Proceedings of the 2014 Winter Simulation Conference
A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, eds.

A NOVEL WORK-SHARING PROTOCOL FOR U-SHAPED ASSEMBLY LINES

Srinath Sriram
Michael E. Kuhl
Brian K. Thorn

Industrial and Systems Engineering Department
Rochester Institute of Technology
81 Lomb Memorial Drive
Rochester, NY 14623, USA

Andres L. Carrano

Industrial and Systems Engineering Department
Auburn University
3301 Shelby Center
Auburn, AL 36849, USA

ABSTRACT

A U-shaped production line is considered one of the most flexible designs used by companies to adapt to varying production conditions and to implement lean concepts. Similarly, work-sharing allows for cross-training of a flexible workforce while achieving high levels of worker utilization. This paper proposes a new protocol for U-shaped assembly lines that relies on work-sharing principles and on an adaptation of bucket brigades to cellular environments. Discrete event simulation is used to maximize throughput while determining buffer locations and buffer levels for each worker. This model is validated with a physical simulation and then tested with industry data. The results show the protocol enables a high level of throughput and worker utilization for the manufacturing cell while capping the maximum amount of WIP in the system. The proposed protocol is generalizable with respect to the number of stations, processing times, types of processes, and worker velocities.

1 INTRODUCTION

Assembly lines date back to early in the twentieth century, when formal recognition was achieved, initially by means of the patent filed by Ransom Olds, the founder of Oldsmobile, in 1901, but more importantly because of Henry Ford who perfected the concept in 1913 by adding conveyor belts. Since then, the concept of simple assembly lines has evolved in an effort to adapt to the ever increasing sophistication of production systems.

In today's competitive world, manufacturing companies are constantly trying to increase their productivity with the same amount of resources. They also find the need to make their systems flexible to counter external demand variability, while dealing with internal process variability. U-shaped production lines, where workers handle one or more machines, are widely used in cellular manufacturing and lean production systems. The main advantages derive from a flexible line with cross-trained workers capable of adapting to changes in demand and production pace. In addition, reducing idle time of a limiting resource is the key to increased productivity (McClain, Schultz, and Thomas 2000). When labor is the limiting resource in a production facility, work-sharing is one way to reduce idle time.

In this paper, we introduce a novel work-sharing protocol for U-shaped assembly lines. We present an overview of the protocol development methodology in which we utilize discrete event simulation models to evaluate and provide feedback to facility an iterative design process. In addition, we present a simulation-based optimization procedure to determine the parameter settings of the newly designed protocol under various system configurations. Finally, we present an experimental performance evaluation to investigate the performance of the protocol for U-shaped assembly lines.

2 BUCKET BRIGADE, MODIFIED WORK-SHARING, AND CELLULAR BUCKET BRIGADE PROTOCOLS

The idea that new line layouts and worker allocations could improve productivity has been investigated in literature. Miltenburg (2001) found that when U-lines replaced linear assembly lines (without adding additional resources), the productivity improved by an average of 76%, WIP dropped by 86%, lead time shrunk by 75%, while defective rates dropped by 83%. Ghirann (2012) proposed that employing workers that shared their work and helped each other in a floating (unassigned) way allowed for ease of task redistribution and line redesign. Our research effort is based on three distinct work-sharing protocols that are available in literature: Bucket Brigades (Bartholdi and Eisenstein 1996), Modified Work-Sharing (Montano et al. 2007), and Cellular Bucket Brigade (Lim 2011).

A bucket brigade (BB) protocol (Figure 1) proposed by Bartholdi and Eisenstein (1996) uses a set of rules that workers follow while working on the assembly line and that achieves balance while converging to a discrete set of preemption points. A forward rule asks the workers to continue processing his job until your successor preempts you (or until you reach the end of the line) while a backwards rule asks you to walk back and take over the job from your immediate predecessor in the line.

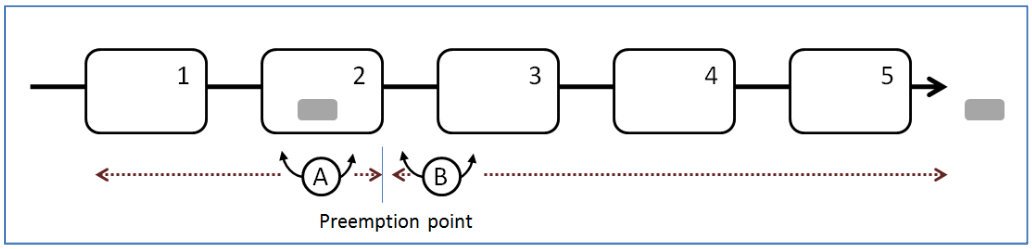


Figure 1. Bucket brigade used in an assembly line (5 tasks, 2 workers).

The modified work-sharing (MWS) protocol (Figure 2) introduces a slight modification of the bucket brigade protocol. Montano et al. (2007) suggest placing 'buffers' or inventory locations between 'zones'. Each worker primarily works in his zone – a series of workstations for which the worker is cross-trained. Instead of being preempted by the worker's successor, the worker drops off the job in a buffer located at the beginning and end of each zone. Each buffer has a pre-assigned control limit for each worker. Thus, each worker can only deposit up to a certain fixed number of parts in each buffer. When the number of parts in the buffer is equal to the control limit, the worker (whose control limit has been reached) crosses over into the next downstream zone and continues processing until another buffer is reached or the worker is preempted. If the inventory level of the buffer at the beginning of his zone is zero, the worker crosses to the zone upstream to preempt the job that from his/her predecessor is working on. Figure 2 illustrates these zones with control levels represented as C_{ij}, (for buffer location i and operator j). Inventory buffers are located between workstations so that the probability of a worker being blocked by a downstream worker is reduced. An infinite buffer ($C_{ij} = \infty$) tells the worker that he/she has to drop off the part at that buffer every time irrespective of the number of parts in that buffer, while a zero buffer ($C_{ij} = 0$) tells the worker to ignore the buffer and continue processing the part downstream. Hence, values of C_{ij} between 0 and ∞ tell the worker to drop off the part at the buffer, till the buffer reaches its control limit. And once the control limit is reached, he/she has to proceed assembling the part downstream from the buffer. The MWS protocol was found to be a good alternative for use in high labor turnover environments where fully cross trained operators are often found and tool replication does not represent a major investment.

The design depicted in Figure 3 shows the cellular bucket brigade (CBB) protocol introduced by Lim (2011) which allows workers to exchange jobs across the line. The idea of workers crossing over to work on stations across the aisle is one of the main advantages of the U-line and allows for increased flexibility in the assembly line balancing problem as a larger set of worker to station assignments are possible

(Miltenburg 2001). The CBB protocol requires that the cell be arranged in the shape of a "U", such that the total length of the line, L, is divided into two halves, with an aisle width of *w*. The two workers process the parts downstream with a velocity of v_1 and v_2, and exchange parts across the aisle when the reach tasks that are opposite each other in the line.

The current literature on the performance of cellular bucket brigades under stochastic processing times and discrete tasks is limited. The available research (Bartholdi and Eisenstein 1996; Bartholdi, Bunimovich, and Eisenstein 1999; Lim 2011) assumes continuous assembly lines where exchanges can be made instantaneously at any point in time at any location. Some papers (Bartholdi, Eisenstein, and Foley 2001; Montano et al. 2007) consider discrete tasks in a limited way. To investigate these issues, we surveyed three local manufacturing facilities and found that: (i) a quality related best-practice is not to divide a task between two workers, and (ii) it is necessary to consider variations in task-times as inherent to the assembly line.

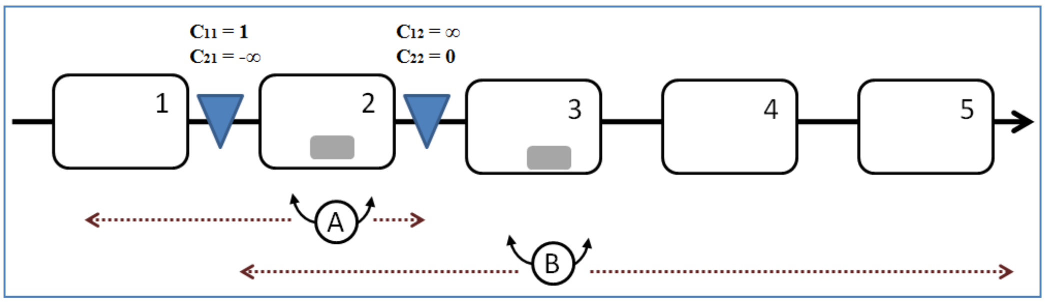


Figure 2. Modified work-sharing protocol (5 stations, 2 workers (A=1, B=2), 2 buffer control levels).

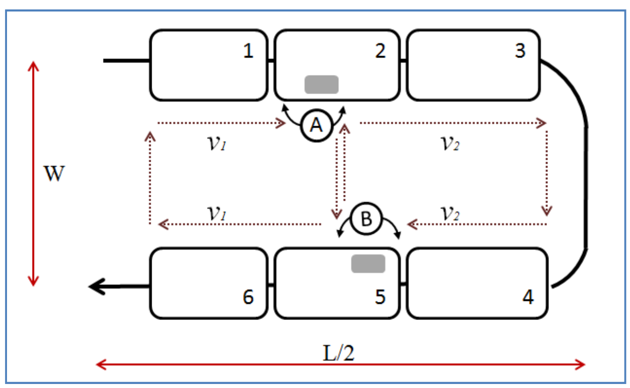


Figure 3. Cellular bucket brigade protocol (5 stations, 2 workers (A and B)).

Based on this literature and our survey of industry, the goal of this work is to design a U-line work-sharing protocol that will incorporate the advantages of bucket brigades, modified work-sharing, and cellular bucket brigade considering discrete tasks and stochastic task completion times.

3 METHODOLOGY

The methodology for designing and evaluating a work-sharing protocol for U-line assembly systems was conducted in two stages (see Figure 4). Stage 1 utilizes an iterative process to develop a production control protocol, and Stage 2 involves conducting a rigorous set of experiments to evaluate the protocols.

3.1 Stage 1: Protocol Design and Development

In Stage 1, an iterative process using simple table-top simulations to gain a preliminary understanding of how work-sharing systems behaved in U-lines resulted in a hypothesis for a new protocol. This hypothesis suggested that it was possible to combine the benefits of both the CBB system and the MWS protocol by including buffers with control levels in a U-line that followed a modified behavior of the cellular bucket brigade protocol.

Once a promising protocol was identified, a discrete event simulation model of the U-line assembly system was constructed. Initial simulation experiments were conducted on the set of promising protocols. Feedback from the simulation models were used to refine the protocols and parameter values. Through an iterative process of simulating the protocols and revisiting the protocols to make changes based on observations, a set of rules for the new protocol was empirically obtained. These rules resulted in a hybrid of MWS and CBB protocols. The hybrid MWS-CBB protocol is shown in Figure 5. This proposed protocol consists of the decisions and the ensuing behavior (e.g. paths to be taken) by the set of $\{i=1,\ldots,W\}$ workers each with as set of buffer control rules, $\{C_{ij};\ i \in W,\ j \in T\}$ and in an assembly U-line with as set of $\{j=1,\ldots,T\}$ tasks,. Given that the system is assumed to have T discrete tasks that cannot be split, the protocol provides four cases to consider when a worker completes a task. (An illustrative example of the protocol is shown in section 3.3).

The final step in Stage 1, is to validate the simulation model and test the protocol. A physical simulation of the system was conducted in an industry-like setting. A U-shaped assembly line was setup in the Toyota Production Systems Laboratory at Rochester Institute of Technology consisting of 24 tasks, 2 workers, and U-line using roller conveyors and flow racks. The experiment was approved by the university IRB committee, and graduate students that volunteered were trained and coached on the assembly process and protocol. Data collected from this experiment were used to calculate output variables such as the number of preemptions and exchanges, throughput, and times when these preemptions and exchanges occurred. The worker velocities, aisle width, length of the line, worker walking velocities, and waiting times were physically recorded and measured. The values for these variables resulting from this experiment were fed into the simulation model to obtain values of outputs such as throughput and utilization. These output values were then compared with the output obtained experimentally to ascertain the validity of the simulation model. By statistically comparing the data, and understanding the anomalies, we concluded that the model was valid (for details, see Sriram 2013).

3.2 Stage 2: Experimental Performance Evaluation of Protocol

To enable the experimental performance evaluation, we designed a set of simulation scenarios to be representative of manufacturing assembly operations. Based on our survey of manufacturers coupled with information from archival literature, we made the following assumptions:

- Each workstation consists of a specified number of discrete tasks;
- Workers can only be preempted only after a task is completed;
- The average work content (in term of average task completion time) is the same for all tasks;
- Task times are distributed based on a gamma distribution; and
- Walking velocity is a normal distribution with a mean of 1.34m/sec, and a variance of 0.37m/sec. (Daamen and Hoogendoorn 2006).

A survey of three local manufacturing companies that provide industrial technology solutions, manufacturing medium to high variability products to serve the power and medical electronics industries was conducted. The survey included a total of thirty two U-lines located within five different facilities in the state of New York. The data collected is presented in Table 1. For worker velocities and velocity ratios, actual data was not available, and expert opinion was collected from company representatives.

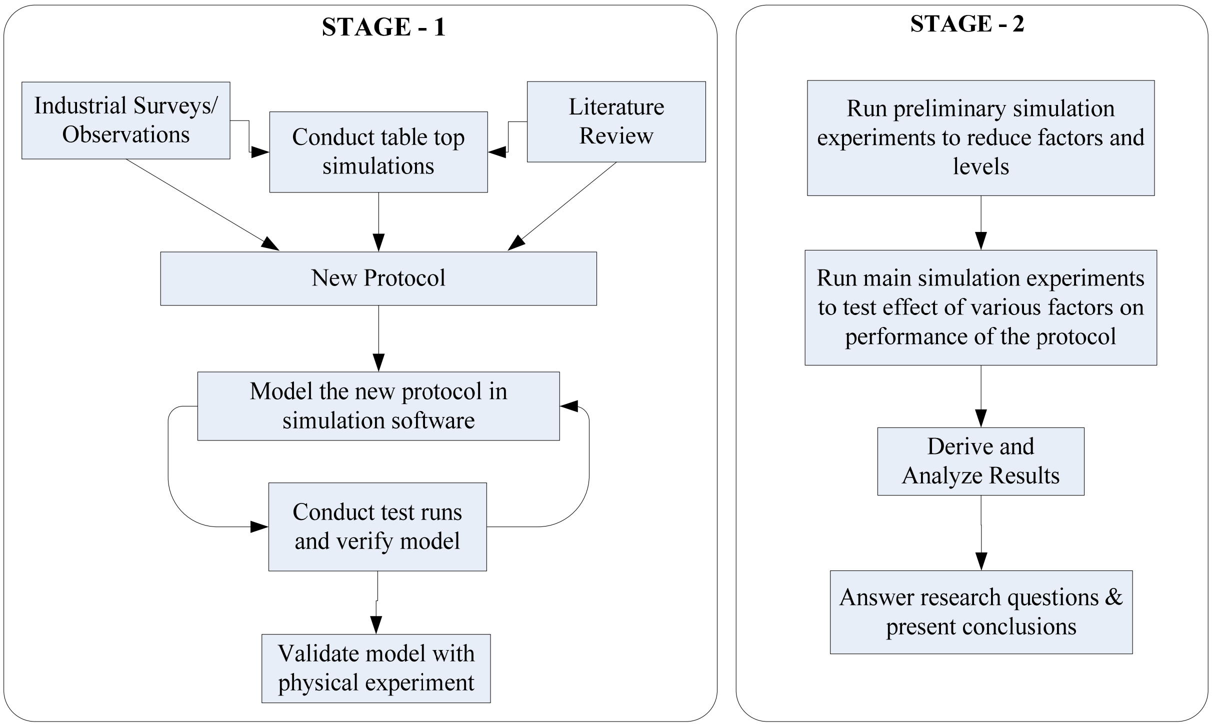


Figure 4. Schematic of the steps used in the methodology.

Hybrid MWS-CBB U-Line Protocol

Given a U-Line with W workers, T tasks, and Buffer Control Rules, $\{C_{ij};\ i \epsilon W,\ j \epsilon T\}$;

Case 1: Worker *i* completes task *j*,
If worker *i′*, is at task *T-j*, and buffer is full, perform CBB exchange;
Else if, worker *i′* is awaiting transfer at task *j*+1, perform MWS preemption, worker *i* goes to start of *j* and follows Control Rule;
Else, worker *i* follows Control Rule.

Case 2: Worker *i*, when following Control Rules going backward, encounters worker *i′* at task *j*,
Wait for *i′* to complete task *j*, perform MWS preemption, *i* continues with task *j*+1, *i′* goes to start of *j* and follows Control Rule.

Case 3: Worker *i*, completes task *j*, Control Rule says continue, but *j*+1 is occupied by worker *i′*,
Wait for *i′* to complete task and then continue with task *j*+1.

Case 4: Worker *i* completes task *T*,
Deposit completed product in finished goods inventory, and go to task 1.

Figure 5. Hybrid MWS-CBB U-Line protocol.

Table 1. Data from 32 U-lines compiled from three local manufacturing companies.

Characteristic	Range			
	Minimum	Maximum	Average	Median
Number of discrete tasks per line	7	25	15	21
Number of workers per line	2	4	2.7	3
Length (L)	6.09m (20 ft)	12.18m (40 ft)	-	12.18m (40 ft)
Worker velocities (v_i)	Varied depending on product, training, tools			
Worker velocity ratios (fastest: slowest)*	1:1	1.5:1	-	1.2:1
Aisle width (a)	1.22m (4 ft)	1.83m (6 ft)	1.52m (5 ft)	1.52 m (5 ft)

* Expert opinion, actual data not available

The discrete event simulation model was constructed utilizing the ARENA simulation software. To determine the various buffer control quantities that would maximize throughput, we applied a simulation-based optimization approach using the Optquest for ARENA optimization software. We utilized the following model:

Variables:
C_{ij} (Integer) = Control level for worker *i* at buffer associated with Task *j*
Objective:
Maximize *Throughput*
Subject to:
$0 \le C_{ij} \le 2 \qquad \forall\, i \in W$ and $\forall\, j \in T$

Since we are primarily interested in the performance of this system in steady state, the simulation model was analyzed as a non-terminating systems using the method of replication-deletion. The warm-up period for the system was determined using inspection. After the warm-up period, the system statistics are cleared and data collection for the analysis period of the replication begins.

The design of experiments and corresponding results are presented in section 4.

3.3 Example: Application of the Hybrid MWS-CBB U-Line Protocol

Consider an example: a two worker – twenty four tasks U-line (grouped into six stations) and with a buffer between each station (Figure 6). Worker A starts a new job (task 1) from raw material, while worker B starts from task 13 with a part that has been processed in tasks 1 through 12. Let workers A and B have constant velocities v_1 and v_2, respectively, such that $2v_1 = v_2$. Under deterministic conditions, by the time worker A completed task 4, B would have completed task 20. Then, workers A and B, who each have a control limit of 1, would drop off their parts in buffers B2 and B6, respectively, walk back to their previous buffers (raw material B1 for A, and buffer B2 for B), grab the part from that buffer, and would continue processing their jobs forward. Next time, when A completes task 4, B would have completed task 12. Now, A would drop off the job in buffer B2 (as this buffer has been previously emptied by worker B), and would walk back again to pick up a new part from B1; and worker B will continue to task 13. Next time when B completes task 20, A will more or less have completed task 4, and as there is a part in each buffer B2 and B6, there will be a CBB exchange (across the aisle) right after task 20 and task 4. The workers then cross over to the buffer across the aisle and continue processing the jobs that were deposited in the buffers.

The idea of expanding the total number of buffer locations from one between consecutive stations to one between consecutive tasks is captured by using buffer notations B_j, representing the location of the buffer between tasks j-1 and j. There will be a total of T+1 buffers. The flowchart starts from worker i completing task j. After finishing task j, the worker checks task T-j (which is diagonally opposite to task j) for the presence of another worker. If there is another worker waiting at task $T-j$, worker i exchanges jobs (CBB protocol type exchange) with that worker. Now, if in the example considered previously, if the workers had stochastic processing times, and there was a cycle when B performed at a slower pace than A, then a scenario as shown in Figure 7 is possible. Suppose, at the point of exchange, $j = 6$, and T = 24; worker A at $j = 6$ will check if there is another worker at task $T-j = 24 - 6 = 18^{th}$ task. Worker B at $j = 18$ would have, in turn, checked at task $T-j = T-18 = 6^{th}$ task. This symmetric nature of the protocol is to be noted. If there was no other worker at task $T-j$, or if the other worker was still processing the job at task $T-j$, then worker i will check if there was another worker waiting at task j+1 to MWS preempt worker i. If not, worker i will then check the buffer level, similar to the MWS protocol. The CBB protocol takes precedence over the MWS protocol here. The premise behind this precedence is that a MWS preemption causes walking back, whereas a CBB exchange does not, which could increase efficiency and throughput by minimizing unproductive walk-back time.

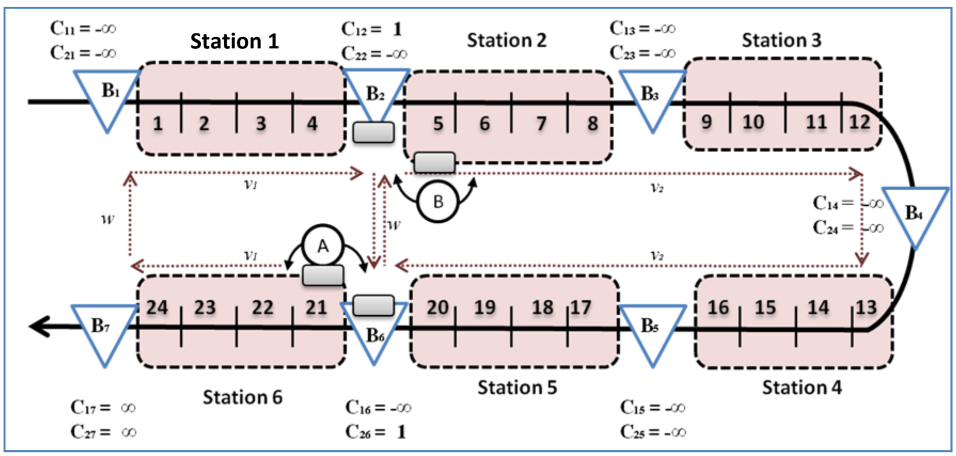


Figure 6. Example case: Two worker – twenty four tasks U-line following the new protocol, with $2v_1 = v_2$, when the worker velocities are constant, and a steady state is reached.

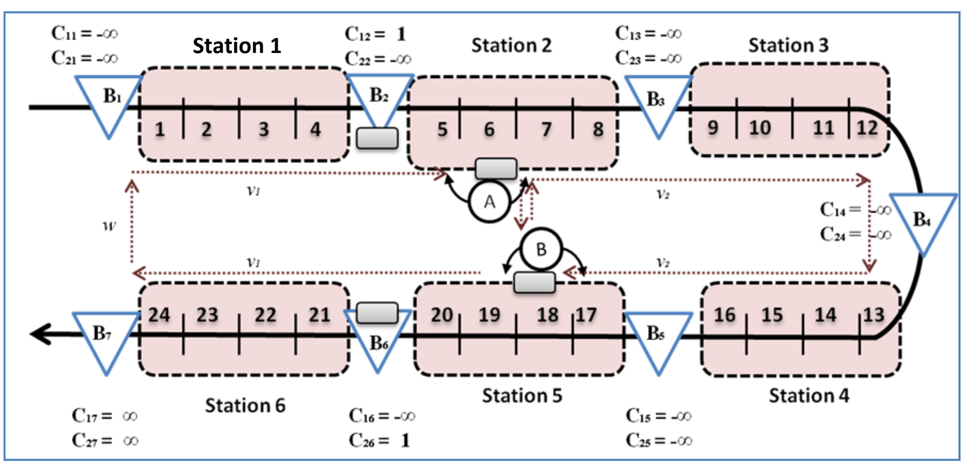


Figure 7. Example case: Workers A and B exchange at tasks 6 and 18 when worker B lags behind due to variable processing times.

4 EXPERIMENTATION, RESULTS, AND ANALYSIS

In Stage 2 of the methodology, the first set of experiments were comprised of a screening experiment to determine which (if any) of the four primary factors were significant. The four experimental factors are displayed in Table 2. The full factorial experiment consisted of 16 treatment combinations that were applied to system configurations consisting of 8 and 16 tasks, respectively. In each configuration, there were two workers and the process time followed a gamma distribution with a mean of 60 seconds and a coefficient of variation (CV) as displayed in Table 2.

Table 2: Screening experiment levels.

Label	**Factors**	**Levels**		**No. of Levels**
		-1	**1**	
A	Gamma distribution CV	0.3	1	2
B	Length	20	40	2
C	Aisle width	0.04	0.10	2
D	$v_1{:}v_2$	1:1	1:1.5	2

For each model and for every treatment level combination, variables (control levels C_{ij}, for every i and j), constraints (C_{ij} = 0,1,2 for every i and j; fixed treatment level combinations), and an objective function (Maximize Throughput) were provided to OptQuest. OptQuest was used to run 50 replications of one set of C_{ij} values by following a branch and bound method. The average throughput of these 50 replications was used to obtain the next set of C_{ij} values until an optimal set of C_{ij} values for which the average throughput is maximum were reached.

From the results of the screening experiments, it was concluded that the main effects of aisle width and length of the line are insignificant within the range observed, thus can be eliminated. For further experiments, the length of the line was set to 40 ft and the aisle width to 10% of the total line length, as these were consistent with the observed industry values (Table 1).

Since two factors were eliminated in the screening experiment, we chose to increase the number of levels for the main experiment. An additional level of the coefficient of variation of the task time distribution was added (CV=0.4). The CV = 0 essentially represents the deterministic case, CV = 0.4 represents a medium variability level, while CV = 0.8 represents high variability. The extreme values of the velocity ratios were kept the same, and an additional level (1.25:1) was added. In addition, the scope was expanded to consider 24 tasks and a 24 tasks model was developed. The factors and associated factor levels are displayed in Table 3.

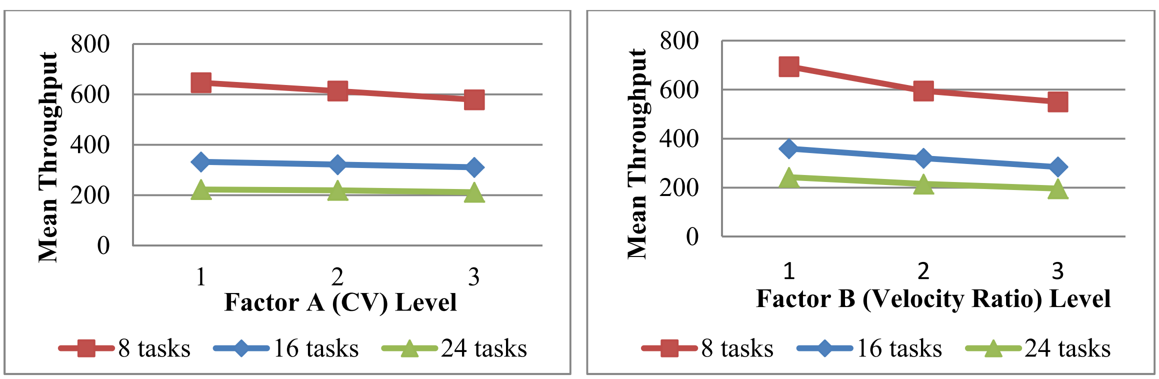
Table 3. Factors and levels for the secondary experiment.

Label	**Factors**	**Levels**			**No. of Levels**
		1	***2***	***3***	
A	Gamma distribution CV	0	0.4	0.8	3
B	$v_1{:}v_2$	1:1	1:1.25	1:1.5	3

The results show that, regardless of the number of tasks, each of the factors main effects and the corresponding two-factor interaction were significant at the 0.01 level of significance. The results show in Table 4 for the 16 task case demonstrate the effectiveness of the protocol to yield a high level of throughput and efficient utilization of the two workers. The average throughput from 50 replications using the hybrid protocol can be compared to the theoretical upper bound for the mean throughput of the system given the respective worker velocities. The values of Table 4 indicate that, although the gap between the upper bound and the average throughput widens as the variation in task processing time and differences in worker processing time increase, the values of throughput and utilization are relatively high. The results for the 8 and 24-task cases show similar behavior. Figure 8 illustrates the main effect of the coefficient of variation (CV) and worker velocity ratio on the mean throughput of the system. Additional detailed results of the experimental evaluation can be found in Sriram (2013).

Table 4. Experimental results of average throughput and worker efficiency for the 16-task case.

Treatment Combinations			**Mean Throughput Upper Bound**	**Hybrid Protocol Average Throughput**	**Worker 1 utilization**	**Worker 2 utilization**
	A CV	**B** v_1:v_2				
1	0	1:1.00	375.00	374.00	99%	99%
2	0	1:1.25	337.50	333.00	97%	99%
3	0	1:1.50	312.00	288.44	95%	92%
4	0.4	1:1.00	375.00	358.10	95%	95%
5	0.4	1:1.25	337.50	318.68	97%	92%
6	0.4	1:1.50	312.00	286.86	98%	88%
7	0.8	1:1.00	375.00	345.26	92%	92%
8	0.8	1:1.25	337.50	307.66	95%	88%
9	0.8	1:1.50	312.00	277.58	96%	84%



(a) (b)

Figure 8. (a) Main effects of Factor A, gamma distribution CV; and (b) Main effects of Factor B, worker velocity ratio.

Finally, in attempt to quantify the benefit of including modified work-sharing aspects (buffers and buffer control rules between tasks), we compared the case of the optimal buffer sizes to the case where the buffer size was equal to 0. The later system would thus contain only the aspects of the cellular bucket brigade applied in a discrete task system. From this experiment, we observed that the hybrid MWS-CBB protocol had average throughput across all treatment level combinations that was approximately 1% greater than a protocol following a CBB behavior. This marginal improvement in throughput is achieved mainly by the avoidance of blocking of faster workers by slower workers.

5 CONCLUSIONS AND DISCUSSION

A new hybrid MWS-CBB protocol is proposed and preliminary experimentation demonstrates its effectiveness in providing the advantages of work-sharing and CBB protocols. The protocol addresses the practical manufacturing issues of discrete tasks, variable processing times, and practical aisle widths. The simulation experiments indicate that protocol is able to achieve good performance with respect to throughput and worker utilization. This protocol performed at least as well as the cellular bucket brigade protocol, improving the throughput by an average of 1%, and a maximum of 14%. The hybrid protocol is generalizable with respect to the number of stations, processing times, types of processes, worker velocities, and choice of task distribution. The experiments conducted and analyzed were for the industrial data collected specifically for this work. The observations made from the analysis could change significantly if different worker velocities are chosen, and if the application required different distributions of velocities. However, the generalized protocol and model presented in this paper are robust to handle these changes. Future work should expand the experimentation into lines with continuous tasks as well as into lines with more than two workers. Also, mathematical proofs of behavior convergence with respect to the location and type of exchanges should be pursued.

REFERENCES

Bartholdi, J. J., L. A. Bunimovich, and D. D. Eisenstein. 1999. "Dynamics of Two- and Three-worker 'Bucket Brigade' Production Lines." *Operations Research* 47(3): 488-491.

Bartholdi, J. J., D. D. Eisenstein, and R. D. Foley. 2001. "Performance of Bucket Brigades when Work is Stochastic." *Operations Research* 49(5): 710-719.

Bartholdi, J. J., and D. D. Eisenstein. 1996. "A Production Line That Balances Itself." *Operations Research* 44(1): 21-34.

Daamen, W., and S. P. Hoogendoorn. 2006. "Free Speed Distributions for Pedestrian Traffic." *Transportation Research Board 2006 Annual Meeting* 06-1666.

Ghirann, G. 2012. *The basics of self-balancing processes: True lean continuous flow*. Taylor & Francis Group.

Lim, Y. F. 2011. "Cellular Bucket Brigades." *Operations Research* 59(6): 1539-1545.

McClain, J. O., K. L. Schultz, and L. J. Thomas. 2000. "Management of Work-sharing Systems." *Manufacturing and Service Operations Management* 2(1): 49-67.

Miltenburg, G. J. 2001. "One-piece flow manufacturing on U-shaped production lines: a tutorial." *IIE Transactions* 33(4):303-321.

Miltenburg, G. J. 2001. "U-shaped Production Lines: A Review of Theory and Practice." *International Journal of Production Economics* 70(3): 201-214.

Montano, A., J. R. Villalobos, M. A. Gutierrez, and L. Mar. 2007. "Performance of Serial Assembly Line Designs Under Unequal Operator Speeds and Learning." *International Journal of Production Research* 45(22): 5355-5381.

Sriram, S. 2013 "A Novel Work-Sharing Protocol for U-Shaped Assembly Lines." M.S. Thesis, Department of Industrial and Systems Engineering, Rochester Institute of Technology.

AUTHOR BIOGRAPHIES

SRINATH SRIRAM is a graduate of the Master of Science in Industrial Engineering program from the Industrial and Systems Engineering Department at Rochester Institute of Technology. He currently works for Qualitrol, an independent subsidiary of Danaher, as a process engineer and one of the company's lean business system leaders. His e-mail address is ssriram@qualitrolcorp.com.

ANDRES L. CARRANO is the Philpott-West Point Stevens Associate Professor in the Department of Industrial and Systems Engineering at Auburn University in Alabama. His research interests are in various aspects of manufacturing, including modern production line designs, additive manufacturing, surface metrology and pallet logistics. He can be reached at carrano@auburn.edu.

MICHAEL E. KUHL is a Professor in the Department of Industrial and Systems Engineering at Rochester Institute of Technology. His research focuses on simulation modeling, analysis, and optimization of industrial and service systems with application including manufacturing, healthcare, cyber security, and project management. He has served as Program Chair for the 2013 Winter Simulation Conference and Proceedings Editor for the 2005 Winter Simulation Conference. His e-mail address is Michael.Kuhl@rit.edu.

BRIAN K. THORN is an Associate Professor in the Department of Industrial and Systems Engineering at Rochester Institute of Technology. His research interests include design and analysis of sustainable systems, and the applications of sustainable engineering. His e-mail address is bkteie@rit.edu.