International Journal of Business, Human and Social Sciences
ISSN: 2517-9411
Vol:9, No:6, 2015

Unreliable Production Lines with Simultaneously Unbalanced Operation Time Means, Breakdown, and Repair Rates

S. Shaaban, T. McNamara, S. Hudson

***Abstract*—**This paper investigates the benefits of deliberately unbalancing both operation time means (MTs) and unreliability (failure and repair rates) for non-automated production lines. The lines were simulated with various line lengths, buffer capacities, degrees of imbalance and patterns of MT and unreliability imbalance. Data on two performance measures, namely throughput (TR) and average buffer level (ABL) were gathered, analyzed and compared to a balanced line counterpart. A number of conclusions were made with respect to the ranking of configurations, as well as to the relationships among the independent design parameters and the dependent variables. It was found that the best configurations are a balanced line arrangement and a monotone decreasing MT order, coupled with either a decreasing or a bowl unreliability configuration, with the first generally resulting in a reduced TR and the second leading to a lower ABL than those of a balanced line.

***Keywords*—**Average buffer level, throughput, unbalanced failure and repair rates, unequal mean operation times, unreliable production lines.

I. Introduction

When designing a production line in series, a major issue is where to place operators who have different working speeds. In the past, a "balanced" line design was perceived as leading to the best efficiency, where the operator average service times at each workstation are the same. So, research has focussed on how best to achieve this type of design.

In real life however, processing times have been shown to be non-identical at different workstations, even in automated lines [1]. In manual unpaced lines, the operators at each station can work at different mean work times (MTs) for several reasons: some are intrinsic to the person: their physical capacity, or their motivation, and some are dependent on the task: it might be a complex task, or just simply that the amount of work along the line cannot be distributed evenly in terms of time. In view of this, the allocation of operators along an unbalanced line to improve efficiency is one that needs to be investigated.

Another source of fluctuation that all production lines are likely to face is that of downtime due to machine failure, with all the accompanying consequences for performance.

S. Shaaban is with ESC La Rochelle, La Rochelle, 17024, France (phone +33 (0) 546 51 77 00; e-mail: shaabans@esc-larochelle.fr).
T. McNamara and S. Hudson are with the ESC Rennes School of Business, Rennes, 35065, France (e-mail: tom.mcnamara@esc-rennes.com, sarah.hudson@esc-rennes.com).

This paper therefore, aims to investigate the twin issues of workstation mean service time imbalance and unreliability in unpaced serial production lines. We present conclusions from simulation experiments, which show that imbalance does not always lead to deterioration in performance, and in some cases can actually enhance line efficiency when compared to a corresponding balanced line system.

The structure of this article is as follows. First, the relevant literature is reviewed. Next, the motivation and objectives of the study are presented. Subsequent sections discuss the methodology and experimental design and give the simulation results and analysis. The results are then summarised and discussed in the last two sections.

II. Literature Review

One of the early findings in the study of mean time imbalance for *reliable lines* suggested that placing workstations with higher average processing times at both ends of the line can lead to improved performance in terms of throughput (TR), compared to the balanced line. This effect was termed the "bowl phenomenon" [2]. There has been continued interest in testing this phenomenon over the years [3]-[5], which show varying degrees of support for this conclusion, with most recently a move towards looking at patterns of imbalance rather than focusing purely on the bowl phenomenon [6], [7]. Reference [8] showed that when the cost of work-in-process (WIP) was high, the optimal allocation that maximises revenue is to assign a higher work load to the front of the line, with a corresponding increased allocation of buffers as one moved towards the end of a line.

In general, most recent studies do seem to be showing that MT imbalance does not necessarily lead to deterioration in performance, and can actually provide improvement to efficiency in terms of total elapsed time, waiting or idle time (IT), TR and average buffer level (ABL).

Most of this research tended to investigate reliable lines, with the assumption of zero breakdowns. The area of non-automated, unpaced *unreliable lines*, however, is a rather less researched field and forms the main part of the literature reviewed here.

Early on in the study of these systems, formulae for predicting proper WIP levels were derived by [9] for lines having random failure rates, random repair rates, as well as both random processing and failure rates. He concluded that for lines where all stations are subject to the same limiting elements, i.e. station downtime or slow mean processing times, buffers are of limited value in maintaining efficiency, and that moving towards a balanced configuration of stations with near equal MTs will be a better strategy for improved efficiency.

In an investigation of unreliable lines having unequal mean processing rates, [10] developed mathematical expressions for a two-stage serial line incorporating a production cost function. The line studied contained intermediate buffers, with both stations being subject to failure. The study found that as the line becomes more unbalanced, fewer buffers are needed. It was also found that buffers are most effective at recuperating lost production in lines having unbalanced production rates but equal failure / repair rates, and least effective in lines with unbalanced production rates and equal failure rates but unequal repair rates.

A two-station flow line with limited buffers and unbalanced MTs was analysed by [11]. Station operation and repair times were considered to be phase-type distributed, with exponentially distributed time between failures. A Markovian numerical method was developed that could predict the average number of pieces in the system, the utilization rate of each station and TR. He found that the effect of increased buffer capcity on output and the average number of jobs in the system decreases as the line becomes more unbalanced, resulting in an increase in the breakdown rate of the first station. The results also showed that output rises as buffer capacity increases, but at a decreasing rate. He concluded that it was best to strive for a balanced line, either by reducing the machine failure rate, or increasing the rate of repair.

Reference [12] introduced a decomposition method for predicting the output of a production line having random service times. The service, failure and repair rates were exponentially distributed. Maximum TR and minimum WIP solutions were obtained for MT unbalanced lines having 3 and 4 stations with fixed buffers. Concerning TR, the study concluded that in case a) a reduction in average station availability results in a more pronounced bowl phenomenon. For case b), an increase in the repair rate leads to a higher TR with the bowl allocation of work still being optimal. For c) a bowl arrangement of MTs is still superior where failure rates increase as one moves down the line. For d) the bowl MT pattern is considerably less beneficial, though not eliminated altogether.

It was also found that for a high (98.9%) average station availability, an increasing order of MTs generates the lowest levels of WIP.

Heuristics for determining minimal buffer levels in unreliable production lines having exponential, Erlang, or Rayleigh distribution of processing times were developed by [13], in which cases of both equal and unequal machines were explored.

A model combining simulation with queuing analysis was developed by [14] for the purpose of determining the optimal mean time to repair (MTTR) rates to maximize TR. Processing and repair rates were exponentially distributed with any distribution for the mean time between failures (MTBF). Results for a 6-station line with unbalanced processing rates indicate that output is maximized when mean processing rates and failure rates are equal and when larger (faster) repair rates are assigned to stations with small upstream and downstream buffers. They also suggested that resources (repair technicians and personnel) should be assigned in a manner that results in a balanced line.

Reference [15] studied assembly systems in which the machines were subject to random jamming, i.e. a machine stoppage due to a problem with processing a part. A genetic algorithm was developed for the optimal allocation of buffers in terms of TR. Systems of 5, 7, 8, 10 and 15 stations with varying station jamming rates and inter-stage buffer limits of 1 to 15 units were analysed. The authors found that the buffers generally mimic the jamming rates of their respective stations, i.e. high jamming rates are associated with high BC. For example, for a line with 5 stations, descending jamming rates lead to an overall descending BC allocation and an inverse bowl allocation of jamming rates is associated with the placement of more buffers in the centre of the line.

Reference [16] developed a method that uses an established list of generic procedures and incorporates a simulation model to analyse the buffer allocation problem with regards to TR. They studied lines of 3, 4 and 5 stations with varying machine reliability across the stations, exponential and Erlang service times, exponential failure rates, and exponential or Erlang-*m* repair rates**.** They extended their investigation to lines having different MTs, with the following patterns of joint MT and machine unreliability imbalance:

- An increasing (/) MT pattern, combined with a balanced and bowl allocation of machine failure rates (the most reliable station is located in the middle of the line).
- A decreasing (\) MT arrangement, combined with a decreasing (\) order of failure rates (the most reliable machine is at the end).

They found that in over 98% of the cases studied, the optimal buffer allocation resulting in maximum TR was arrived at for exponential service and repair times. As the number of stations increases, the efficiency of the method decreases.

Reference [17] developed a method for identifying bottlenecks due to station downtime (DT) caused by random failures in production lines with fixed cycle times.

A study by [18] investigated lines of 5, 10, and 15 stations with fixed buffers of 2, 5 and 10 units with the aim of observing protective capacity. The bottleneck station had an MT of 10 and was placed consecutively at the beginning, middle and end of the line. The MTs of the remaining stations were set in turn at 9.5, 9, 8, 7, and 6 minutes. This resulted in protective capacity levels of 5%, 10%, 20%, 30, and 40%. The variability of the operating time coefficient of variation (CV) was set at four levels with all stations subject to downtime. Cycle time was used as the primary measure of performance.

In the above study, it was found that the location of the constraint does not greatly influence line performance. She observed that the greatest influence on cycle times is WIP, with higher WIP levels resulting in higher cycle times and a reduction in the effectiveness of protective capacity.

Increasing protective capacity reduces cycle times, but at a diminishing rate. Increasing CV has a degrading effect on the line. Another contribution of the above mentioned study is the development of a regression equation for predicting throughput, given the line length, CV and protective capacity.

An investigation by [19] furnished a method for estimating the production rate of stochastic flow lines subject to random failure that could also account for scrapping of material.

Reference [20] studied the optimal allocation of buffer in terms of a business decision with the goal of maximising profit, which in turn needs to take into account the net present value (NPV) of the capital invested. The numerical formulae developed showed that for an 8- station MT balanced line the highest NPV is obtained by an inverted BC bowl allocation. In the case of more reliable lines, a corresponding lesser amount of BC is needed to provide similar results.

A study by [21] developed a queuing network model to analyze manufacturing systems, subject to breakdown. Their method was capable of estimating individual station TR rates for a proposed new product line.

Reference [22] analyzed lines having exponential, Erlang and Rayleigh MTBF and MTTR. They developed heuristics to determine the smallest amount of BC (lean buffering) that results in TR levels that were 95, 90, or 85% of a theoretical maximum TR. Lines of 2, 3, 5 and 10 stations were investigated. They found that higher levels of BC are linked to higher CV values for MTBF / MTTR, and that buffer sizes increase as a function of line length, but at a decreasing rate.

Research by [23] looked at unreliable serial production lines with random processing times and unequal buffers in order to determine the optimal allocation of workload among the stations. Numerical results showed that as stations become more unreliable, a bowl arrangement (i.e. slower stations at both ends of the line and faster stations in the middle) becomes more advantageous with regards to output rate. It was also found that, for the three station line, as the unreliability of stations increases towards the end of a line, the optimal degree of workload imbalance (again, with regards to output) also increases. As far as optimal WIP levels are concerned, it was generally found that a decreasing allocation of workload is beneficial in unreliable lines.

An investigation by [24] studied lines subject to downtime having Weibull, gamma and lognormally distributed MTBF and MTTR rates, with the objective of determining the minimum amount of BC needed to maintain a desired TR level Expressions were obtained for the efficient buffer sizes needed to achieve a minimum TR level. They found that the buffer levels are more sensitive to the CV of MTTR than to the CV of MTBF.

A paper by [25] provided an analytical method for predicting the TR of serial lines in which the production rate of each machine was exponential, but the up and down times followed the Gamma, Weibull, or log normal distribution. The authors stated that a limiting factor of the procedure is that for it to be effective, the total buffer capacity must be sufficient enough to satisfy the longest downtime of all the machines in the line.

A procedure for predicting line production rate and identifying bottleneck stations was developed by [26]. Their method was applied to a 6-station line having cycle times that were both equal and unequal (inverted bowl, increasing and decreasing allocations), as well as other lines with unequal buffers, unequal reliability rates, unequal reliability rates and buffers combined, and finally unequal reliability, buffers and cycle times.

A study of unreliable stochastic production lines having probabilistic operation times and limited buffers were performed by [27]. Approximation methods were developed for the efficient allocation of buffers and determining adequate levels of initial stock (“pre-buffering”).

A review by [28], which provides a thorough discussion of the literature on automated production systems with finite buffers and subject to machine failure, is an indication of the continued interest in the area.

A simulation study on serial production lines having a constraining station and in which the frequency and duration of downtimes was varied was conducted by [29]. Their findings indicated that the ideal operating condition is to have a full buffer immediately adjacent to a station about to experience a failure. Where failure occurred and the preceding buffer was less than full, the likelihood of starving a constraining station increases.

Reference [30] found that operating models tend to overestimate TR rates for asynchronous unbalanced lines subject to failure, and developed a heuristic method to correct a production system’s TR estimate.

A cross comparison of production lines subject to failure was carried out by [31], finding that quite often total TR values do not vary by much between lines, even though the failure rates among the stations could vary.

III. Motivation and Objectives

This study focuses on lines having two sources of imbalance, caused by allowing MTs and reliabilities (both failure and repair rates) to differ amongst stations. The two other variables, buffer capacity (BC) and coefficients of variation (CV) are set so that all buffers along the line have the same capacity and all CVs are held equal.

The main objective of this investigation is to assess the performance of unreliable unpaced lines for four joint patterns of MT and reliability imbalance in terms of two performance indicators, throughput and average buffer level. The research questions to be addressed are as follows:

1. What is the influence of the joint patterns of MT imbalance and unequal failure and repair rates on the performance of the unreliable lines simulated compared to that of a balanced line?
2. Which of the patterns simulated lead to the best performance?
3. What are the relative contributions of imbalance patterns, imbalance degree, line length and buffer capacity to performance?

IV. Research Methodology and Experimental Design

In view of the fact that no mathematical method can currently assess the more realistic serial flow lines typically reported with positively skewed operation times, computer simulation was viewed as the most suitable tool for this study, The unbalanced line behaviour was studied using a ProModel Version 7.5 coded manufacturing simulation model.

A. Factorial Design

A full factorial design was deemed to be the most apt for the current study. For the specific line studied, the independent variables used were:

- Line length (number of stations), **N**.
- Capacity of each buffer, **BC.**
- Degree of unbalanced service time means **DI** - the percentage difference in MT between successive stations.
- MT imbalance pattern, **MTP**.
- Unreliability (failure and repair rates) pattern, **URP**.

In order to simulate more realistic processing times, a right shifted Weibull distribution was employed. An investigation by [32] reported that the unpaced service times found in real practice are more closely described by this probability function.

B. Performance Measures and Statistical Tools

Two performance measures were used in this investigation, namely; line throughput (**TR**), and the average buffer level (**ABL**) for the whole line. Evidently, the study goals are to find conditions which increase TR and reduce ABL.

The following statistical techniques were used to analyse the TR and ABL data:

- Generalized Linear Model analysis (GLM) to identify the relative contributions of the independent variables to the dependent variable performance.
- Multiple comparisons with control using Dunnett's t-test for comparison of the performance of unbalanced lines to the balanced line control.
- Independent sample t-tests to compare performance of the two line lengths.

Statistical analyses were carried out using SPSS v20.

C. Simulation Run Parameters

In order to ensure that observations are as close to normal operating behaviour as possible, a sufficiently long warm up period is desired. The method used here is in accordance with the technique proposed by [33], i.e. to run a preliminary simulation of the system under investigation, choosing and observing one output variable, in this case WIP as they suggest. To ensure that observations are independent, minimum autocorrelation values of between -0.20 and +0.20 should be achieved [34]. A trial procedure has established that after an initial run of 20,000 minutes, acceptable autocorrelation values of between -0.163 and +0.153 were achieved, leading to the conclusion that adjacent blocks were relatively independent. In order to ensure more valid statistical data, this initial warm up period was extended to 30,000 minutes. All data collected during the first 30,000 minutes were discarded and a production run of 20,000 minutes, broken down into 50 blocks (subruns) of 400 minutes each was gathered. This resulted in mean TR and ABL values being calculated every 400 minutes and the average (grand mean) of these 50 mean values was computed with the objective of reducing serial correlation to a negligible level.

Finally, in order to generate an identical event sequence for all the designs and highlight the contrast amongst the configurations, all the experiments used the same random number seed.

D. Failure and Repair Parameters

In unreliable lines the stations are subject to random mechanical failure and repair events. An empirical study by [35] found that an exponential probability distribution with regard to both the mean time between failures (MTBF) and mean time to repair (MTTR) appeared to be representative of what is found on actual manufacturing systems.

The failure rates used for this investigation were 0.2. 0.3 and 0.4 breakdowns per minute per station, resulting in MTBF values of 25.00, 16.67 and 12.50 minutes respectively, with the repair rates being 0.04, 0.06 and 0.08 repairs per minute, meaning that MTTRs were 5.00, 3.33 and 2.50 minutes respectively (the same rates used by [23]). As a result, line efficiency in terms of MTBF was fixed at 83.33% for all the three levels of reliability (for example, the line efficiency for high reliability is MTBF 25 / (MTBF 25 + MTTR 5 = 83.33%)). Each production run of 20,000 minutes has been broken down into 16,000 minutes of uptime and 4,000 minutes of down time.

Both the failure and repair rates were assumed to be independent, exponentially distributed random variables, and as suggested by [36], all downtimes were considered to be usage and not clock based. Table I shows the 3 levels of reliability, together with their failure & repair rates, MTBF & MTTR, total downtime, and line efficiencies for MTBF & MTTR.

E. Line Design

The line lengths investigated are N = 5 and N = 8. Values of buffer capacity are allocated evenly between all work stations and are set at BC = 1, 2 and 6 units.

The CV for each station is fixed at 0.274. The mean processing time base case was set at 10 minutes. The degrees of mean time imbalance (the percentage deviation from the mean time) are set at DI = 2%, 5% and 12%, with 2% reflecting a slight imbalance and 12% representing a relatively high degree of imbalance. With regards to the shape of mean time imbalance, four different patterns were considered in Table I.

- A monotone decreasing order (\) - going from slowest to fastest operators/stations.
- A monotone increasing order (/) - going from fastest to slowest operators/stations.
- An inverted bowl arrangement (^) - the slowest operators placed in the middle.

- A bowl arrangement (V) - the fastest operators positioned in the middle.

As for machine reliability imbalance, four different configurations were considered:

- A monotone decreasing order (\) – stations get less reliable as you move down the line.
- A monotone increasing order (/) – stations get more reliable as you move down the line.
- Inverted bowl arrangement (/\) – most reliable station in the middle of the line.
- A bowl arrangement (V) – least reliable station in the middle of the line.

TABLE I
FAILURE & REPAIR RATES, MTBF & MTTR, DOWNTIME, AND MTBF & MTTR LINE EFFICIENCIES FOR 3 LEVELS OF RELIABILITY

Reliability Level	Failure Rate	MTBF (Minutes)	Repair Rate	MTTR (Minutes)
High (H)	0.20	25.00	0.04	5.00
Medium (M)	0.30	16.67	0.06	3.33
Low (L)	0.40	12.50	0.08	2.50
Reliability Level	Number of Events (Failures) in 20,000 Minutes	Total Down-time (Minutes)	Line Efficiency (MTBF)	Line Efficiency (MTTR)
High (H)	800	4	83.33%	16.67%
Medium (M)	1,2	4	83.33%	16.67%
Low (L)	1,6	4	83.33%	16.67%

Table II depicts the 4 unreliability imbalance patterns:

TABLE II
UNRELIABLE IMBALANCE PATTERNS

Unreliability Imbalance Pattern	N = 5	N = 8
Decreasing (\)	H M M M L	H H M M M M L L
Increasing (/)	L M M M H	L L M M M M H H
Inverted Bowl (/\)	L M H M L	L L M H H M L L
Bowl (\/)	H M L M H	H H M L L M H H
Balanced (--)	M M M M M	M M M M M M M M

Unreliability imbalance patterns utilized for N = 5 and 8

Tables III-V portray individual stations' MTBF and MTTR figures for N = 5 and TR data for an unreliable 5-station line with BC = 1, 2, 6 units and DI% of 2, 5, 12 for 4 jointly unbalanced MT and unreliability patterns, and a balanced line counterpart, *p< 0.05, **p<0.01, ***p<0.001. 8 for each of the 4 unreliability imbalance patterns as shown in Table III.

Overall, 2 line lengths x 4 levels of BC x 3 levels of DI x 4 MT imbalance patterns x 4 unreliability imbalance patterns = 384 cells were simulated.

V. EXPERIMENTAL RESULTS AND DATA ANALYSIS

In the following sections, two sets of tables of results for the two performance indicators, TR and ABL are displayed, followed by a presentation of the statistical analyses performed and an interpretation of the results, allowing us to address the research questions identified in section III.

The mean values (grand mean of 50 measurements) of the performance indicators TR and ABL are presented in Tables VI-IX respectively. For ease of reading, TR values which are higher, and ABL values that are lower than the values for the balanced line are marked in bold, indicating positive performance. Significant differences with the balanced control line (--) analysed using Dunnett's t-test are indicated with asterisks.

A. Analysis of the Effects of Imbalances

In order to test the effects of MT & reliability imbalance patterns, multiple comparisons with control using Dunnett's t-test were performed on the TR and ABL data at each level of N, BC and DI, comparing them to corresponding means obtained for the balanced control. Those results differing significantly from the balanced line value are flagged with asterisks in Tables VI-IX.

While occasional improvements in terms of TR were generated by some of the four jointly unbalanced MT and unreliability patterns, none was found to be statistically significant, so a balanced arrangement is the best as far as TR is concerned.

TABLE III
MTBF & MTTR VALUES

	N=5			
	Station 1		Station 2	
Unreliability Imbalance Pattern	MTBF	MTTR	MTBF	MTTR
Dec. (\)	25.00	5.00	16.67	3.33
Inc. (/)	12.50	2.50	16.67	3.33
Inv. Bowl (/\)	12.50	2.50	16.67	3.33
Bowl (\/)	25.00	5.00	16.67	3.33
Balanced (--)	16.67	3.33	16.67	3.33
	Station 3		Station 4	
Unreliability Imbalance Pattern	MTBF	MTTR	MTBF	MTTR
Dec. (\)	16.67	3.33	16.67	3.33
Inc. (/)	16.67	3.33	16.67	3.33
Inv. Bowl (/\)	25.00	5.00	16.67	3.33
Bowl (\/)	12.50	2.50	16.67	3.33
Balanced (--)	16.67	3.33	16.67	3.33
	Station 5			
Unreliability Imbalance Pattern	MTBF	MTTR		
Dec. (\)	12.50	2.50		
Inc. (/)	25.00	5.00		
Inv. Bowl (/\)	12.50	2.50		
Bowl (\/)	25.00	5.00		
Balanced (--)	16.67	3.33		

Station MTBF and MTTR values for 4 unreliability imbalance patterns (N = 5).

For TR, the best jointly unbalanced pattern is a bowl-shaped MT configuration in conjunction with an inverted bowl-shaped unreliability arrangement. In many cases, it performs as well as the balanced line. On the other hand, the descending

MT order pattern coupled with the descending reliability patterns is in general amongst the worst configurations in terms of TR.

TABLE IV
MTBF & MTTR VALUES

Unreliability Imbalance Pattern	N=8			
	Station 1		Station 2	
	MTBF	MTTR	MTBF	MTTR
Dec. (\)	25.00	5.00	25.00	5.00
Inc. (/)	12.50	2.50	12.50	2.50
Inv. Bowl (/\)	12.50	2.50	12.50	2.50
Bowl (\/)	25.00	5.00	25.00	5.00
Balanced (--)	16.67	3.33	16.67	3.33
Unreliability Imbalance Pattern	Station 3		Station 4	
	MTBF	MTTR	MTBF	MTTR
Dec. (\)	16.67	3.33	16.67	3.33
Inc. (/)	16.67	3.33	16.67	3.33
Inv. Bowl (/\)	16.67	3.33	25.00	5.00
Bowl (\/)	16.67	3.33	12.50	2.50
Balanced (--)	16.67	3.33	16.67	3.33

Station MTBF and MTTR values for stations 1 - 4 for 4 unreliability imbalance patterns (N = 8)

TABLE V
MTBF & MTTR VALUES

Unreliability Imbalance Pattern	N=8			
	Station 5		Station 6	
	MTBF	MTTR	MTBF	MTTR
Dec. (\)	1.67	3.33	16.67	3.33
Inc. (/)	16.67	3.33	16.67	3.33
Inv. Bowl (/\)	25.00	5.00	16.67	3.33
Bowl (\/)	12.50	2.50	16.67	3.33
Balanced (--)	16.67	3.33	16.67	3.33
Unreliability Imbalance Pattern	Station 7		Station 8	
	MTBF	MTTR	MTBF	MTTR
Dec. (\)	12.50	2.50	12.50	2.50
Inc. (/)	25.00	5.00	25.00	5.00
Inv. Bowl (/\)	12.50	2.50	12.50	2.50
Bowl (\/)	25.00	5.00	25.00	5.00
Balanced (--)	16.67	3.33	16.67	3.33

Station MTBF and MTTR values for stations 5 - 8 for 4 unreliability imbalance patterns (N = 8)

For ABL, a descending MT order combined with the descending unreliability arrangement patterns consistently show significant improvements over the balanced line, followed in the second place by a descending MT pattern coupled with a bowl unreliability order. The ascending order pattern, together with either an ascending or bowl unreliability patterns perform significantly worse than the control in the vast majority of cases.

B. Analysis of the Effects of the Various Factors

Generalized linear model (GLM) analysis was carried out on the data in order to ascertain the relative contributions of the independent variables, namely N (line length), BC (buffer capacity), DI (degree of MT imbalance), MTP (MT pattern) and URP (unreliability pattern) on the dependent variables. Best fit was found for a Gaussian distribution for TR and ABL. The results for TR are below in Table X. To save space, only TR results for the main effects are shown. It should be noted that 13 of the 26 possible 1st to 4th degree interactions turned out to be very highly significant at the 0.000 level.

TABLE VI
TR DATA FOR N=5

Line Length		N = 5		
Buffer Capacity		BC = 1		
Imbalance Degree		DI%		
MT Imbalance Pattern	Unreliability Pattern	2	5	12
Inv Bowl (/\)	Dec (\)	0.755	0.754	0.747
	Inc (/)	**0.758**	**0.758**	0.749
	Inv Bowl (/\)	**0.760**	**0.761**	**0.778**
	Bowl (\/)	**0.759**	**0.757**	0.752**
Balanced (--)			0.755	
Buffer Capacity		BC = 2		
Imbalance Degree		DI%		
MT Imbalance Pattern	Unreliability Pattern	2	5	12
Inv Bowl (/\)	Dec (\)	0.791	0.799	0.787
	Inc (/)	0.799	0.796	0.788
	Inv Bowl (/\)	0.793	**0.802**	**0.817**
	Bowl (\/)	0.797	0.794	0.793
Balanced (--)			0.799	
Buffer Capacity		BC = 6		
Imbalance Degree		DI%		
MT Imbalance Pattern	Unreliability Pattern	2	5	12
Inv Bowl (/\)	Dec (\)	0.840	0.820**	0.808***
	Inc (/)	0.840	0.838	0.818***
	Inv Bowl (/\)	0.842	0.827*	0.851
	Bowl (\/)	0.837	0.847	0.825**
Balanced (--)			0.851	

TR data for an unreliable 5-station line with BC = 1, 2, 6 units and DI% of 2, 5, 12 for 4 jointly unbalanced MT and unreliability patterns, and a balanced line counterpart, *p< 0.05, **p<0.01, ***p<0.001.

TABLE VII
TR DATA FOR N=8

Line Length		N = 8		
Buffer Capacity		BC = 1		
Imbalance Degree		DI%		
MT Imbalance Pattern	Unreliability Pattern	2	5	12
Inv Bowl (/\)	Dec (\)	0.748	0.733**	0.729**
	Inc (/)	0.747	0.733**	0.720***
	Inv Bowl (/\)	0.746	0.734**	0.720***
	Bowl (\/)	0.742	0.740	0.728***
Balanced (--)			0.753	
Buffer Capacity		BC = 2		
Imbalance Degree		DI%		
MT Imbalance Pattern	Unreliability Pattern	2	5	12
Inv Bowl (/\)	Dec (\)	0.783	0.782	0.771
	Inc (/)	0.782	**0.789**	0.766*
	Inv Bowl (/\)	0.787	0.775	0.757***
	Bowl (\/)	0.773	0.782	0.771
Balanced (--)			0.788	
Buffer Capacity		BC = 6		
Imbalance Degree		DI%		
MT Imbalance Pattern	Unreliability Pattern	2	5	12
Inv Bowl (/\)	Dec (\)	0.840	0.832	0.805***
	Inc (/)	0.832	0.828*	0.795***
	Inv Bowl (/\)	0.818**	0.818**	0.787***
	Bowl (\/)	0.825*	0.835	0.808***
Balanced (--)			0.848	

TR data for an unreliable 8-station line with BC = 1, 2, 6 units and DI% of 2, 5, 12 for 4 jointly unbalanced MT and unreliability patterns, and a balanced line counterpart, *p< 0.05, **p<0.01, ***p<0.001.

TABLE VIII
ABL DATA FOR N=5

Line Length			N = 5	
Buffer Capacity			BC = 1	
Imbalance Degree			DI%	
MT Imbalance Pattern	Unreliability Pattern	2	5	12
Dec (\)	Dec (\)	0.416**	0.373***	0.246***
	Inc (/)	0.463	0.449	0.290***
	Inv Bowl (/\)	0.457	0.232***	0.268***
	Bowl (\/)	0.248***	0.231***	0.222***
Balanced (--)			0.487	
Buffer Capacity			BC = 2	
Imbalance Degree			DI%	
MT Imbalance Pattern	Unreliability Pattern	2	5	12
Dec (\)	Dec (\)	0.756***	0.600***	0.439***
	Inc (/)	0.902**	0.812***	0.403***
	Inv Bowl (/\)	0.878**	0.744***	0.474***
	Bowl (\/)	0.932	0.726***	0.386***
Balanced (--)			1.023	
Buffer Capacity			BC = 6	
Imbalance Degree			DI%	
MT Imbalance Pattern	Unreliability Pattern	2	5	12
Dec (\)	Dec (\)	1.278***	1.248***	0.552***
	Inc (/)	2.712	1.638***	0.759***
	Inv Bowl (/\)	2.624*	1.858***	0.741***
	Bowl (\/)	2.213***	1.327***	0.580***
Balanced (--)			3.028	

ABL data for an unreliable 5-station line with BC = 1, 2, 6 units and DI% of 2, 5, 12 for 4 jointly unbalanced MT and unreliability patterns, and a balanced line counterpart, *p< 0.05, **p<0.01, ***p<0.001.

TABLE IX
ABL DATA FOR N=8

Line Length			N = 8	
Buffer Capacity			BC = 1	
Imbalance Degree			DI%	
MT Imbalance Pattern	Unreliability Pattern	2	5	12
Dec (\)	Dec (\)	0.405***	0.338***	0.400***
	Inc (/)	0.532	0.450**	0.502
	Inv Bowl (/\)	0.505	0.413***	0.492
	Bowl (\/)	0.498	0.377***	0.410***
Balanced (--)			0.506	
Buffer Capacity			BC = 2	
Imbalance Degree			DI%	
MT Imbalance Pattern	Unreliability Pattern	2	5	12
Dec (\)	Dec (\)	0.710***	0.587***	0.400***
	Inc (/)	1.019	0.840**	0.507***
	Inv Bowl (/\)	0.940	0.784***	0.492***
	Bowl (\/)	0.874*	0.681***	0.410***
Balanced (--)			0.974	
Buffer Capacity			BC = 6	
Imbalance Degree			DI%	
MT Imbalance Pattern	Unreliability Pattern	2	5	12
Dec (\)	Dec (\)	1.801***	1.115***	0.709***
	Inc (/)	2.719	1.800***	0.780***
	Inv Bowl (/\)	2.244***	1.700***	0.802***
	Bowl (\/)	1.713***	1.185***	0.725***
Balanced (--)			2.742	

ABL data for an unreliable 8-station line with BC = 1, 2, 6 units and DI% of 2, 5, 12 for 4 jointly unbalanced MT and unreliability patterns, and a balanced line counterpart, *p< 0.05, **p<0.01, ***p<0.001.

TABLE X
GLM RESULTS FOR TR

Performance	Throughput (TR)	
Source (Factor)	Wald Chi-Square	Significance Level
BC	5,206.246***	0.000
DI	1,002.837***	0.000
MTP	302.375***	0.000
N	169.270***	0.000
URP	75.667***	0.000

Significant at*p< 0.05, **p<0.01, ***p<0.001.

For TR, BC has the strongest, very highly significant effect, and the second strongest influence arises from DI. TR is also very significantly impacted by MTP, N and URP respectively.

The results of the GLM analysis for ABL are shown in Table XI. Again for the purpose of space reduction, only ABL results for the main effects are presented.

TABLE XI
GLM RESULTS FOR ABL

Performance	Average Buffer Level (ABL)	
Source (Factor)	Wald Chi-Square	SignificanceLevel
BC	261,121.119***	0.000
MTP	4,347.393***	0.000
URP	780.286***	0.000
DI	112.211***	0.000
N	0.295***	0.587

Significant at *p< 0.05, **p<0.01, ***p<0.001.

As seen for TR, buffer capacity is having the strongest effect on ABL, but the next strongest contribution comes from MTP, followed respectively by URP, DI and N. In fact, all of the 5 main effects and the 26 possible 1^{st} to 4^{th} degree interactions are very highly significant at the 0.000 level.

It should be noted that BC is very important for both TR & ABL and that MT & unreliability patterns are more important for ABL than for TR, where BC and DI influence performance more.

C. Effects of Line Length, N

TR: N has an influence on many of the lines simulated, with TR lower for N = 8. The biggest differences are observed for the inverted MT bowl combinations. Notably there is no significant difference in TR between N = 5 and N = 8 for the balanced line.

ABL**:** N has no observable effect on ABL, significant differences are found only for patterns MT bowl + Unreliability descending and MT bowl + unreliability inverted bowl (where t = 2.542, significance level = 0.011 and t = 2.538, significance level = 0.011, respectively). N = 8 has lower ABL than N = 5 for both cases.

D. Effects of Buffer Capacity, BC

TR: TR increases for higher levels of BC. ABL**:** BC significantly affects all lines simulated. Higher ABL is seen for higher levels of BC (ANOVA + Tukey's post hoc tests).

E. Effects of Degree of Imbalance, DI

TR: TR is higher when DI is lower for both the MT descending and ascending orders plus all unreliability pattern combinations.

For the MT bowl and inverted bowl combinations along with unreliability imbalance, the effect of DI is less strong – there are significant differences between DI = 2 and DI = 12, but DI = 5 always falls into the same homogeneous subgroup as one of the others. Exceptions: no TR difference.

ABL: ABL decreases as DI rises. There is a significant difference between ABL for the three values of DI for the descending and ascending MT patterns plus all combinations of unreliability patterns.

For all MT inverted bowl combinations with unreliability imbalance, there is no significant difference in ABL between the three DI values. This is also true for the MT bowl + unreliability inverted bowl and MT bowl + unreliability bowl patterns.

VI. Summary

We can draw a number of conclusions from the findings presented above. For a line that is subject to combined MT and unreliability imbalance, a balanced configuration is the best when throughput is the performance measure of interest. This generally agrees (ignoring the unreliability imbalance part) with the results of [9] and [11] that moving towards a balanced configuration of stations with near equal mean operation times would be a better strategy for improved efficiency.

It was also found that in general, the most favourable unbalanced MT& unreliability pattern in terms of throughput is a bowl MT configuration, coupled with an inverted bowl unreliability imbalance. This is in broad agreement (disregarding the unreliability imbalance) with the earlier findings of [2].

In contrast, when we observe the results in terms of average buffer level performance, the pattern giving rise to the lowest ABL is a descending MT order (\), (under which the bottleneck or constraint station is positioned at the beginning of the line), in conjunction with either a descending or bowl unreliability configuration. As far as the unreliable MT part is concerned, his agrees in general with the findings for unreliable line performance in the work of [37], and [23], and also to the results obtained for reliable lines by [9]. It should be noted that for the patterns giving the best ABL results, consistent, very highly significant improvements over the balanced line are obtained for practically all the N, BC, and DI values explored**.**

In addition to the effects of patterns of MT imbalance, a number of observations can be made about the other design factors, namely buffer capacity, degree of MT imbalance and line length on performance. In general, BC was seen to have the biggest influence on performance of ABL and TR separately.

A more detailed analysis shows that as buffer capacity increases, throughput rises. This lends support to the contention of [10] that buffers are most effective at recuperating lost production in lines having unbalanced production rates. Increasing buffer capacity is less effective above a certain level and for more highly imbalanced patterns - in line with the finding of [9] that buffers are of limited value in maintaining efficiency and the results of [11] that argue that the effect of increased buffers on output decreases as the line becomes more unbalanced.

The general effect of higher buffer availability on ABL is to worsen performance for the unbalanced MT& unreliability imbalanced lines. On examination of the influence of the degree of mean time imbalance, we can see that when DI increases, TR falls. This is in general agreement with [11], who stated that as the line becomes more unbalanced, the breakdown rate of the first station increases.

TR and ABL fall. This implies that more extreme imbalance actually has a positive effect in terms of ABL performance. There have been no previous studies to our knowledge which explicitly investigate the effects of degree of imbalance, but the data reported by [6] seem to indicate that percentage working time along an unbalanced line increases as the degree of imbalance grows, and then deteriorates on further imbalance which lends support to the findings for TR presented here.

Finally, in terms of improvement in performance, the greatest % improvements in TR and ABL over the unreliable balanced line counterpart are: TR: 3.05% (statistically insignificant), and ABL 81.77% (very highly significant). When data are compared to the IT and ABL results reported by [37] for a corresponding unreliable MT line with fixed station's downtown and repair rates, we find similarities in their best unbalanced patterns and operating behaviour.

VII. Discussion and Conclusions

This investigation has shown that equivalent performance to that achieved by a balanced line in terms of throughput, or superior performance for average buffer level is attainable. When ABL is considered, the savings obtained are very highly significant (around 82% for the best case). This would appear to justify unbalancing MT unreliable production lines that experience machine failure and repair in many situations, especially since the improvement in throughput or average buffer level only requires appropriately assigning line operators to the same stations and arranging the machines with different failure and repair rates in a certain favourable order, which does not entail any further expenditure on capital or other resources.

In spite of this, the results do raise a dilemma. A line manager will have to make decisions as to where the greatest benefits can be reaped. It may be to enhance throughput, or reduce idle time should it be costly, for instance in an industry where demand is high and operators are working full out, such as on the production lines in consumer goods (e.g. computer, mobile phones), or where manpower is expensive.

Several avenues for future research are possible in this area; for example, studies aimed at assessing the effectiveness of unreliable lines with two or more sources of imbalance, such as buffer and mean time imbalance combined. Another possibility is to consider unreliable merging assembly lines. A third possibility is to study unreliable disassembly lines.

References

[1] H. Tempelmeier, "Practical considerations in the optimization of flow production systems," *International Journal of Production Research*, vol 41, no.1, pp. 149-170, 2003.

[2] F. S. Hillier and R. W. Boling , R. W. (1966) "The effect of some design factors on the efficiency of production lines with variable element times," *Journal of Industrial Engineering*, vol. 17, no. 12, pp. 651-658, 1966.

[3] T. El-Rayah, T, "The effect of inequality of inter-stage buffer capacities and operation time variability on the efficiency of production line systems," *International Journal of Production Research*, vol.17, no.1, pp.77-89, 1979.

[4] K. So, "Optimal buffer allocation strategy for minimizing work-in-process inventory in unpaced production lines," *IIE Transactions*, vol. 29, no. 1, pp. 81-88, 1997.

[5] H. T. Papadopoulos and M. I. Vidalis, "Minimizing WIP inventory in reliable production lines", *International Journal of Production Economics*, Vol. 70, pp. 185-197, 2001.

[6] B. Das, J. M. Sanchez-Rivas, A. Gacia-Diaz and C. A. MacDonald, "A computer simulation approach to evaluating assembly line balancing with variable operation times," *Journal of Manufacturing Technology Management*, vol. 2, no. 7, pp. 872-887, 2010.

[7] S. Shaaban, and T. McNamara, "Improving the efficiency of unpaced production lines by unbalancing service time means", *International Journal of Operational Research, v*ol. 4, no. 3, pp. 346-361, 2009.

[8] M. Hillier, "Designing unpaced production lines to optimize throughput and work-in-process inventory," *IIE Transactions*, vol. 45, no. 5, pp. 516-527, 2013.

[9] J. A. Buzacott, "The role of inventory banks in flow-line production systems," *International Journal of Production Research*, vol. 9, no. 4, pp. 425-436, 1971

[10] J. Wijngaard, "The effect of inter-stage buffer storage on the output of two unreliable production units in series, with different production rates," *AIIE Transactions*, Vol. 11, No. 1, pp. 42-47, 1979.

[11] T. Altiok, "Production lines with phase-type operation and repair times and finite buffers," *International Journal of Production Research*, vol. 23, no. 3, pp. 489-498, 1985.

[12] Y. F. Choong and S. B. Gershwin, "A decomposition method for the approximate evaluation of capacitated transfer lines with unreliable machines and random processing times", *IIE Transactions*, Vol. 19, No. 2, pp. 150-159, 1987.

[13] D. E. Blumenfeld, "A simple formula for estimating throughput of serial production lines with variable processing times and limited buffer capacity", *International Journal of Production Research*, vol. 28, no. 6, pp. 1163-1182, 1990.

[14] V. S. Kouikoglou and Y. A. Phillis, "Discrete event modelling and optimization of unreliable production lines with random rates," *IEEE Transactions on Robotics and Automation*, vol. 10, no. 2, pp. 153-159, 1994.

[15] A. A. Bulgak, P. D. Diwan and B. Inozu, "Buffer size optimization in asynchronous assembly systems using genetic algorithms," *Computers and Industrial Engineering*, vol. 28, no. 2, pp. 309-322, 1995.

[16] G. A. Vouros and H. T. Papadopoulos, "Buffer allocation in unreliable production lines using a knowledge based system," *Computers and Operations Research*, vol. 25, no. 12, pp. 1055-1067, 1998.

[17] S. Y. Chiang, C. T. Kuo and S. M. Meerkov, "DT-bottlenecks in serial production lines: theory and application," *IEEE Transactions on Robotics and Automation*, vol. 16, no. 5, pp. 352-359, 2000

[18] W. L. Sloan, "A study on the effects of protective capacity on cycle time in serial production lines", M.Sc. Thesis, *Mississippi State University*, Mississippi, 2001.

[19] H. Tempelmeier and M. Bürger, "Performance evaluation of unbalanced flow lines with general distributed processing times, failures and imperfect production," *IIE Transactions*, vol. 33, pp. 293-302, 2001.

[20] S. Helber, "Cash-flow-orientated buffer allocation in stochastic flow lines," *International Journal of Production Management*, vol. 39, no. 14, pp. 3061-3083, 2001.

[21] J. W. Herrmann and M. M. Chincholkar, "Reducing throughput time during product design," *Journal of Manufacturing Systems*, vol. 20, no. 6, pp. 416-428, 2001/2002.

[22] E. J. Enginarlar, J. Li, S. M. Meerkov, and R. Q. Zhang, "Buffer capacity for accommodating machine downtime in serial production lines," *International Journal of Production Research*, vol. 40, no. 3, pp. 601-624, 2002.

[23] M. I. Vidalis and C. Heavey, "On the workload allocation problem of short unreliable production lines with finite buffers," in *Proc. 4th Aegean Int. Conf. Analysis of Manufacturing Systems*, Samos Island, Greece, pp. 1158–1162, 2003.

[24] E. J. Enginarlar, J. Li and S. M. Meerkov, "Lean buffering in serial production lines with non-exponential machines," *OR Spectrum*, vol. 27, pp. 195-219, 2005

[25] J. Li and S. M. Meerkov, "Evaluation of throughput in serial production lines with non-exponential machines," *In* Boukas, E. K. and Malhame, R. (Eds.), *Analysis, Control and Optimization of Complex Dynamic Systems*, Berlin, Springer, pp. 55-82, 2005

[26] S. Y. Chiang, A. Hu and S. M. Meerkov, "Lean buffering in serial production lines with nonidentical exponential machines," *IEEE Transactions on Automation Science and Engineering*, vol. 5, no. 2, pp. 298-306, 2008.

[27] J. K. Cochran, A. Kokangul and T. A. Khaniyev, "Stochastic approximations for optimal buffer capacity of many-station production lines," *International Journal of Mathematics in Operational Research*, vol. 1, nos. 1/2, pp. 211-227, 2009.

[28] J. Li, D. E. Blumenfeld, N Huang and J. M. Alden, "Throughput analysis of production systems: recent advances and future topics," *International Journal of Production Research,* vol. 47, pp. 3823–3851, 2009.

[29] A. L. Patti and K. J. Watson, "Downtime variability: the impact of duration-frequecny on the performance of serial production systems", International Journal of Production Research, vol. 48, no. 19, pp. 5831-5841, 2010.

[30] N. Huang, "Mean station reliabilities cause throughput overestimates in production system design," *Journal of Manufacturing Systems*, vol. 31, pp. 184– 195, 2012.

[31] W. Guo, J. Jin, and J. Hu, "Allocation of maintenance resources in mixed model assembly systems," *Journal of Manufacturing Systems*, vol. 32, pp. 473– 479, 2013.

[32] N. Slack, "Work time distributions in production system modelling", research paper, *Oxford Centre for Management Studies*, 1982.

[33] A. M. Law and W. D. Kelton, *Simulation Modeling and Analysis*, Illinois, Irwin / McGraw-Hill, 2000.

[34] C. Harrell, B. K. Ghosh and R. O. Bowden, *Simulation using ProModel*, New York, McGraw – Hill, 2004.

[35] R. R. Inman, "Empirical evaluation of exponential and independence assumptions in queuing models of manufacturing systems," *Production and Operations Management*, vol. 8, no. 4, pp. 409-432, 1999.

[36] A. M. Law, *Simulation Modeling and Analysis*, Illinois, Irwin / McGraw-Hill, 2007

[37] S. Shaaban, T. McNamara and S. Hudson, "Mean time imbalance effects on unreliable unpaced serial flow lines," *Journal of Manufacturing Systems*, vol. 33, no. 3, pp. 357-365, 2014.