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Capacity choice, work-in-process inventory and throughput: A simulation study

G. G. Hegde
K. Ramamurthy
P. R. Tadikamalla
Katz G.S.B., University of Pittsburgh

and

Sunder Kekre
Graduate School of Ind. Admn.
Carnegie Mellon
Pittsburgh

ABSTRACT

We investigate in this paper alternative configuration choices of serial assembly lines. In particular, we analyze the impact on throughput and work-in-process inventory levels from several design choices. These are the number of work-stations, tasks allocated to various stations and buffers between workstations. A simulation model is used to evaluate the sensitivity of various designs to variability in the operating environment arising due to process time variations (operator variability) as well as variations due to breakdowns and repair (machine variability). Insights of the tradeoffs for making capital investment and setting operating policies are also discussed.

INTRODUCTION

Different configurations of serial production lines provide interesting tradeoffs between capital investment and operating costs. Consider for instance three alternative configuration of an assembly line shown in Figure (1). Configuration 'C' has 12 work stations and the line has an output of 60 JPH, based on one minute cycle at each of the 12 work stations. In configuration (B), the line has been re-configured to form 2 lines each of 30 JPH. This has been achieved by doubling the work content of each station to 2 minutes, and 6 stations perform the same task as the 12 stations of line 'C'. Configuration 'A' has 4 lines of 15 JPH, with only 3 stations in each line with work content of 4 minutes. Clearly as the number of lines have increased, task fractionation has decreased. All the three configurations are identical with respect to total job content, number of work stations, and ideal throughput of 60 JPH. The major difference between the three configurations is that the distribution of work content is different.

These three configurations provide interesting tradeoffs from a production and operations management perspective. From a capital investment standpoint, line 'A' will be the most expensive, since it will have to have the tooling and setup fixtures for jobs for 4 minute cycle as compared to 1 minute for line 'C'. The training costs and costs of monitoring quality would be higher for 'A' also because each work-station performs more variety of jobs. Moreover, because of longer cycle, and the ability to handle

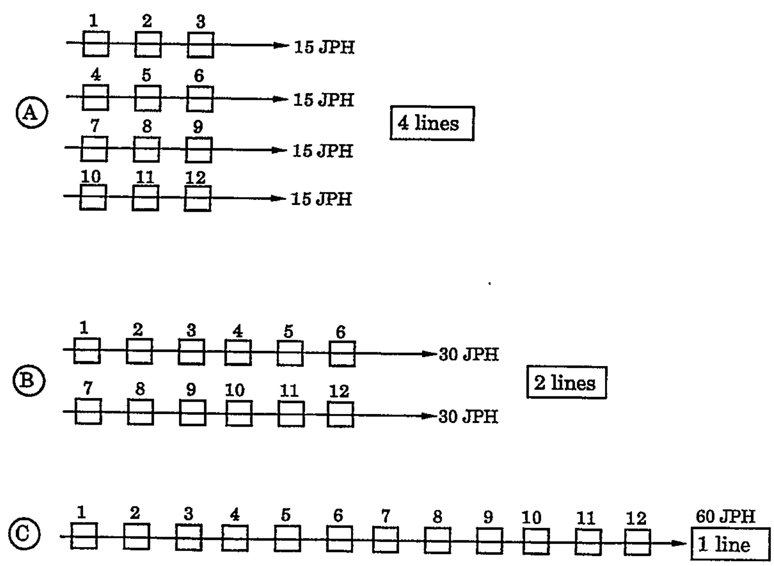

Figure 1: Design Configurations Under Investigation

variety of jobs, the machines will be complex and hence could be more prone to breakdowns. Also, there could be more operator variability due to larger variety of jobs. Thus variability from machines as well as operators could be more severe in 'A' than 'C'. However, in design 'A', there is less serial dependencies, because of fewer work-stations. As discussed by Conway et al. (88), variability in processing times in serial lines causes throughput to fall as line length increases. Also from a supervisory standpoint, line 'A' is more flexible, since it has 4 separate lines and provides more operational flexibility to do maintenance, process improvements and the opportunity to dedicate products to each of the lines.

The impact of design configuration on system performance has been documented in the manufacturing systems literature. Karmarkar & Kekre (87) discuss impact of configuration on throughput, batchsize and WIP levels in the context of batch manufacturing. In the case of high volume manufacturing using assembly lines, several factors like size of buffers [Conway et al. (88), Rao (75), (76), Buzacott (67), Joneja & Maxwell (86) etc.], location of unbalanced stage [Hillier and Bolling (66)], and effect of multiple servers [Iyama & Ito (87)] have been investigated. In this paper, we focus on configuration choices as shown in Fig. (1); our motivation being to investigate how the manufacturing performance is affected by the uncertainty in the three designs.

We capture three sources of uncertainty in our analysis. One is external, and represents flow of jobs from the customers or the previous stage of the production process. Within the system, we model uncertainty from manufacturing operations. Operator variability leads to variable processing times and is due to rework, tooling problems and fatigue. Machine variability arises from random breakdowns and variable times for diagnosing and fixing breakdowns. Specifically, we investigate the net impact of these sources of variability on the output of the line and WIP levels built in the buffers. The simulations provide the sensitivity of the configurations to uncertainty in the manufacturing environment. In general, the more complex and larger the cycle - more uncertainty creeps in from machine variability (maintenance problems) and operator variability (quality problems).

Despite the additional costs in the form of capital and training for line 'A', from a human factors perspective, there are some positive aspects of line 'A'. Hackman & Oldham (80), have argued that enriching job content leads to more work satisfaction, work effectiveness and enhanced system performance. The question then is whether these intangible benefits justify the higher capital and additional operating costs arising from the increased variability from longer cycle experienced in line 'A'.

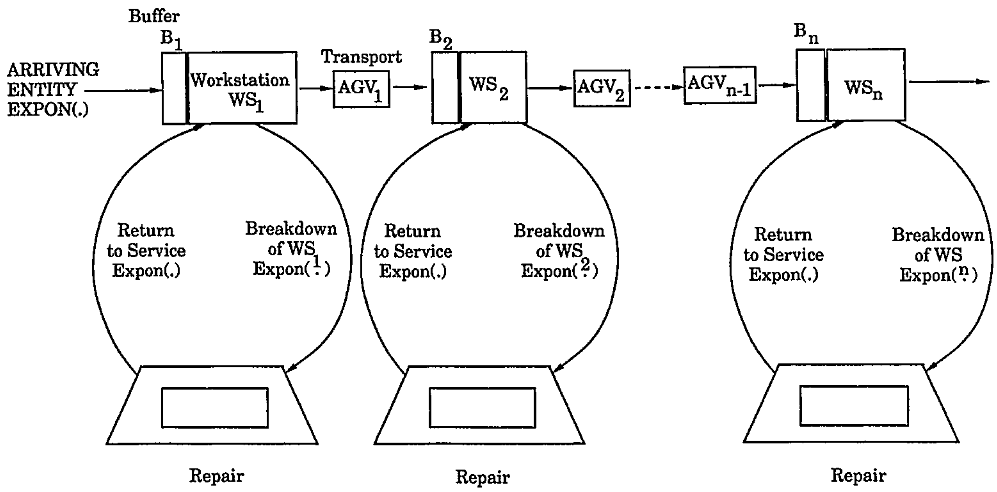

Figure 2: The Manufacturing System

Thus the configurations we examined, are of interest to managers from maintenance, operation, investment and human factors perspective. The model we develop captures the effects of breakdowns, operator variability and dependencies between work stations. We briefly describe the model next.

THE PRODUCTION PROCESS AND MODEL

The configuration choices are modelled as shown in Fig. (2). The choices modelled are based on data from an actual auto assembly facility. Data has been masked for confidentiality. Job entity arrival at the first work-station is governed by an exponential law. There is a finite capacity buffer in front of every work-station. After completing the required operation at a given work-station, the job is transported and stored in the buffer awaiting operation at the following work-station. In the first phase of our investigation, the processing time at each work-station and transportation time are assumed to be deterministic. We relax these assumptions later. The job moves from one work-station to the next in a serial fashion.

The process is also prone to machine failures and there is shutdown of station during repair. The failures are assumed to be random and have random repair time. When a machine breaks down while processing a job, the job is removed and placed at the head of the line in the incoming buffer, and gets priority as soon as the repair is over.

Simulation Experiment:

The production process is modelled through SLAM II [Pritsker, A. A. B. (86)]. The network flow diagram for SLAM II for a typical work-station is shown in Fig. (3). The CREATE node generates job entities according to an exponential distribution. The entities flow to the buffer in front of the first work-station - AWAIT1 node and then move on to the first work-station AWAIT2 node. This is done to achieve a blocking operation; a new job from the buffer is released only after the processing is complete at the work-station. If the AWAIT1 node is full, then the new arrivals are lost. The job after completing processing at the work-station moves on to AWAIT3 node via a FREE node; and then to AWAIT4 for completing the transportation. The process is repeated thereafter.

The first phase of the study had 1944 (3x6x3x6x6) sample points. We investigated the functional relationship between output and input variables. The motivation was to estimate the marginal effects of the input variables on output variables as impacted by configuration rather than use the functional relationship to predict throughput or work-in-process inventory.

ANALYSIS OF RESULTS

Throughput and Number of Work Stations: Linear regression results using step wise regression on a SAS package are reported in Table 1. The most important variable to explain the variability in throughput is the number of workstations and the estimated equation is:

$$\text{THROUGHPUT} = 3775 - 156 * \text{WORKSTATIONS} \tag{1}$$

Clearly as the number of work-stations increases, the throughput of the line decreases. Thus 156 is the production loss for every work-station increase in the length of the line. For instance, line 'B' would net on an average 468 = (156 * 3) less than line 'A'.

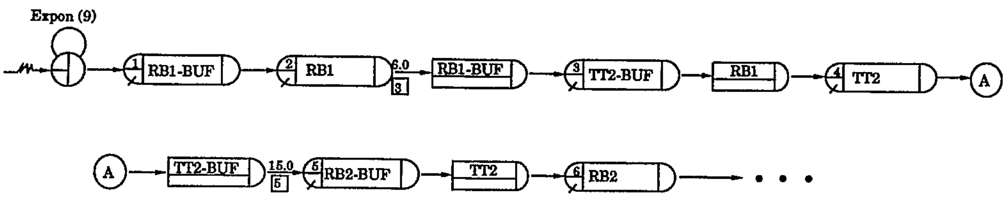

Figure 3: Network Flow Diagram

Input parameters are varied at the following levels:

(i) Number of Workstations: 3,6,12

(ii) Process Time at Workstation: 24,26,28,30,32,34 for 3 W.S.; 12,13,14,15,16,17 for 6 W.S.; 6,6.5,7,7.5,8,8.5 for 12 W.S.

(iii) Buffer Size 3,6,9

(iv) Mean Time Between Failures (MTBF) 900,1800,2700,3600 4500, 5400 seconds

(v) Mean Time to Repair (MTTR) 30,60,90,120,150, 180 seconds

Thus a sample data point obtained at the end of the 8 hour shift has the information on throughput, WIP, number of workstations, buffer size between work-stations, MTBF, MTTR, average occupancy of buffers. As far as possible, running conditions of the simulation were standardized so as to provide meaningful comparison.

Hence the expected throughput as predicted by our model is as follows for the various configurations:

LINE A	:	3307	(100%)
LINE B	:	2839	(85%)
LINE C	:	1903	(61%)

TABLE 1: THROUGHPUT (DEPENDENT) VERSUS INPUT VARIABLES

Regression	Constant	WSN	MTTR	MTBF	Adjusted R^2
ONE VARIABLE	3775	-156	--	--	0.83
TWO VARIABLE	3884	-156	-1.04	--	0.84
THREE VARIABLE	3814	-156	-1.04	0.02	0.84

The best two variables and three variable regressions were estimated as:

THROUGHPUT = 3884 - 156 * WORKSTATIONS - 1.04 MTTR (2)

THROUGHPUT = 3884 - 156 * WORKSTATIONS - 1.04 MTTR + .02 MTBF (3)

Note that in (2) and (3) the signs of the coefficient are as expected for MTBF and MTTR. The effect of MTTR is higher than MTBF on throughput.

A similar study to study the effect of the input variables on WIP inventory is under investigation for the three configurations, and will be reported later.

SENSITIVITY ANALYSIS

From the above analysis, it is clear that as we increase the reliability (MTBF) of the work-stations, throughput will increase. However, we wanted to pick which configuration had the highest gains of throughput. To answer this question, we ran 3 separate regressions (for each of the lines 'A',' B', & 'C') and the results are summarized in Table 2 and the regression lines depicted in Fig. 4. Note that the slope is maximum for configuration B (six station lines). This means, that the marginal benefits of increase in reliability by increasing MTBF is higher for the six station lines than either for the 3 station line (configuration 'C') or 12 station line (configuration 'A'). Thus we conclude that for every unit increase of MTBF, from a value at say 5000, the increase in throughput for the three designs will be:

Configuration	Marginal Gains in Throughput per Unit Increase of MTBF
Line 'B'	150 ↑
Line 'A'	100 ↑
Line 'C'	50 ↑

This phenomenon can be explained as follows. Two opposing forces are at play here. First, is the negative impact of serial work-stations. As the number of work-stations increases, more serial dependencies cause throughput to fall. However, this loss is counterbalanced by the gains in production due to higher MTBF. Initially as the number of work-stations increases from 3 to 6, the MTBF effect dominates. However, as the number of station increases, the effect of MTBF gains decreases and the serial effect takes over. This suggests that the gains from better maintenance and increased MTBF are highest for intermediate level of the number of stations.

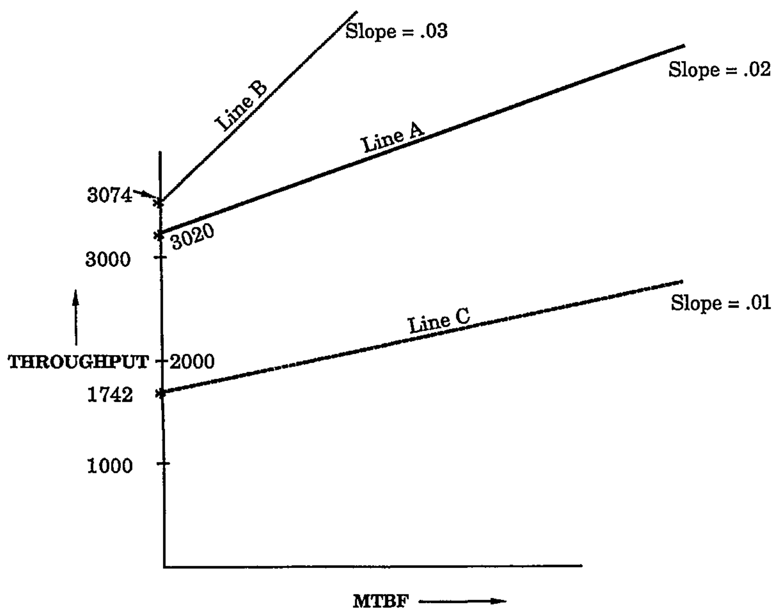

Figure 4: Sensitivity of MTBF on Throughput for Various Work Stations

TABLE 2: SENSITIVITY OF MTBF ON THROUGHPUT FOR VARIOUS DESIGNS

WSN	CONSTANT	MTBF	$ADJR^2$
3	3020	0.02	0.18
6	3074	0.03	0.08
12	1742	.01	0.10

CONCLUSIONS

The investigations done till date on the comparative performance of the three configurations highlighted the robustness of each design to maintenance problems and serial dependencies. Initial results indicate that despite higher capital and operational costs, line 'A' has the maximum throughput. However, the marginal effects of improved reliability is lower for 'A' than 'B', which in turn is higher than 'C'.

The next phase of the study will capture the effect of variable process times at each station, an investigate the impact of throughput on decreased task fractionation, but with higher operator variability. This will assess the impact of human factors - where on one hand longer cycles can lead to positive motivational effects - but come at the price of variability. The opposing effects of higher variability and reduced serial dependencies will be thoroughly analyzed from throughput and WIP perspectives.

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G.G. Hegde is an Assistant Professor of Business Administration at the Katz Graduate School of Business of the University of Pittsburgh. His research interests are in the areas of production and quality management. His publication has appeared in the European Journal of Operational Research.

P.R. Tadikamalla is an Associate Professor of Business Administration at the Katz Graduate School of Business of the University of Pittsburgh. His research interest lies in simulation methodology and production/operations management. He has published more than 20 articles in various professional journals.

K. Ramamurthy is a doctoral candidate in the MIS area at the KGSB. His research focus is on identifying factors affecting the implementation of information systems, with special reference to advanced manufacturing systems.

Sunder Kekre is an Assistant Professor of Industrial Administration at Carnegie-Mellon University, Pittsburgh, Pennsylvania. Dr. Kekre's research is interdisciplinary. Currently, he is investigating flexibility in vehicle assembly systems, coordinating manufacturing, marketing, and design engineering to exploit flexibility. His work has been published in the Journal of Manufacturing Systems, Operations Research, Interfaces, IIE Transactions, the Journal of Accounting and Economics, and the Journal of Manufacturing and Operations Management.