Performance Trade-offs in Mixed-model S-line and U-line Balance Designs

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Abstract: Mixed-model production lines provide operating efficiencies to meet today's market requirements of low cost and high customization. In this research we will evaluate the performance of mixed model S-shaped U-shaped lines in terms of efficiency and inventory requirements. A discrete-event simulation software, Pro-model, will be used to simulate several mixed-model U-shaped lines under varying operating conditions. The results indicate that U-line performed better in terms of output compared to S-lines. However, the work-in-process inventory level is higher for all the U-line configurations compared to the corresponding S-line configurations. We found that the Sum of Cycle time Violation (SCV) objective function has only a limited prediction power, indicated by a correlation of -0.58 with the throughput performance.

Keywords: Mixed Model Lines, S and U Line Balancing, Cellular Manufacturing

I. Introduction

Today's market requirements for product variety at low cost have made many manufacturing plants position their processes towards mass customization. At face value the term mass customization is an oxymoron. However, the word mass implies using an efficient processing mode such as an assembly line, while at the same time providing customization by processing multiple items through the line. The notion of using mixed-model lines to achieve greater customization started in the 1960's, at least in the automobile industry [11].

Womack et al. [13] in their study of the global automobile industry entitled "The machine that changed the world" have described the Toyota Production System. In their study they show how Toyota has achieved greater customization and at the same time contained costs through efficient use of resources and elimination of waste by effectively using economies of scope rather than economies of scale. Mixed-model U-Lines have been described by authors such as [4] [5] [7] [9] as the special type of cellular manufacturing used in just-in-time (JIT) production systems by Japanese manufacturing. Miltenburg [6] indicates that in cellular manufacturing dissimilar but sequentially related machines are clustered near each other to meet the processing needs of a family of products, while in JIT each cluster or cell is further improved by moving employees, workstations, or both into a U-shaped configuration that increases the possible interaction among employees.

According to Miltenburg [6], when setup times are negligible, U lines are run as mixed-model lines where each station is able to produce any product in any cycle. He also reports that the average U line has 10.2 machines and 3-4 operators and that productivity improved by an average of 76%, work-in-process dropped by 86%, lead-time shrank by 75%, and defective rates dropped by 83%.

Thomopoulos [11] first studied the mixed-model serial assembly line balancing problem. He found that starving and blocking at work stations were caused by variation in station times owing to varying processing times each model requires at each station. According to Gosh and Gagnon [3], the mixed model line balancing problem consists of a) assigning tasks to work stations to meet production line design criteria such as minimum number of work stations and work-in-process inventory, and b) sequencing the product models to be produced on the line in order to meet demand requirements and to reduce work load imbalances between work stations.

This research focuses on comparing straight lines and U-lines for a mixed-model assembly line operation. We developed balancing solutions for 24 Thomopoulos problem instanced both for Serial lines and U-lines. Then, we simulated these balancing solutions in an event-based process modeling simulation software, ProModel, to analyze the relationships among various performance measures: labor utilization, work-in-process inventory, degree of blockage, and throughput.

II. Mixed Model Problem for Study

We considered a three product and 19 task mixed-model line discussed by Thomopoulos [11]. Table 1 shows the processing time requirements and precedence relationships.

Table 1 Nineteen Task Mixed-model Line balancing Problem

	Model Task Time			Model Precedence		
Task	A	B	C	A	B	C
Task1	5	0	10			
Task2	4	8	12			
Task3	0	2	4			
Task4	4	0	0			
Task5	2	2	2			
Task6	2	0	0	1		
Task7	4	5	6	1.2	2	1,2
Task8	0	5	5		2	2
Task9	4	3	2	2	2,3	2,3
Task10	0	0	2			3
Task11	3	3	3	4,5	5	5
Task12	1	3	5	7	7,8	7,8
Task13	1	0	1	11		11
Task14	2	2	2	11	11	11
Task15	7	10	15	9,12	9,12	9,12
Task16	0	1	0		3	
Task17	5	5	0	13	11	
Task18	3	5	3	14	14	14
Task19	4	3	0	14,17	14,17	

For this problem set, we obtained balancing solutions for cycle times of 15, 16, 17, 19, and 20 seconds and for various product sequences and product mix. We used SALOME [8] for serial lines and ULINO [8] for U-lines to obtain initial balancing solutions and then improved these initial solutions using Great Deluge search heuristic [2] with Sum of Cycle time Violation (SCV) objective function [12]. Altogether, we had 24 different line-balancing problems resulting from combinations of different cycle times, product sequences, and product mixes. Figure 1 shows examples of Serial line and U-line balancing solution for a cycle time of 19 seconds, product sequence of A-B-C, and product mix of 1:1:1. Figure 1 illustrates that four workers are used with worker 3 working on the front of the line and also on the back of the line. The U-line layout has seven locations for holding work-in-process inventory.

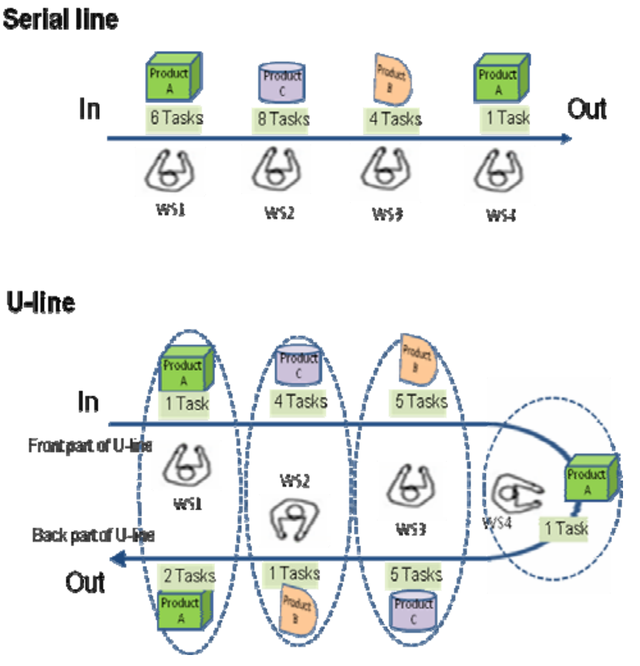

Figure 1 Serial and U Line Layout examples for a T1-15_ABC model

To further understand the problem, Gantt charts of operator time were developed, as shown in Figure 2. It indicates that the constraint for the problem is not simply operator time, but a combination of worker availability, part blockage, and starving. Figure 2 illustrates that blockage and starving occur in various places throughout the U-line. This difference results in different effective cycle times: 23 second per unit for serial line and 20 seconds per unit for U-line.

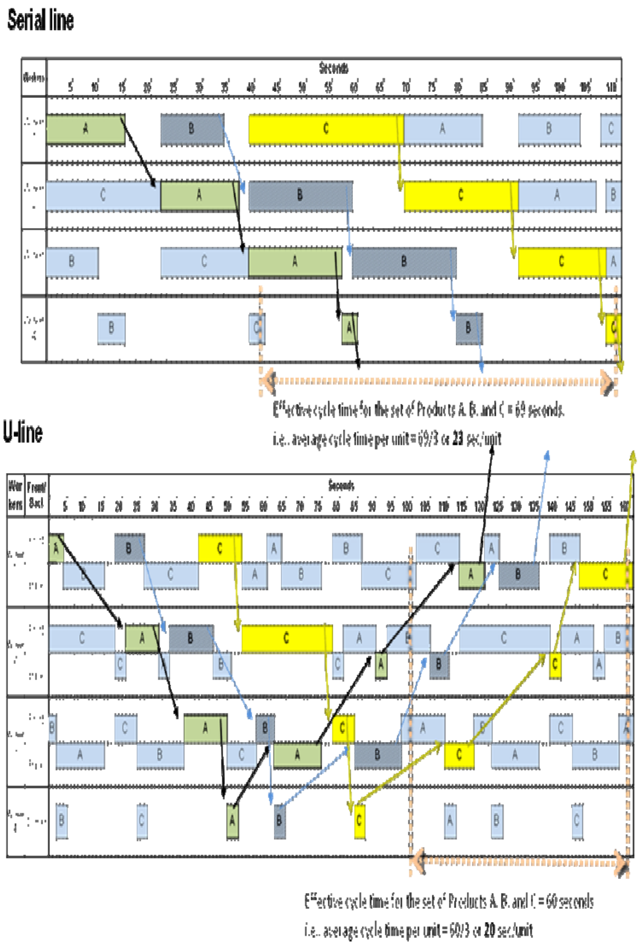

Figure 2 Gantt chart for workers based on a U-line Solution for T-15_ABC Problem

The unpredictable patterns of blockage and its complex effect on efficiency are not easily studied using Gantt charts. Therefore, we chose the simulation methodology to investigate the behavior of mixed-model U-lines and capture more performance measures than just the efficiency measure typically used in the line balancing literature.

III. Research Hypotheses

We developed hypotheses regarding the relative performances of serial liens and U-lines for labor utilization, work-in-process inventory level, the degree of blockage, and production throughput. For mixed-model lines with the same number of workers with no-buffer WIP, we hypothesize:

H1: U-lines have higher labor utilization than Serial lines
(because of two sources of work (front and back) for a worker on a U-line)

H2: U-lines have more work-in-process inventory than Serial lines
(because of more places to park WIP inventory)

H3: U-lines experience less blockage than Serial lines.
(because of worker's self-buffering between front and back tasks)

H4: U-lines produce more output than Serial lines.
(because of less blockage and higher labor utilization)

IV. Simulation results and Implications

We used a paired t-test to compare serial vs. U-lines (Table 2). The results indicate that U-lines performed better in terms of labor utilization and throughput compared to S-lines. However, the work-in-process inventory level is higher for all the U-line configurations compared to the corresponding S-line configurations. This result indicates performance trade-offs.

Table 2. Comparison of S-line and U-line: Various performance dimensions

	Utilization (%)	Work-in-Process (units)	Blockage (%)	Output (%)
Serial line (Avg. N=24)	79.96	**3.669**	**11.28**	91.43
U-line (Avg. N=24)	**82.95**	5.317	12.57	**94.22**
$H_{Alt(hypothesized)}$	$m_s<m_u$	$m_s<m_u$	$m_s>m_u$	$m_s<m_u$
T-value	2.95	11.23	-0.62	2.41
p-value	0.004	0.000	0.729	0.012

We also analyzed how well the SCV objective function predicts the performance of production lines. The Pearson correlation between the SCV values of 48 S- and U-balances with the throughput performance was found to be -0.579 (p=0.000). This moderate correlation between the SCV and throughput indicates that the objective function used in finding the balancing solutions may not be an accurate indicator of actual performance of the production lines. In a mixed-model production line, the variability of processing times across product models creates unpredictable blockage and starving, which the SCV cannot accurately capture.

V. Concluding Remarks

This study focuses on comparing the performance of U-lines and Serial lines for a mixed-model production, using ProModel simulation software. The work-in-process inventory level is higher for U-lines where work-in-process inventory items go through more places (front and back part of the line) than a serial line. We hypothesized that the more work-in-process inventory would lead to less blockage in U-lines: However, we found that the degree of blockage is not significantly different between U-lines and S-lines. The U-lines are indeed more efficient with respect to labor utilization and throughput, as the literature suggested.

We are in the process of expending this study using a different problem set with more number of tasks and product models. Future research can include the impact of worker's travel time, cost of labor training, and stochastic task times.

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