the model as simple and flexible as possible, while still maintaining good realism and accurate predictability. As a starting point, the model was constructed based upon the physical relationships shown in Figure 1. The data base to drive the model was collected and assembled as shown by the sample given in Tables 1 and 2. Table 1 provides information for each unit type/size in the following areas:

1. Assembly Specifications: The current assembly station number and the number of assembly operators per shift at the station as specified from Figure 1. Assembly time standards in minutes per unit are likewise specified for each unit by number of reductions.

2. Testing Specifications: The current testing station (spindle) number and the number of test plate operators is specified from Figure 1. The percent of units which fail inspection and conse-

Unit	Assembly Specifications							Testing Specifications					
Type	Station	Assm. Time				Men/Shift		Station	Percent	Test Times		Men/Shift	
Size	Number	Sgl.	Dbl.	Trp.	Quad	1st	2nd	Number	Rejection	Current	Proposed	1st	2nd
40A	1	90	150	—	—	1	1	1 or 2	5%	10.0	15.0	1	.5
50A	1	110	160	—	—	1	1	1 or 2	5%	10.0	16.5	1	.5
60A	1	140	200	—	—	1	1	1 or 2	5%	10.0	17.5	1	.5
70A	1	150	210	—	—	1	1	1 or 2	5%	12.0	17.5	1	.5
80A	1	160	230	—	—	1	1	1 or 2	5%	14.0	19.5	1	.5
90A	1	210	260	—	—	1	1	1 or 2	5%	14.0	19.5	1	.5
120A	2	300	400	500	—	1	0	1 or 2	15%	20.0	30.0	1	.5
150A	2	350	460	510	—	1	0	1 or 2	15%	20.0	30.0	1	.5
180A	2	410	480	530	—	1	0	1 or 2	15%	20.0	35.0	1	.5
1B	3 or 4	15	27	39	54	1	1	1 or 2	12%	5.0	10.0	1	.5
etc.													

TABLE 1

quently get recycled through the area is likewise shown. Testing times in standard minutes per unit are given for the current practice, and for a "new" practice being considered by Engineering. Note that the testing times are independent of the reduction.

Table 2 provides information for each unit type/size in the following areas:

1. Physical Dimensions: The length, width, and weight of each unit are used by the model to calculate queue length in linear feet, and loading requirements for conveyors and pallet loads.
2. Sales Volume: Sales in number of units by single, double, triple, or quadruple reduction are given based upon 1981 activity levels. Future years sales are projected as a percent increase or decrease of the 1981 values.

Unit Size (Type)	Physical Dimensions			1981 Sales Volume by Reduction			
	Length in.	Width in.	Weight lbs.	Sgl.	Dbl.	Trp.	Quad
40A	15.50	13.62	150	175	50	0	0
50A	17.87	15.00	240	200	60	0	0
60A	20.32	16.25	340	235	70	0	0
70A	22.75	17.82	440	190	50	0	0
80A	24.63	18.50	630	160	50	0	0
90A	29.87	22.78	980	80	30	0	0
120A	34.50	25.88	1590	20	30	10	0
150A	43.0	30.28	2610	5	15	5	0
180A	49.0	34.75	3710	5	10	10	0
1B	14.25	13.00	110	50	150	75	50
etc.							

TABLE 2

The physical dimensions given in Table 2 are used by the simulation model to provide a more realistic analysis, and results which are easy to interpret. Since the size and weight of the units vary considerably, this information facilitatess analyzing the system under different alternatives regarding types of material handling and storage methods/equipment.

The data in Tables 1 and 2 also are used by the simulation model to determine the various cumulative frequency distributions required to simulate the system. For example, it is a straight forward calculation to determine that assembly station #1 assembles 1350 units in two shifts requiring a total of 3374 hours. Accordingly, after performing similar calculations for the other nine assembly stations, it can be determined that station #1 has work which represents 4.5% of the total number of units assembled and 10.5% of the total assembly hours. Likewise, the computer program calculates the relative work of each unit size (i.e., 40A, single reduction) as a percent of the total work at assembly station #1. The simulation model thus uses actual data to automatically generate the cumulative distributions from which the individual unit type/size is randomly selected as part of the customer arrival process. In this study, the overall arrival process was assumed to be Poisson with mean arrival rates of 8.55 units/hour and 6.45 units/hour respectively on first and second shift.

Given the usual practice of working on a Saturday to eliminate queues at the testing area, the simulation model is most accurately classified as a terminating simulation [2] rather than a steady state simulation. Consequently there was no attempt to ascertain the occurance of a "steady state condition," even though such a state may occur depending on the experimental conditions under which the model was run.

Model validation was conducted in a casual manner by comparing simulation runs under current operating conditions with actual occurrences as evaluated by shop floor managers. In effect, the model was fine tuned until it performed well. This straightforward approach had several advantages. For one, the users of the results of the simulation analysis had knowledge and experience regarding the structure of the model and the input information being used. They thus tended to believe the results of simulation analysis. Secondly, several refinements in the model were identified and made as a result of the first hand experience of the shop personnel. It is unlikely that these necessary refinements would have resulted if a purely statistic comparison with existing data was conducted. Thirdly, this casual validation procedure was conducted in a very quick manner with minimal efforts. Nevertheless, the results were quite satisfactory.

The simulation model logic was coded using Fortran IV and run on a Harris (Datacraft) computer #6024. Fortran was chosen since a simulation language was not readily available, and the model was quite straightforward such that the coding was not difficult nor time consuming. Fortran also provided considerable programming flexibility, and efficient execution times.

EXPERIMENTAL DESIGN

The simulation analysis was conducted with the objective of answering many questions regarding design details of the overall size, equipment specification, and layout configuration of the assembly and testing facility for various operating conditions. In order to evaluate the effects of these conditions on the design requirements at a 95% level of confidence, a two level factorial design with full replication was used. The following variables at the low and high levels shown below were selected.

Variable	Low Level	High Level
X_1: Spin Test Procedure	Present Policy	New Engr. Recom.
X_2: Sales Volume Levels	1981	1985
X_3: Work Force Levels at Testing	2 men/First Shift 1 man/Second Shift	2 men/First Shift 2 men/Second Shift 1 man/Third Shift

For each of the eight resulting test conditions, the following responses were recorded at the end of each shift for each of the j assembly assembly stations (j=1,2....9)

Y_{1j}: The mean number of units in queue at testing originating from assembly station j.

Y_{2j}: The mean length of the queue in linear feet for the units at testing originating from assembly station j.

Y_{3j}: The mean number of hours of testing work in the queue at testing originating from assembly station j.

Y_{4j}: The mean loading requirements in lbs./ft. for the queue at testing originating from assembly station j.

These responses were measured in terms of the assembly station origin since this factor was known and fixed, whereas the physical queue at testing was an unknown - being a result of the overall design project. Each test condition was run for 10 weeks of activity (10 shifts/week), thereby providing a sample size of 100 observations for each of the responses. In effect, each response is the mean of a time series of 100 observations having a sample interval of eight hours. The entire experiment was then replicated providing two independent observation (mean values) for each response.

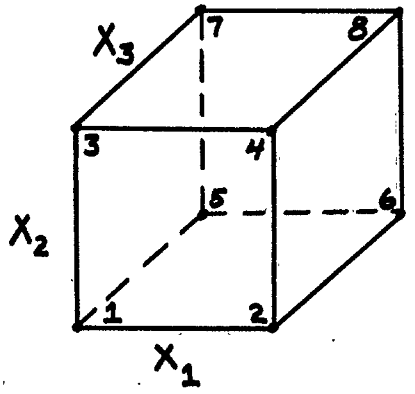


FIGURE 2 Experimental Design

The experiment which consists of eight test conditions, can be described geometrically as shown in Figure 2. Evaluating the average effects of each variable amounts to comparing the mean value of measured responses on opposite sides of the cube. For example, the average effect of increasing variable 1 (spin test times) from the low level to the high level is the difference between the mean of responses Y_1, Y_3, Y_5, Y_7 (left face) and the mean of responses Y_2, Y_4, Y_6, Y_8 (right face). This can be expressed mathematically as follows:

$$E_1 = 1/4[(\bar{Y}_2+\bar{Y}_4+\bar{Y}_6+\bar{Y}_8)-(\bar{Y}_1+\bar{Y}_3+\bar{Y}_5+\bar{Y}_7)]$$

where E_1 is the average effect associated with variable X_1 and $\bar{Y}_i$ represents the average of the responses for test number i, (i=1,2....8). A similar procedure applies for variables X_2 and X_3, as well as the interaction effects.

The statistical significance of each effect can then be assessed by calculating a 95% confidence interval as follows:

$$\text{STATISTIC}\pm t_8(0.025)\sqrt{(Sp^2/4)}$$

where

Sp^2 is the pooled (average) variance of the eight sample variances (S^2_i, i=1,2...8) which are estimated from the original and replicate response values obtained at each of the eight test combinations. Note that Sp^2 is calculated separately for each of the response variables.

$t_8(0.025)$ is the t distribution value with eight degrees of freedom at the 5% level of significance.

Common pseudorandom numbers, obtained with common initial random number seeds, were used for each of the simulation experiments in order to obtain time series having reduced variances.

EXPERIMENTAL RESULTS

Numerical results will be presented for response Y_2 (length of queue in linear feet) since this response is the most interesting, being most closely related to the size of the layout. The results for the other responses will be limited to discussion.

As shown in Figure 1, units assembled at stations #1 thru #7 are tested at one of the three spindles at test plate #1. Units assembled at stations #8 or #9 proceed to test plate #2. Table 3 shows the average total queue length in linear feet for each test plate as calculated by the simulation model. The "original" and "replicate" values were obtained by summing Y_{21} thru Y_{27} and Y_{28} thru Y_{29} respectively for the original and replicate test results. Also shown are the mean and variance of the original and replicate values. The main and interaction effects were then calculated for each test plate and are presented in Table 4. Note that the 95% confidence interval is identical (in this case by chance) for test plates #1 and #2, and equal to ±1.40 feet.

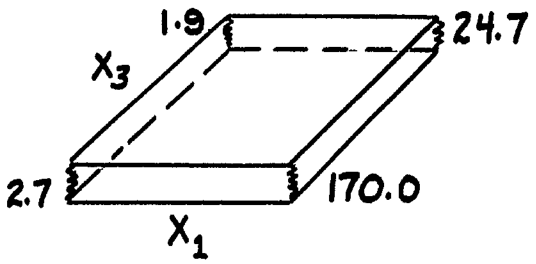
Test No.	Average Total Queue Length in Linear Feet at Test Plate No.							
	Original		Replicate		Mean		Variance	
Plt#→	1	2	1	2	1	2	1	2
1	2.5	1.3	2.0	1.1	2.3	1.2	.12	.02
2	169.5	113.9	173.6	116.1	171.6	115.0	8.41	2.42
3	3.3	1.3	2.9	1.8	3.1	1.8	.08	.00
4	167.5	116.5	169.4	118.3	168.5	117.4	1.81	1.62
5	1.9	.5	1.7	.3	1.8	0.4	.02	.02
6	22.2	3.6	21.7	3.7	21.9	3.7	.13	.005
7	1.6	.4	2.5	.4	2.1	0.4	.41	.00
8	26.9	17.4	28.1	21.3	27.5	19.4	.72	7.61

TABLE 3 Experimental Results for Response Y_2

	Main & Interaction Effects (Feet)	
	Plate #1	Plate #2
E_1	95.08	62.90
E_2	.90 NS	4.65
E_3	-73.03	-52.90
E_{12}	0.35 NS	4.38
E_{13}	-72.28	-51.80
E_{23}	2.00	3.18
E_{123}	2.30	3.48
Mean	49.84	32.4
95%CI	±1.40	±1.40

TABLE 4 Main and Interaction Effects for the Length of Queues at Plate 1 and Plate 2 in feet

The results in Table 4 show that variables X_1 (spin test procedure) and X_3(work force levels at testing) have the largest effects on the number of feet of queue for both test plates. Variable X_2 (sales volume levels) has no statistically significant effect on test plate #1 and no practical effect on test plate #2. The interaction effect between variables X_1 and X_3 is large and provides some insight for designing the system. As an example, the experimental design for test plate #1 can be viewed as shown below after removing the nonsignificant variable x_2 and averaging the responses obtained.



This shows that if the new spin time recommendations are adopted ($+X_1$), additional manpower ($+X_3$) will be required, given that sufficient conveyor to accommodate an average queue length of 170 feet is not practical in this case. Furthermore, even with the additional manpower, the average size of the queue will increase by a factor of 10. Very similar results are evident for test plate #2. This example shows the impact that operating policy changes can have on the physical layout.

The effects of variables X_1, X_2 and X_3 on Y_1 (units in queue) and Y_3 (hours of work in queue) are quite similar to those discussed for response Y_2. These results also show the need for additional manpower and a large surge area between assembly and test if the spin times recommendations are adopted. Variables X_1, X_2, and X_3, however, did not have any significant effect on variable Y_4 (loading requirements in lbs./ft.). Accordingly, conveyor and pallet loading specifications were determined directly from the results of the simulation model.

In summary, the experimental results showed that the currently considered set of variables affecting the layout were less than ideal. Adopting the new spin/test times recommended by engineering would necessitate the addition of both manpower and considerable additional physical facility. It was then relatively easy to estimate the cost to these changes.

PROJECT SUMMARY

The project then followed an interesting and somewhat natural progression.

1. Engineering carefully reviewed the spin/test time requirements and associated costs. This precipitated the issuing of a new set of recommended spin time requirements which were around 20% lower than the initial values.

2. The simulation model was rerun with the new spin times at the additional manpower level.

3. The "queue" originating from each of the assembly areas then was analyzed separately. It was decided that the work from assembly stations #2, #5, #6 and #7 were too large and heavy to be handled efficiently by roller conveyors. Thus allowances were made to move and surge this material using pallets, loading platforms, and pallet racks.

4. Assembly stations #1, #3, and #4 were consolidated into one area. This allowed the formation of a conveyor system whereby three spurs feed one central input conveyor into test plate #1. Based on the time series of this queue as generated by the simulation model, it was determined that 18 feet of conveyor with a 40% off line surge was sufficient.

5. Assembly stations #8 and #9 were consolidated in a similar fashion, facilitating the design of a central 25 foot conveyor into test plate #2.

CONCLUSIONS

Designing the operating plan and associated layout of any manufacturing facility involves the analysis of many sources of information, in order to make the many interelated decisions to obtain an operating system layout which best balances many and often conflicting objectives. A computer simulation model based on actual operating data provides a useful tool in assisting in this decision making process. The application for simple simulation models is especially advantageous in designing a detailed layout of departmental facilities at the work station level since the well known computerized layout models do not apply. In addition to providing a flexible and powerful tool for analyzing the effects of various operational factors on the physical layout, a computer simulation model facilitates the involvement of shop personnel in the decision process in a very constructive fashion. The model provides a means to evaluate and incorporate both the ideas and experience of the "user" in the design process. Consequently, the results of the simulation model are "easy to believe" and well accepted. It tends to eliminate the traditional and often fruitless arguments over layouts in which suggestions are made, the merits of which are difficult to evaluate.

In this study, a computer simulation model was designed, programmed, tested, and advantageously used to design a large facility for assembling and testing 30,000 motoreducers per year in hundreds of different configurations. The project involved less than 100 man-hours of effort and under $250 in computer expenses. Nevertheless, the model provided to be a valuable tool for both establishing a good operating policy and designing the details of an associated layout. Without the simulation model, it is most likely that a considerably more expensive operation and physical layout would have resulted. There is little question that the simulation model provided a valuable tool to evaluate and improve the design alternatives available.

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