Transient Behavior of Unbalanced Lines

S. Shaaban, and T. McNamara

Abstract—**This paper studies the operating behaviour of non-automated production lines that are either individually or jointly imbalanced in terms of their operation time means, coefficients of variation and / or buffer sizes. The lines were simulated under their non-steady state mode of operation with various values of line length, buffer storage size, degree of imbalance and patterns of imbalance. Idle time and average buffer level output data were generated and analysed. It was found that the transient idle time is larger than the steady-state counterpart, whereas the opposite is true for the transient average buffer level. In addition, a longer line extends the transient idle time duration. Furthermore, as the degree of imbalance goes up, the transient period is shortened.**

***Index Terms*—Production line, simulation, transient, patterns of imbalance.**

I. INTRODUCTION

The steady-state (SS) phase of a production line's operation starts as soon as nearly all the transient / non-steady state (NSS) effects die down. During the transient period, the mean values of the performance measures are not stable and can be quite different from those of the SS. Gradually but ultimately, the line will converge to an equilibrium behavioural mode.

There are a number of reasons why an un-paced manual line experiences non-equilibrium working conditions, including the following:

- Start-up of the line: the line usually starts operating at the beginning of the working day in an 'idle and empty' state, where all the stations being idle and all the buffers being empty, so the line passes through an initial transient period before settling down.
- Depletion of raw material supply to the first station: if for any reason the stock of raw materials feeding the first station is exhausted and not replenished, the station will stop working during the period of the cessation of the external supply, leading to a series of chain stoppages in all the succeeding stations down the line. When the supply is resumed and the line starts functioning, a NSS situation occurs.
- Stoppage of the line as a whole: the entire line may stop at certain intervals, such as tea or lunch breaks, shift changes, power supply failure, routine maintenance checks, etc. As soon as work is restarted a start-up period will result.
- Temporary increase in a station's service time: the production rate of a station may drop in the short term from its normal level, due to human factors, e.g. contingency and personal needs, thus increasing blocking idle times at the preceding stations.
- Central station stoppage: when a middle station is forced down for whatever cause, all the preceding buffers will become full and all succeeding buffers will be rendered empty after a relatively short period. Throughout the stoppage period, the preceding stations will be entirely isolated from the succeeding stations and so the line may be viewed as being composed of two separate lines. As the stoppage ends and work resumes, these two independent lines will initially behave as if they have full and empty buffers, respectively.
- Learning: whenever a new product or process is introduced, workers will experience a NSS period before reaching a stable level of productivity as a consequence of learning effects.

This paper is organized 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 provide the simulation results and analysis. The last part provides discussion of the results and research implications.

II. LITERATURE REVIEW

A three-station line was simulated by [1] to determine the effects of unequal mean processing times on idle time and output. He observed that an arrangement of fast – medium – slow workers provided the best overall performance, but a configuration that places a slow station at the front of the line generates a slightly higher output than other patterns.

Simulation was used by [2] to investigate unbalanced lines. They found that placing the slow stations towards the end of the line led to lower %IT and that positioning the faster stations near the end of the line results in lower average queue lengths. In both cases the results were better than those of an equivalent balanced line, but at the cost of diminished production. Furthermore, the authors simulated lines with unequal coefficients of variation (CVs). They reported that an ascending allocation of CVs resulted in less idle time than a descending configuration, but the opposite is true with regard to inter-station queue size. They also indicated that superior results were obtained from unbalancing the line's variability, but again the output will decline.

A four station un-paced production line with uneven CV assignment was simulated by [3]. They stated that when the

Manuscript received June 2, 2009.
S. Shaaban is with the ESC Rennes School of Business, Rennes, 35065, France (phone: +33(0) 299 54 63 31; fax: +33(0) 299 33 08 24; e-mail: sabry.shaaban@esc-rennes.fr).
T. McNamara is with the ESC Rennes School of Business, Rennes, 35065, France (phone: +33(0) 299 54 63 63; fax: +33(0) 299 33 08 24; e-mail: tom.mcnamara@esc-rennes.fr).

station with a slightly higher CV is located at the end of the line, output increases slightly and idle time decreases. On the other hand, work in process level remains fairly constant irrespective of the placement of the high CV stations.

Lines having both increasing and decreasing mean service time configurations were simulated by [4]. He noted that the increasing pattern accelerates buffer build up during the transient period, resulting ultimately in a higher buffer level than that of a balanced SS line. In addition, the greater the degree of imbalance, the quicker the balanced SS buffer level is reached and the more substantial the subsequent overshoot. For the decreasing arrangement, buffers are depleted fast in the direction of the balanced SS levels. Furthermore, for both the ascending and descending orders, comparatively lower idle times than a balanced line counterpart were obtained.

A two-stage production system was analyzed by [5] and [6], resulting in mathematical expressions for manufacturing progress (representing learning effects) and early equipment failure rate. They found that for an un-buffered line, increasing the manufacturing progress rate increases output rate and shortens transient length. However, the use of zero buffers greatly decreases a line's utilization rate.

It was observed by [7] that the transient duration for a production system rises almost linearly with the increase in line length. Also, transient's idle time and average buffer levels can be improved by introducing a slight degree of imbalance.

A 3-station line system was studied by [8] in which it was observed that a balanced arrangement of servers provides the best results with regard to both the time needed to arrive at the stable state and line performance in terms of % idle time, average number of pieces and their waiting time in the system. For an unbalanced line, the best performance was obtained by using a descending order of mean operation times.

The transient phase for a line having 5 stations was investigated by [9]. Formulas were derived to estimate autocorrelation values for the moments of a station's starting and finishing times. It was noted that autocorrelations reach some lower limit, i.e. steady state is attained, at the end of a 100-piece production run. As for unbalanced lines, it was observed that serial correlation reaches a limiting low value (signalling the end of the transient phase) as the number of jobs processed goes up. For lines with increasing sequences of both operation time means and standard deviations, or with an ascending means order coupled with a descending coefficient of variation allocation, steady-state conditions were attained prior to the end of the 100- piece production run, indicating that a shorter warm up period is probably required.

III. Motivation and Objectives

This investigation seeks to study the NSS operating characteristics of lines having either one or two simultaneous sources of imbalance that are caused by allowing mean service times (MTs), coefficient of variation (CVs), and /or buffer capacities (BCs) to differ amongst the stations.

The motivation for conducting this research stems from the fact that very little is known about the behaviour of such lines, as the majority of the published papers on flow lines have thus far focused on analysing their SS performance. This is probably due to the belief in general that the NSS stage represents an unfortunate feature of the line operations and consequently, is of little value. However, there are sound grounds for believing that in practice, large segments of working time for some lines are being spent under NSS conditions, therefore a natural extension of the abundant work on the SS phase would be to investigate the transient component (see [4]).

The main objectives of this research are to:

- Assess the broad ranking of the various policies and patterns of imbalance.
- Examine the effects of line design factors on the dependent measures of performance.
- Determine the transient length properties of such lines.
- Compare the relative performances of transient and SS lines and find transient size characteristics.

IV. Methodology and Experimental Design

Since no mathematical procedure is capable at present of handling the unbalanced transient characteristics of serial production lines, computer simulation was utilized as the most apt technique for this kind of study.

A. *Factorial Design*

As the most efficient and powerful of the many experimental designs available is the complete factorial design, it was chosen for the present investigation.

For the particular un-paced production lines studied, the independent (exogenous) variables are:

- Total number of stations in the line, N.
- Total amount of buffer capacity for the line, TB.
- Capacity of each buffer, B / mean capacity of each buffer, MB.
- Degree of imbalance of service time means, DI.
- Range of CV values.
- Pattern of mean work time imbalance
- Pattern of CV imbalance
- Pattern of buffer capacity imbalance

B. *Performance Measures*

Two main performance criteria were chosen for this study, namely total idle time (IT), i.e. the % of line inactive time to total working time and average buffer level for the whole line (ABL).

C. *Work Times Distribution*

A detailed study of published histograms of work times experienced in practice was conducted by [10]. He concluded that the work time distribution is positively skewed and follows a Weibull distribution, with a CV value varying between 0.08 and 0.50 and averaging around 0.274. This probability distribution was chosen for this study.

D. Unbalanced Lines Investigated

The following unbalanced lines were studied:

i. Lines with only one source of imbalance. These are:

- Unequal service time means (MT investigation): each station in this study has the same CV value of 0.274 and all the buffer capacities are equal.
- Unbalanced coefficients of variation (CV investigation): each station has identical mean operation time value of 10 time units and all buffers have the same capacity.
- Uneven buffer sizes (BC investigation): each station has the same mean processing time and CV values of 10 time units and 0.274, respectively, but buffer sizes are unequal.

ii. Lines with two sources of imbalance. They are:

- Joint imbalance of both mean service times and CVs (MT&CV investigation): each station has equal buffer sizes, whereas both the means and CVs vary.
- Combined imbalance of both means and buffer sizes (MT&BC investigation): CVs of 0.274 are utilized for each station. However, both the means and the buffer capacities are allowed to be unequal.
- Simultaneous imbalance of both CVs and buffer capacities (CV&BC investigation): all operation time means are equal to 10 time units, but the buffer sizes and CVs are unbalanced.

E. Initial Simulation Conditions

Since the system is being studied from the time it begins working until the point at which it reaches the SS, the most reflective state of its initial conditions is to start with idle operators and empty buffers.

Furthermore, identical initial conditions were employed for all the experiments conducted as using different starting conditions will bias the outcome of any comparisons.

F. Simulation Run Length

In his study, [4] showed that approximately 4,500 time units (TU) will be needed before the NSS values of IT and ABL become statistically hard to differentiate from those of the SS. Consequently, it was decided to set the NSS run length for all the unbalanced line investigations to 5,000 TU. This decision was made for two reasons. Firstly, since no clear prior knowledge of the necessary transient duration for the unbalanced lines is available, an interval of the same size as that of balanced lines seems to be a logical choice. Secondly, a specific transient period has to be initially selected in order to determine whether its data will differ significantly from those representing the SS.

G. Total Number of Observations

The number of observations selected for a fixed simulation period is affected by the choice of the length of each separate observation, which should be long enough to avoid serial correlation, but not so lengthy, thus a trade-off is necessary.

It was decided to divide the NSS run length into two batches of 2,500 TU each in order to avoid autocorrelation.

H. Number of Replications

The replication method is the most suitable for investigating the transient operating characteristics. Though it was statistically feasible to have as little as 2 batches and 4 replications (a total of 8 observations) to ascertain normality and independence, it was felt that 20 observations (2 batches x 10 replications each) would be a far better sample size for generating reliable results. Furthermore, for the sake of obtaining identical flow of events, it was decided to use the same set of 10 different random number seeds, each of which accounts for one replication.

I. Transient Length and Size Considerations

After determining the best patterns in terms of IT and ABL for each investigation, transient length and transient size (TS) were then computed. The reason for focusing on the best patterns is the fact that the superior patterns are the most important and so are worthy of further exploration. TS was computed by dividing the mean IT or ABL of the first batch (the mean after the elapse of 50% of the simulation run) by their SS counterparts.

As for the transient length, the Dunnett's t statistic was used to test the significance of differences between the transient's IT and ABL values and their SS counterparts, i.e. to determine if the transient length of 5,000 TU is sufficient.

It should be noted that the computer simulation program was coded in FORTRAN.

J. Specific Design Features

The particular design variables and their values are as follows:

- Line length: N values of 5 and 8 were specified in this study.
- Buffer capacity (for the MT, CV and MT&CV investigations): BC values of 1 and 6 were decided upon.
- Mean buffer capacity (for the BC, MT&BC and CV&BC investigations): MB values of 2 and 6 were selected.
- Degree of imbalance: DI values of 5%, and 12% were chosen.
- Means imbalance pattern: four patterns were considered:
  - A monotone increasing order (/).
  - A monotone decreasing order (\).
  - A bowl arrangement (V).
  - An inverted bowl shape (Λ).
- CV imbalance policy: four policies were considered:
  - Separating the variable stations from one another by steadier stations (patterns P1- P3 portray this policy).
  - Assigning steadier stations to the line centre, i.e. a bowl arrangement (patterns P4 and P5 depict this policy).
  - The stations with medium variability are allocated

to the middle of the line. This policy represents both a decreasing order (pattern P6) and an increasing sequence (pattern P7) of CVs along the line.
- The most variable stations are assigned to the centre of the line centre - an inverted bowl arrangement (pattern P8).

- Total buffer capacity allocation policy: four policies were explored:
  - o Concentrating available capacity closer to the end of the line. This policy displays an increasing order of BC (pattern A).
  - o Concentrating buffer capacity nearer the middle of the line. This policy portrays an inverted bowl BC sequence (pattern B).
  - o Concentrating capacity towards the beginning of the line. This policy shows a decreasing order of BC (pattern C).
  - o No concentration. This policy is broken into three main sub-policies:
    - General (pattern D1).
    - Alternating BC between high and low a1ong the line (pattern D2).
    - Positioning smaller BC towards the centre - a bowl shape (pattern D3).

In all, the total number of cells simulated for the six investigations was 32 + 16 + 16 + 128 + 128 + 64 = 384.

Figures 1 to 3 below show the CV and BC imbalance patterns used:

Pattern (Pi) of Unbalanced CVs	Line Length	
	5	8
P1	MSVMS	MSVMSVMS
P2	VMSVM	VMSVMSVM
P3	SMVSM	SMVSMVSM
P4	MSSSV	MMSSSSVV
P5	MSSSV	MMSSSSVV
P6	VMMMS	VVMMMMSS
P7	SMMMV	SSMMMMVV
P8	MVVVS	MMVVVVSS

S = relatively steadier CV (CV = 0.08)
M = medium CV (CV = 0.27)
V = relatively more variable CV (CV = 0.50)
Fig. 1: Unbalanced CV patterns

Line Length		5	
Mean Buffer Size		2	6
P1	A	1,1,1,5	3,3,3,15
P2	B	1,1,5,1	3,3,15,3
P3	C	5,1,1,1	15,3,3,3,
P4	D1	2,2,3,1	6,6,9,3
	D2	2,3,2,1	6,9,6,3
	D3	2,1,3,2	6,3,9,6
TB		8	24

Pi = policy of buffer capacity imbalance
Fig. 2: Unequal buffer size patterns for the BC, MT&BC and CV&BC investigations for N = 5

Line Length		8	
Mean Buffer Size		2	6
P1	A	1,1,1,1,6,2,2	3,3,3,3,18,6,6
P2	B	1,1,6,2,2,1,1	3,3,18,6,6,3,3
P3	C	6,2,2,1,1,1,1	18,6,6,3,3,3,3
P4	D1	2,2,2,3,3,1,1	6,6,6,9,9,3,3
	D2	2,2,3,3,2,1,1	6,6,9,9,6,3,3
	D3	2,2,1,1,3,3,2	6,6,3,3,9,9,6
TB		8	14

Pi = policy of buffer capacity imbalance
Fig. 3: Unequal buffer size patterns for the BC, MT&BC and CV&BC investigations for N = 8

V. Results

A. Idle Time and Average Buffer Level Data

Tables 1 - 9 and Tables 10 - 18 below show respectively, IT and ABL data for the best patterns, along with TS values:

Table I: IT data for pattern (V): MT investigation N = 5

N	5			
B	1		6	
% DI	5	12	5	12
% IT	9.589	10.112	3.543	5.748
TS	1.011	1.006	1.655	1.242

Table II: IT data for pattern (V): MT investigation N = 8

N	8			
B	1		6	
% DI	5	12	5	12
% IT	11.519	11.834	3.609	6.303
TS	1.036	1.021	1.658	1.249

Table III: IT data for pattern P2: CV investigation

N	5		8	
B	1	6	1	6
% IT	8.568	2.156	14.217	3.601
TS	1.002	2.098	1.100	1.487

Table IV: IT data for pattern D: BC investigation

N	5		8	
MB	2	6	2	6
% IT	5.595	2.512	7.132	3.975
TS	1.011	1.715	1.038	2.161

Table V: IT data for pattern (^) + P2: MT&CV investigation N = 5

N	5			
B	1		6	
% DI	5	12	5	12
% IT	8.150	9.127	2.949	5.259
TS	1.143	1.016	1.329	1.167

Table VI: IT data for pattern (^) + P2: MT&CV investigation N = 8

N	8			
B	1		6	
% DI	5	12	5	12
% IT	11.729	12.455	4.152	5.428
TS	1.140	1.117	1.196	1.154

Table VII: IT data for pattern (V) + D: MT&BC investigation N = 5

N	5			
MB	2		6	
% DI	5	12	5	12
% IT	6.137	7.514	3.267	5.635
TS	1.048	1.040	1.536	1.156

Table VIII: IT data for pattern (V) + D: MT&BC investigation N = 8

N	8			
MB	2		6	
% DI	5	12	5	12
% IT	7.296	8.829	3.833	6.007
TS	1.195	1.189	1.735	1.212

Table IX: IT data for pattern P2 + C: CV&BC investigation

N	5		8	
MB	2	6	2	6
% IT	4.323	1.967	6.676	3.959
TS	1.273	1.652	1.097	2.348

Table X: ABL data for pattern (\): MT investigation N = 5

N	5			
B	1		6	
% DI	5	12	5	12
% IT	0.389	0.228	0.781	0.389
TS	0.955	0.851	0.885	0.806

Table XI: ABL data for pattern (\): MT investigation N = 8

N	8			
B	1		6	
% DI	5	12	5	12
% IT	0.400	0.269	1.013	0.443
TS	0.975	0.940	0.873	0.849

Table XII: ABL data for pattern P2: CV investigation

N	5		8	
B	1	6	1	6
% IT	0.386	1.521	0.278	1.181
TS	0.967	0.520	0.965	0.818

Table XIII: ABL data for pattern A: BC investigation

N	5		8	
B	1	6	1	6
% IT	0.386	1.521	0.278	1.181
TS	0.967	0.520	0.965	0.818

Table XIV: ABL data for pattern (\) + P2: MT&CV investigation N = 5

N	5			
B	1		6	
% DI	5	12	5	12
% IT	0.199	0.132	0.551	0.325
TS	0.878	0.970	0.799	0.885

Table XV: ABL data for pattern (\) + P2: MT&CV investigation N = 8

N	8			
B	1		6	
% DI	5	12	5	12
% IT	0.191	0.131	0.626	0.339
TS	0.908	0.963	0.812	0.827

Table XVI: ABL data for pattern (\) + A: MT&BC investigation N = 5

N	5			
MB	2		6	
% DI	5	12	5	12
% IT	0.350	0.214	0.751	0.339
TS	0.982	0.977	0.980	0.916

Table XVII: ABL data for pattern (\) + A: MT&BC investigation N = 8

N	8			
MB	2		6	
% DI	5	12	5	12
% IT	0.367	0.234	0.892	0.398
TS	0.961	0.947	0.911	0.865

Table XVIII: ABL data for pattern P2 + A: CV&BC investigation

N	5		8	
MB	2	6	2	6
% IT	0.281	0.635	0.245	0.615
TS	0.883	0.646	0.911	0.670

B. General NSS Findings

From the above tables, the following two conclusions can be drawn:

The transient best patterns for both IT and ABL for each of the six unbalanced line investigations are identical to those of the SS. Table 19 below exhibits the SS and NSS best patterns found:

Table XIX: SS and NSS best IT and ABL patterns for the six unbalanced investigations

Investigation	Best IT Pattern	Best ABL Pattern	Reference
MT	Bowl shaped	Descending order	[11]
CV	Bowl	Bowl	[12]
BC	Nearly balanced	Ascending order	[13]
MT&CV	MT inverted bowl + CV bowl	MT descending order + CV bowl shaped	[14]
MT&BC	MT bowl + BC nearly balanced	MT descending order + BC ascending order	[15]
CV&BC	CV bowl + BC descending order	CV bowl + BC ascending order	[16]

The NSS effects of the design factors N, B/MB and DI on the response variables (IT and ABL) for all the six transient investigations were found to be generally very similar to those of the SS counterparts, though they differed in their absolute magnitude.

C. Transient Length Results

A significant Dunnett's t value indicates that the mean transient IT (or ABL) value differs substantially from the corresponding SS value, in other words, 5,000 TU are insufficient for the SS to be approached. Table 20 below shows the (very few) instances where the 5,000 TU were relatively insufficient at the 95% level or above for the best IT and ABL patterns only:

Table XX: Instances of relatively insufficient transient durations

Dependent Variable	Investigation	N	BC/MB	%DI
IT	MT	8	6	5
	BC	8	6	-
	MT&CV	5	1	12
	MT&CV	8	6	5
.	MT&BC	8	2	5
ABL	BC	8	6	-

Based on table 20 above, it is interesting to note the following:

- In the vast majority of cases in all the six investigations, the chosen transient length was enough for the SS to be reached. This largely justifies the selection of 5,000 TU.
- A significant difference in ABL was registered in one instance only, i.e. the chosen transient duration is almost always sufficient in terms of ABL.
- Significant differenced in IT are mostly seen in 8-station lines with a DI of 5%.

D. Transient Size Results

From Tables 1 – 18**,** the following can be observed concerning TS:

For IT:

- All TS values are greater than 1, indicating that the mean IT of the transient period is larger than that of the SS counterpart.
- TS is increased (i.e. the transient period lengthens), as BC/MB becomes higher. This is in line with the findings of [4] for the NSS balanced line, especially at low DI.
- TS is bigger for N = 8 than for N = 5, i.e. a higher N lengthens the transient duration.

For ABL:

- All TS values are less than1, indicating that the mean ABL of the transient is smaller than the SS counterpart.
- As BC/MB is increased, TS is reduced (i.e. buffer build up is decreased). This result agrees with that of [4] for the NSS balanced line, particularly at smaller DI levels.
- As DI goes up, TS declines, therefore the transient period is shortened, particularly for higher BC/MB. This is in agreement with the results of [4].

VI. Conclusion

This investigation sought to analyse the transient behaviour of unbalanced production lines with unequal mean processing times, coefficient of variation, and /or buffer sizes.

The characteristics of such lines are not well known as the bulk of published research on serial flow lines mainly deals with their performance under stable working conditions. This is due in part to the general belief that the transient is an unfortunate phase of line operations with little value. However, in practice many lines spend a relatively sizeable segment of their working time under unstable conditions, therefore investigating the transient behaviour is an integral part of the study of production lines.

One of the main purposes for carrying out this research was to determine whether the best unbalanced patterns found under NSS conditions will be any different from those of the SS. As it turned out, the best transient unbalanced configurations, both in terms of IT and ABL are virtually identical in both SS and NSS for all of the six investigations. In addition, the relationships between line performance and design factors were also broadly similar under transient and SS conditions for all types of imbalance considered, though their absolute magnitude differed. In addition, with only few exceptions in almost all the cases studied, the selection of a transient period of 5,000 TU seems largely justified for both IT and ABL. As for the transient size, the following main conclusions can be cited:

- The mean IT of the transient period is larger than the SS counterpart, whereas the mean ABL of the NSS is smaller than that of the SS.
- The IT transient period lengthens as BC/MB becomes higher, while in terms of ABL when BC/MB is increased, buffer build up is decreased.
- A higher N lengthens the transient IT duration.
- As DI goes up, the transient period is shortened.

It is hoped that the present study has thrown some lights on the transient behaviour of unbalanced lines. Numerous opportunities still exist for carrying out further research, including for instance the analysis of transient features of unreliable production lines, as well as investigating the start-up aspects of both reliable and unreliable merging lines.

References

[1] L. E. Davis, “Pacing effects on manned assembly lines,” *International Journal of Production Research*, vol. 4, no. 3, 1966, pp. 171-184.
[2] S. Payne, N. Slack, and R. Wild, R, “A note on the operating characteristics of ‘balanced’ and ‘unbalanced’ production flow lines,” *International Journal of Production Research*, vol. 10, no. 1, 1972, pp. 93-98.
[3] R. Kala, and G. G. Hitchings, “The effects of performance time variance on a balanced, four station manual assembly line”. *International Journal of Production Research*, vol. 11, no. 4, pp. 1973, 341-353
[4] N. D. Slack, "Un-paced manual flow line operating characteristics under steady-state and non-steady state conditions," Ph.D. Thesis, Brunel University 1975.
[5] T. Sastri, “An investigation into of a stochastic flow line during start ups,” M.Sc. Thesis, Ohio University. 1977
[6] W. E. Wilhelm, and T. Sastri, "An investigation of flow line operating characteristics during start-up," *International Journal of Production Research*, vol.17, no.4, 1979, pp.345 - 358.
[7] N. D. Slack, and R. Wild, "The non-steady state performance of un-paced manual assembly lines," *International Journal of Production Research*, vol.18, no. 5, 1980, pp. 583 - 595.
[8] U. C. Gupta, and O. P. Sharma, “On the transient behaviour of a model queues in series with finite capacity,” *International Journal of Production Research*, vol. 21, no. 6, 1983, pp. 869 - 879.
[9] S. Saboo, and W. E. Wilhelm, “Description of certain process in flow-lines,” *International Journal of Production Research*, vol. 25, no. 9, 1987, pp. 1355 -1 392.
[10] N. Slack, “Work time distributions in production system modelling,” Research Paper, Oxford Centre for Management Studies, 1982.
[11] S. Shaaban, and T. McNamara, “Improving the efficiency of un-paced production lines by unbalancing service time means,” *International Journal of Operations Research*, vol. 4, no. 3, 2009, pp. 346 – 360.
[12] S. Shaaban, and S. Hudson, “The performance of un-paced serial production lines with unequal coefficients of variation of processing times,” *International Journal of Computer Applications in Technology*, vol. 34, no. 2, 2009, pp. 122 – 128.
[13] S. Shaaban, and S. Hudson, “Improving production line performance - simulations make the case for uneven buffering, placed appropriately between workstations,” *Circuits Assembly*, June, 2008, pp. 1 – 3.
[14] S. Shaaban, and T. McNamara, “The effects of joint operation time means and variability unbalance on production line performance,” *International Journal of Manufacturing Technology and Management*, Vol. 18, No. 1, 2009, pp. 59 - 78.
[15] S. Shaaban, and S. Hudson, “Lean is cake,” *Industrial Engineer, Institute of Industrial Engineering*, vol. 41, no. 4, April, 2009, pp. 48 – 53.
[16] S. Shaaban, and S. Hudson, “How to get the most from an unbalanced production line,” *Industry Week*, May 2008, pg. 4.