THE BEHAVIOUR OF UNPACED PRODUCTION LINES WITH UNEQUAL MEAN PROCESSING TIMES, VARIABILITY, OR BUFFER CAPACITIES

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ABSTRACT

In this paper we study the operating behaviour and performance of reliable, unpaced and unbalanced serial production lines with either imbalanced service time means, unequal coefficients of variation, or uneven buffer capacities. The lines were simulated with various values of line length, buffer storage size, degree of imbalance, coefficient of variation, along with a number of imbalance configurations. The primary measures of efficiency were idle time and average buffer level. Output data from the discrete event simulation of such lines under their steady-state mode of operation were analyzed using a set of statistical methods. Various relationships between the independent and response variables, rankings of configurations and comparisons with balanced lines were obtained. For the mean processing times imbalance, it turned out that a bowl-shaped arrangement provides smaller idle time amounts and lower average buffer levels than those of a balanced line counterpart. As regards the variability imbalance, it was found that the best configurations are respectively, a bowl allocation and a monotone decreasing order, with the first resulting in decreased idle times and the second leading to lower average buffer levels than those of a balanced line. As far as the buffer size imbalance is concerned, it was concluded that the most advantageous patterns that generate lower idle times and average buffer levels as compared to a balanced line are to respectively distribute total available buffer capacity as evenly as possible along the buffers and to allocate more buffer capacity towards the end of the line.

Keywords: unpaced serial production lines; simulation; one source imbalance; imbalanced operation time means; unequal coefficients of variation; uneven buffer sizes; idle time; average buffer level
1. INTRODUCTION

When setting up an unpaced production line (with no form of mechanical pacing), how you design it is going to impact its efficiency quite considerably. For instance, where to place operators who work at different speeds, or vary in the speed they work at or where to keep unfinished items along the production line are just some of the problems facing the line manager.

Buffer Allocation
One factor that needs thinking about is determining the size of the storage space (buffer) in between workstations where partly finished products are kept, awaiting the next step of the process. Lines unbalanced with respect to their buffer capacities are of great interest as technical considerations often restrict the amount of space available in the line, thereby making it difficult to allocate total buffer capacity evenly amongst individual buffers.

Average Working Time of an Operator
Not all the operators are going to be able to complete their tasks at the same time. People work at different average speeds for several reasons, some are personal, their physical capacity, their motivation and some are inherent to the task, it might be a complex task or just simply that the amount of work along the line just can’t be distributed evenly in terms of time. It is clear that some tasks cannot be completed until the preceding steps have taken place; a very simplistic example being we can’t pack a product until it’s made.

Worker Variability
Not only do different operators work at different speeds, the one and same person can vary in the rate at which he or she works over the day for example. A person’s working speed can vary considerably from his or her average. This can be for different reasons: fatigue, boredom and tasks that are complex or changing.

Figure 1 shows a 5-station serial line with 4 buffers, where the squares depict the stations and the diamonds represent the buffers:

![Figure 1. An unpaced production line](image)

This paper is organized as follows. First, the relevant literature is reviewed. Next the objectives, methodology and experimental design of the study are presented. Subsequent sections give the simulation results, their analysis and compare the performance of balanced and unbalanced lines. The two last sections provide summary of the results, discussion and conclusions.

2. LITERATURE REVIEW

Unpaced serial production lines are a vitally important type of production system. A multitude of industries rely on them to provide a whole host of goods and services. Because of this critical role, they have deservedly received a great deal of attention in the literature.
2.1 Unbalanced Operation Time Means

Numerous studies have been reported on the performance and behaviour of unbalanced lines with unequal mean service times (MTs). These investigations can be classified into three general groups; bowl phenomenon, algorithmic and theory of constraint studies. These will be briefly reviewed in turn:

The Bowl Phenomenon
One of the most important investigations is that of [1], who analysed lines having up to 4 stations, exponential work time distributions, and equal buffer capacities. They found that the optimal throughput rate (TR) is achieved by assigning more work (higher MT) to the end stations and less work (smaller MT) to the middle stations, resulting in a gain of 0.54% in TR over that of the balanced line. They called this discovery the “bowl phenomenon”. It was found, however, that as the size of the buffers increases, this phenomenon quickly disappears, resulting in an optimal balanced line configuration. Later on, [2] & [3] extended their analysis to lines of up to six stations with Erlangian distributions and found that the improvement in TR due to unbalancing rises to 1.37% for a six-station line.

Since then several other papers have been published on various aspects of the bowl phenomenon (see for example [4] [5] [6]).

Algorithmic Approaches
A second line of research focused on the development of mathematical and algorithmic approximation methods to obtain various performance measures (mainly TR). Several investigations have been conducted, resulting in predictive formulas being developed and applied to various MT unbalanced conditions (see e.g. [7] [8] [9]).

Theory of Constraints
A third research area is in line with the Theory of Constraints (TOC). Briefly, TOC is concerned with the identification of the slowest station (the bottleneck or constraint), and adding more resources to it so that it will never be starved of work. TOC is based on the drum-buffer-rope (DBR) concept. The drum represents the bottleneck station, which dictates the overall movement and TR of the line. The buffers are used to provide protection for the bottleneck against statistical fluctuations. The rope is a signalling device from the bottleneck to drive all stations to work in harmony with the pace of the bottleneck, pulling work into it. Another TOC control system is constant work in process (CONWIP), under which a limit is imposed on the line’s total work in process (WIP).

One of the earliest investigations into this domain was that of [10]. They modelled 6-station uniform as well as exponential single bottleneck lines, with buffer capacities of up to 20 units. They found that the average buffer content is highest in the buffer that immediately precedes the bottleneck.

[11] studied three types of line design: a traditionally balanced line, a just-in-time line, and a TOC line. He concluded that the TOC line performed better than the other two designs. Similar findings were obtained by [12] for a six-station line with the bottleneck being located at the last station.

[13] simulated two line designs; a CONWIP line with protective capacity and another without
it (balanced). The results indicate that a line with protective capacity achieves lower cycle times (higher TR) than a balanced line.

[14] studied a 4-station TOC line. Their results show that both protective capacity and location of the constraint lead to significantly improved output, smaller idle time, and less work in process, but with diminishing returns. They also found that it is beneficial to position the constraint at the first station.

[15] used simulation to investigate CONWIP lines with a single constraint located at the first, middle and last station. Some generalizations concerning the protective capacity amount and location were obtained.

[16] simulated single bottleneck lines and found that a DBR line outperforms a CONWIP line by 15%, with the percentage gain increasing when the bottleneck is placed near the beginning of the line. However, as the difference in capacity between the bottleneck and non-bottleneck stations falls below 2%, CONWIP starts to outperform the DBR.

[17] reported the same finding on the superiority of DBR line as compared to CONWIP, but at the cost of accumulating large WIP at the constraint station. [18] studied over 80 firms that instituted TOC methods and in each case they found significant improvements in operational performance.

[19] used a drum development method for manufacturing environments with bottleneck re-entrant flows, in an attempt to implement an effective DBR management system.

2.2 Unbalanced Variability of Service Times

[20] simulated a 4-station line with buffer capacity of 6 or more and found that interspersing the 2 deterministic stations with the 2 variable resulted in higher IT levels than those of the balanced line.

Other early studies, employing mostly simulation, seemed to show that placing stations incrementally, with the highest CVs towards the end of the line gave good results in terms of getting lower idle time (IT) than the balanced line, or a slight increase in output rate, or sometimes both (see e.g. [21] [22] [23]).

[24] found that the bowl phenomenon also existed for lines unbalanced in terms of their coefficients of variation (CVs). Their simulation of 4 and 10 station lines showed that a bowl-shaped line (stations with lowest CVs placed in the middle) gave lower IT and higher production rates than an inverted bowl-shaped line. They found that the gains due to unbalancing the CVs were higher than those seen when unbalancing the MTs. [25] confirmed the results of [24] concerning the favourable performance of the bowl arrangement.

In a study of 3, 4 and 12 station lines, [26] found that for the shorter 3 and 4 station lines, slight reductions in IT were obtained for the bowl pattern over the balanced line. For the longer 12 station line however, ITs were significantly higher than for the control, suggesting that the superiority of the bowl pattern only existed for shorter lines. This tendency was also observed by [27], with the best patterns for shorter lines being bowl-shaped, while for longer lines (N ≥ 9), the bowl pattern gave results inferior to the balanced line.
Other approaches include the use of heuristic or optimization methods to assess the performance of CV-unbalanced lines, mostly in terms of throughput rate (see for instance [28] [29] [30] [31]). These algorithms have been applied to lines having unequal CVs, squared CVs or standard deviations under a variety of operating conditions and for differing CV patterns.

2.3 Uneven Buffer Capacities

There is a significant body of literature on the issue of buffer allocation in production lines and its effects on performance.

[32] found no substantial improvement in throughput from uneven buffering. In addition, if unbalancing was unavoidable, larger buffer capacity (BC) should be allocated to the central stations and smaller BC to the end stations.

[33] developed an algorithm to determine the optimal buffer allocation with regard to throughput. Results showed that for a limited number of occasions, a line with unbalanced buffers can provide a superior throughput to that of a balanced line. [34] indicated that BC should be placed as evenly as possible along the line, but any small additional amount of BC should be allocated to the line’s centre.

[35] stated that for a limited total buffer capacity, a balanced allocation is best. As more BC becomes available, preferential treatment should be given to the centre of the line.

[36] concluded that there is no single optimal buffer allocation policy for all operating conditions, but that preference should be given to the central locations of the line. Should an optimal buffer configuration be unknown; it is best then to strive for an inverted bowl arrangement. This was referred to as the ‘storage bowl phenomenon’.

[37] studied a three station line with two buffer locations, namely B1 and B2. He found it best to alternate between the two placed (i.e. assigning the first unit to B1, the second unit to B2, the third unit again to B1 and so on). This policy was termed the ‘Alternation Rule’.

[38] advised that the central stations should be given priority when allocating BC. [39] found that the optimal placement of a single unit of buffer is toward the central location, resulting in an increase in throughput.

Other authors developed a variety of buffer allocation algorithms. [29] used dynamic programming to determine an optimal BC allocation. [40] developed a solution procedure for optimizing profit within buffer and production constraints. [41] worked out a cash-flow oriented buffer allocation method. [42] employed a simulated annealing approach to find an optimal BC policy. [43] developed an algorithm for allocating buffer capacity to minimize average work-in-process.

[44] stated that if the interest is to maximize throughput, then an inverted bowl or a close approximation is generally the preferred arrangement. On the other hand, if the objective was a reduction in average WIP level, then it is better to allocate more buffers towards the end of the line.

[45] in a comparison study of three rules for buffer allocation using search methods found that
lines where buffer space was evenly distributed should be avoided when combined with ascending or descending mean-time operation patterns in terms of throughput.

[46] utilized a dynamic programming algorithm for the efficient distribution of BC, with the stated objectives of maximizing throughput and minimizing cycle time, WIP, and the probability of a station being blocked.

[47] tested the bowl storage hypothesis in balanced and unbalanced lines. In the case of a line with buffer imbalance, optimal solutions in terms of cost showed that the bowl storage pattern performed best for lines with more buffer space, and that more evenly allocated buffers gave the optimal solution when buffer space was limited. These results were confirmed in a later study by [48] with the same patterns being seen for limited or plentiful buffer space availability in lines unbalanced in terms of their mean operation times.

[49] looked at buffer allocation in terms of whether and when a push or pull strategy was best at different line lengths. For lines where the buffer was allocated evenly, throughput was maximised, whereas unbalancing the buffer allocation gave better results in terms of WIP, ascending buffer patterns being superior to descending patterns.

More recently, [50] considered buffer allocation in balanced and unbalanced lines as part of a study investigating both reliable and automated lines.

### 3. STUDY OBJECTIVES, METHODOLOGY AND EXPERIMENTAL DESIGN

This research aims at studying the operating behaviour of reliable unpaced lines, with unequal mean service times, variability, or buffer sizes. The main objectives of the investigation are:

- To assess the merits of various patterns of imbalance and identify the best ones.
- To compare and contrast the performance of the unbalanced lines studied with that of a balanced line counterpart and determine possible performance improvement.
- To gauge the effects of line design factors – line length, buffer capacity / mean buffer capacity and degree of imbalance on the dependent measures of performance; idle time and average buffer level.
- To identify the most important factors influencing the dependent variables.

As no mathematical procedure is presently capable of handling the unbalanced steady-state characteristics of the more realistic lines, computer simulation was utilized as the most suitable technique for this kind of study.

#### 3.1 Factorial Design

The most efficient and powerful of the many experimental designs is the complete factorial design. This type of design has been chosen for the current investigation. In the context of the particular lines being studied, the independent variables were:

- Total number of stations in the line (N).
- Total amount of buffer capacity for the line (TB).
- Buffer capacity, BC / mean buffer capacity (MB), where MB = TB divided by the number of buffers.
- Degree of unbalanced service time means (DI).
- CV value range
- Pattern of mean work time (MT) imbalance.
- Pattern of coefficients of variation (CV) imbalance.
- Pattern of buffer capacity (BC) imbalance.

### 3.2 Work Times Distribution and Performance Measures

[51] undertook a detailed investigation of published histograms of operation times experienced in real life and concluded that processing times follow a Weibull distribution (positively skewed), with an average CV value of around 0.274. This probability distribution was utilized in this study.

One way to measure how efficiently a line is working is through the calculation of the average buffer level for the whole line (ABL); obviously, we want to keep the number of unfinished pieces in storage as low as possible. Another approach is to compute the time that the line is not functioning (idle time or IT) as a percentage of total working time. This needs to be kept as low as possible as well in the interests of keeping labour costs down.

### 3.3 Simulation Run Parameters and Model Assumptions

The following parameter values were employed:

- **Initial conditions:** start the simulation run with all the buffers being nearly half-full.
- **Length of the transient period:** discard all accumulated statistics produced during the 5,000 time units (TU) start-up period.
- **Length of the simulation run and number of observations of performance measures:** use a steady-state run length of 30,000 TU, divided into 12 batches of 2,500 TU each, i.e. the mean dependent variable values are recorded every 2,500 TU and then the grand mean, representing the average of these 12 mean values, is computed. Results obtained from a trial procedure confirmed that these figures were sufficient to reduce the IT and ABL autocorrelations to the negligible values of 0.001 and 0.000 respectively.

The basic operating assumptions for the reliable unpaced serial flow line simulated are as follows:

- The first station is never starved and the last station is never blocked.
- No breakdowns occur and no defective parts are produced.
- Only one type of product flows in the system, with no changeovers.
- Time to move the work units in and out of the storage buffers is very small, hence negligible.

### 3.4 Unbalanced Lines Investigated

Three types of unbalanced lines with only one source of imbalance were studied. Their designs are summarized in Table 1 on the next page.

In the investigations into the effects of imbalance from single sources, the independent variables not directly under study were kept constant, whereas the variable of interest was simulated in different patterns along the line, and the outcome variable computed for each of these configurations.
Source of Imbalance | MT | CV | BC / MB | Line Length (N)
--- | --- | --- | --- | ---
SINGLE SOURCE | a. Mean Operation Time (MT Investigation) | Degree of Imbalance: 2%, 5% and 12% | CV = 0.274 | 1, 2 and 6 units equal for each station | 5 and 8 stations
b. Variability (CV Investigation) | 10 units/station | CV = 0.08; 0.27 and 0.50 | 1,2 and 6 units equal for each station | 5 and 8 stations
c. Buffer Capacity (BC Investigation) | 10 units/station | CV = 0.274 | MB 2 and 6 allocated unevenly | 5 and 8 stations

Table 1. Line designs studied (source of variability in bold)

For all three of the investigations, the line length was specified at two values, a shorter 5-station line (N = 5) and a longer 8-station line (N = 8).

The single source lines were those imbalanced in terms of:

- **a. 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. Buffer capacity (BC) was set at 1, 2 and 6 units. Mean time imbalance patterns were simulated with degrees of imbalance at 2% (very low imbalance), 5% (relatively low imbalance), and 12% (higher imbalance).

- **b. Unbalanced coefficients of variation (CV investigation):** each station has identical mean operation time value (MT), held constant at 10 units per workstation for both line lengths, and buffer capacity was 1, 2 and 6 units. The coefficients of variation were defined as steady, S (CV = 0.08), medium, M (CV = 0.27) and variable, V (CV = 0.5).

- **c. Uneven buffer sizes (BC investigation):** each station has the same mean processing time and CV values (10 time units and 0.274, respectively), but buffer sizes are unequal. Mean buffer values were 2 and 6 units, allocated unevenly between stations.

### 3.5 Patterns of Imbalance

In this section we will go into more detail with respect to the specific patterns of imbalance that are studied here.

In the study where mean operation times are imbalanced (MT Investigation), four patterns of imbalance are considered:

- A monotone increasing order (↑).
- A monotone decreasing order (↓).
- A bowl arrangement (V).
- An inverted bowl shape (ʌ).

When coefficients of variability were imbalanced (CV Investigation), four CV imbalance policies were simulated; these were as follows:
• 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).

These CV imbalance policies are illustrated in Table 2 below:

<table>
<thead>
<tr>
<th>Pattern (Pi) of Unbalanced CVs</th>
<th>Line Length (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>P1</td>
<td>MSVMS</td>
</tr>
<tr>
<td>P2</td>
<td>VMSVM</td>
</tr>
<tr>
<td>P3</td>
<td>SMVSM</td>
</tr>
<tr>
<td>P4</td>
<td>MSSSV</td>
</tr>
<tr>
<td>P5</td>
<td>MSSSV</td>
</tr>
<tr>
<td>P6</td>
<td>VMMMS</td>
</tr>
<tr>
<td>P7</td>
<td>SMMMV</td>
</tr>
<tr>
<td>P8</td>
<td>MVVVS</td>
</tr>
</tbody>
</table>

*Table 2: Unbalanced CV patterns S: (CV = 0.08), M (CV = 0.27), V: (CV = 0.50)*

In the case of buffer capacity imbalance (BC Investigation), four policies were also explored for total buffer capacity allocation – these can be described as:

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

These policies are displayed on the next page in Table 3.
<table>
<thead>
<tr>
<th>Line Length (N)</th>
<th>5</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Buffer Size (MB)</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>P1 A</td>
<td>1,1,1,5</td>
<td>3,3,3,15</td>
</tr>
<tr>
<td>P2 B</td>
<td>1,1,5,1</td>
<td>3,3,15,3</td>
</tr>
<tr>
<td>P3 C</td>
<td>5,1,1,1</td>
<td>15,3,3,3</td>
</tr>
<tr>
<td>P4 D1</td>
<td>2,2,3,1</td>
<td>6,6,9,3</td>
</tr>
<tr>
<td>D2</td>
<td>2,3,2,1</td>
<td>6,9,6,3</td>
</tr>
<tr>
<td>D3</td>
<td>2,1,3,2</td>
<td>6,3,9,6</td>
</tr>
<tr>
<td>Total Buffer Capacity (TB)</td>
<td>8</td>
<td>24</td>
</tr>
</tbody>
</table>

Table 3. Unequal buffer size patterns (Pi = policy of buffer capacity imbalance)

### 4. RESULTS

Due to space limitations, only IT and ABL results for the best, second best or good, and the worst patterns will be shown.

#### 4.1 Idle Time Results

#### 4.1.1 IT Data

Tables 4-7 exhibit IT data for a number of unbalanced and balanced line configurations for the MT, CV and BC investigations:

<table>
<thead>
<tr>
<th>Buffer Size</th>
<th>1</th>
<th>2</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Imbalance Degree</td>
<td>2</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Balanced Line</td>
<td>9.522</td>
<td>4.985</td>
<td>2.066</td>
</tr>
</tbody>
</table>

Table 4. MT investigation: IT data for patterns \, /, ^, V and the balanced line (5 stations)

<table>
<thead>
<tr>
<th>Buffer Size</th>
<th>1</th>
<th>2</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Imbalance Degree</td>
<td>2</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>V</td>
<td>11.123</td>
<td>11.239</td>
<td>11.774</td>
</tr>
<tr>
<td>Balanced Line</td>
<td>11.522</td>
<td>5.935</td>
<td>2.174</td>
</tr>
</tbody>
</table>

Table 5. MT investigation: IT data for patterns \, /, ^, V and the balanced line (8 stations)
Table 6. CV investigation: IT data for patterns P2, P4-P6 and the balanced line.

<table>
<thead>
<tr>
<th>Line Length</th>
<th>5</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffer Size</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>P2</td>
<td>11.019</td>
<td>6.656</td>
</tr>
</tbody>
</table>

Table 7. BC investigation: IT data for patterns A1-A2, B1, C1, D1-D2 and the balanced line.

<table>
<thead>
<tr>
<th>Line Length</th>
<th>5</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Buffer Size</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>A2</td>
<td>7.978</td>
<td>3.094</td>
</tr>
<tr>
<td>B1</td>
<td>7.532</td>
<td>2.696</td>
</tr>
<tr>
<td>C1</td>
<td>9.009</td>
<td>3.149</td>
</tr>
<tr>
<td>D1</td>
<td>5.707</td>
<td>2.082</td>
</tr>
<tr>
<td>D2</td>
<td>5.598</td>
<td>1.733</td>
</tr>
<tr>
<td>Balanced Line</td>
<td>4.985</td>
<td>2.066</td>
</tr>
</tbody>
</table>

4.1.2 Ranking of Policies and Patterns

From Tables 4-7, the following observations can be made:

MT investigation:
- The results indicate that the bowl arrangement (V) is the best unbalanced pattern, followed by the inverted bowl pattern (^).
- A decreasing mean pattern (\) is the worst.
- Pattern (/) is generally better than pattern (\), with the difference in IT being slight.

CV investigation:
- It is not possible to discern one overall policy as being the best or the worst with respect to all constituent patterns.
- Pattern P4, a bowl arrangement, is the best overall pattern, followed by P5 (the second bowl pattern).
- Configuration P6 is the worst.

BC investigation:
- None of the four policies can be regarded as the best or the worst in terms of all its constituent patterns.
• D2 (N = 5) and D1 (N = 8) are the best unbalanced patterns, i.e. the best configuration is one where the available capacity is distributed as uniformly as possible along the line.
• D1 (N = 5) and D2 (N = 8) can be deemed as good configurations.
• A1 (the increasing order arrangement) is the worst.
• Within policies 1, 2, and 3, patterns A1, B1, C1 are respectively the worst; lending support to the strategy of avoiding extreme allocation of TB (i.e. most TB is assigned to one buffer and the rest to the other buffers).
• The descending order policy may be considered as generally the best alternative if a balanced, or close to balanced buffer arrangement is not feasible.

4.1.3 Effects of the Independent Variables on IT

The simulation results show the following relationships between the design factors and idle time:

MT investigation:
• An increase in N causes a corresponding rise in IT, particularly for smaller levels of BC in the case of the best pattern.
• As BC increases IT decreases, with the rate of decrease for the best pattern slowing down as BC and N continue to increase.
• IT goes up as DI becomes higher, with the rate of increase accelerating for larger BC values.

CV investigation:
• IT increases with N especially the lower BC is in the case of the best pattern.
• When BC is expanded IT goes down.

BC investigation:
• As N increases, IT tends to increase. For the best pattern, the IT tendency to increase with N is more substantial the lower MB is.
• IT decreases as MB goes up. The marginal decrease in IT for the best pattern falls as both MB and N increase.

4.1.4 ANOVA

ANOVA outcomes for the MT, CV and BC investigations show that all of the main effects are highly significant at the 99% confidence level and that all of the interactions are significant at the 95% level or above. The sub-run (batch size) effect appears to be non-significant, lending support to the contention that all the data represent the steady state condition. The ranking of the variables influencing IT are as follows:

MT investigation: the most important factor affecting IT is DI. The second and third factors are BC and MT pattern, respectively.

CV investigation: the strongest effect on IT comes from BC, whereas the pattern of CV imbalance has a lesser impact.

BC investigation: The main independent variable influencing IT is MB, followed by the
imbalance pattern

4.2 Average Buffer Level Results.

4.2.1 ABL Data

Tables 8-11 show ABL data for various unbalanced and balanced line configurations for the MT, CV and BC investigations:

<table>
<thead>
<tr>
<th>Buffer Size</th>
<th>1</th>
<th>2</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Imbalance Degree</td>
<td>2</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Pattern of Unbalanced Means</td>
<td>/</td>
<td>0.591</td>
<td>0.673</td>
</tr>
<tr>
<td>\</td>
<td>0.468</td>
<td>0.398</td>
<td>0.249</td>
</tr>
<tr>
<td>V</td>
<td>0.533</td>
<td>0.560</td>
<td>0.588</td>
</tr>
<tr>
<td>^</td>
<td>0.542</td>
<td>0.526</td>
<td>0.542</td>
</tr>
<tr>
<td>Balanced Line</td>
<td>0.526</td>
<td>1.033</td>
<td>3.321</td>
</tr>
</tbody>
</table>

Table 8. MT investigation: ABL data for patterns \, /, ^, V and the balanced line (5 stations)

<table>
<thead>
<tr>
<th>Buffer Size</th>
<th>1</th>
<th>2</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Imbalance Degree</td>
<td>2</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Pattern of Unbalanced Means</td>
<td>/</td>
<td>0.614</td>
<td>0.698</td>
</tr>
<tr>
<td>\</td>
<td>0.503</td>
<td>0.406</td>
<td>0.284</td>
</tr>
<tr>
<td>V</td>
<td>0.569</td>
<td>0.554</td>
<td>0.575</td>
</tr>
<tr>
<td>^</td>
<td>0.552</td>
<td>0.548</td>
<td>0.544</td>
</tr>
<tr>
<td>Balanced Line</td>
<td>0.559</td>
<td>0.970</td>
<td>2.601</td>
</tr>
</tbody>
</table>

Table 9. MT investigation: ABL data for patterns \, /, ^, V and the balanced line (8 stations)

<table>
<thead>
<tr>
<th>Line Length</th>
<th>5</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buffer Size</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Pattern of Unbalanced CVs</td>
<td>P4</td>
<td>0.397</td>
</tr>
<tr>
<td>P5</td>
<td>0.668</td>
<td>1.373</td>
</tr>
<tr>
<td>P6</td>
<td>0.503</td>
<td>0.992</td>
</tr>
<tr>
<td>P8</td>
<td>0.674</td>
<td>1.271</td>
</tr>
<tr>
<td>Balanced Line</td>
<td>0.526</td>
<td>1.033</td>
</tr>
</tbody>
</table>

Table 10. CV investigation: ABL data for patterns P4, P5, P6, P8 and the balanced line.
<table>
<thead>
<tr>
<th>Line Length</th>
<th>5</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Buffer Size</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Pattern of Buffer Size Imbalance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>0.531</td>
<td>1.457</td>
</tr>
<tr>
<td>A2</td>
<td>0.534</td>
<td>1.679</td>
</tr>
<tr>
<td>A3</td>
<td>0.615</td>
<td>1.733</td>
</tr>
<tr>
<td>D2</td>
<td>1.218</td>
<td>2.792</td>
</tr>
<tr>
<td>Balanced Line</td>
<td>1.033</td>
<td>3.321</td>
</tr>
</tbody>
</table>

Table 11. BC investigation: ABL data for patterns A1-A3, D2 and the balanced line

### 4.2.2 Ranking of Policies and Patterns

Based on Tables 8-11 it is interesting to note the following:

**MT investigation:**
- The best pattern turns out to be the descending (\(\) order.
- The second and third best patterns being respectively, an inverted bowl (\(^{\wedge}\)) and a bowl (V) arrangements.
- The worst pattern is the increasing (\(/\)) configuration.

**CV investigation:**
- Since each policy includes a number of patterns with varying performance, it is impossible to label one specific policy as either the best or the worst. Specific configurations within the policies however, may be regarded as superior or inferior.
- The bowl-shaped pattern P4 is the best for ABL. This is the same pattern that gave the best results for IT.
- The worst patterns are generally P5 and P8.

**BC investigation:**
- Again, no one policy can be said to be the best or the worst.
- The best pattern is A1 for \(N = 5\), and A2 for \(N = 8\), i.e. the best pattern has its buffer capacity concentrated towards the end of the line (an ascending order).
- When \(N = 5\), A2 is the second best pattern and when \(N = 8\), A3 is the second best configuration.
- In general, configuration D2 (the random arrangement) can be viewed as the worst.

### 4.2.3 Effects of the Independent Variables on ABL

As regards the impact of the exogenous variables on average buffer level, the simulation data indicate the following relationships:

**MT investigation:**
- ABL becomes higher as BC is increased. This increase in ABL continues at a diminishing rate as BC rises and as \(N\) is reduced.
- As DI increases ABL falls, with the drop in ABL becoming less marked as DI continues to go up and as BC decreases.
CV investigation:
  - As BC rises, so does ABL.

BC investigation:
  - ABL increases with MB.

It should be noted that in the three investigations the influence of line length seems not to be important; there is no directly observable pattern of change of ABL levels with N.

4.2.4 ANOVA.

The analysis of variance of the simulated ABL data for the MT, CV and BC investigations produced the same findings as those found in section 4.1.4 on IT results. The rankings of the independent parameters influencing ABL are as follows:

MT investigation: the most important factor affecting ABL is BC, followed respectively by MT pattern and DI.

CV investigation: as was the case for idle times, the most salient variable influencing ABL is BC, followed by the CV pattern.

BC investigation: the most significant exogenous factor impacting ABL is MB, followed by the pattern of buffers.

5. BEST UNBALANCED PATTERNS’ SAVINGS OVER THE BALANCED LINE

In the MT investigation, the most favourable unbalanced MT pattern in terms of IT was a bowl configuration (V). Table 12 (see next page) shows the percentage differences in this pattern’s IT vis-a-vis the balanced line (the control).

From Table 12, the following can be observed:
  - The highest improvement in IT for the most favourable configuration over the balanced line is 3.46%
  - An increase in DI either reduces or immediately eliminates the advantage in IT, especially for higher BC values.
  - As BC increases, this advantage either instantly or gradually disappears.
  - When N becomes larger, the advantage goes up in magnitude.

On the other hand, the best pattern in ABL is a decreasing MT order (\). Table 13 (see next page) exhibits the percentage savings in the best configuration’s ABL over the balanced line:

The following can be discerned from Table 13:
  - The highest saving in ABL for the best pattern over the balanced line is 87.56%. So, placing the fastest operators at the end of the line can bring considerable advantages in terms of ABL performance.
  - The best pattern outperformed the balanced line for all line lengths, buffer capacities and degrees of imbalance in mean times.
  - As DI goes up, the superiority of the best pattern over the control increases.
- Increasing BC has the effect of raising the best pattern’s advantage.

<table>
<thead>
<tr>
<th>Buffer Size</th>
<th>% Imbalance Degree</th>
<th>% Difference</th>
<th>Buffer Size</th>
<th>% Imbalance Degree</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>-1.27</td>
<td>1</td>
<td>2</td>
<td>-3.46</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>0.31</td>
<td>1</td>
<td>5</td>
<td>-2.46</td>
</tr>
<tr>
<td>1</td>
<td>12</td>
<td>6.41</td>
<td>1</td>
<td>12</td>
<td>2.18</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-0.88</td>
<td>2</td>
<td>2</td>
<td>-2.74</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>1.79</td>
<td>2</td>
<td>5</td>
<td>14.50</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>30.95</td>
<td>2</td>
<td>12</td>
<td>23.90</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>-0.31</td>
<td>6</td>
<td>2</td>
<td>-0.82</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>22.80</td>
<td>6</td>
<td>5</td>
<td>18.86</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>141.77</td>
<td>6</td>
<td>12</td>
<td>160.26</td>
</tr>
</tbody>
</table>

(-) indicates saving

Table 12. MT investigation: % differences in the best pattern’s IT over the control

<table>
<thead>
<tr>
<th>Buffer Size</th>
<th>% Imbalance Degree</th>
<th>% Saving</th>
<th>Buffer Size</th>
<th>% Imbalance Degree</th>
<th>% Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>-11.30</td>
<td>1</td>
<td>2</td>
<td>-10.02</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>-25.29</td>
<td>1</td>
<td>5</td>
<td>-27.37</td>
</tr>
<tr>
<td>1</td>
<td>12</td>
<td>-52.66</td>
<td>1</td>
<td>12</td>
<td>-49.20</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>-10.94</td>
<td>2</td>
<td>2</td>
<td>-14.74</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>-48.11</td>
<td>2</td>
<td>5</td>
<td>-33.92</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>-71.83</td>
<td>2</td>
<td>12</td>
<td>-64.23</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>-49.65</td>
<td>6</td>
<td>2</td>
<td>-15.96</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>-70.16</td>
<td>6</td>
<td>5</td>
<td>-59.67</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>-87.56</td>
<td>6</td>
<td>12</td>
<td>-82.66</td>
</tr>
</tbody>
</table>

(-) indicates saving

Table 13. MT investigation: % savings in the best pattern’s ABL over the control

For the CV investigation, the best overall results for reducing both idle times and average buffer levels came from pattern 4, one of the two bowl shaped patterns considered, with the steadier workers in the middle. A summary of the % differences in IT and ABL are shown for the best pattern in Table 14 (see next page).
Table 14. CV investigation: % differences in the best pattern IT and ABL compared to the control

From Table 14, the following points can be noted:

- The best IT saving over the balanced line (-43.08%) and the best ABL superiority (-53.75%) represent considerable savings.
- The improvements in IT disappear as the line lengthens, whereas the savings in ABL increase with the number of workstations.
- The unbalanced line is consistently superior to the balanced line for the ABL results across the board.
- There is no consistent trend which appears with the increase in buffer levels.

As regards the BC investigation, Table 15 summarises the % differences in IT and ABL for the best unbalanced patterns in comparison with those of the balanced line:

Table 15. BC investigation: % savings in the best pattern’s ABL over the control

As is exhibited in Table 15 above, the following can be concluded:

- Pattern D2 (no concentration of available buffer capacity) shows a reduction in IT of 16.14% as compared to the balanced line, whereas for configuration A1 (buffer capacity is concentrated towards the end of the line), the savings obtained in ABL are considerable (over 56%).
- As N increases, any saving in IT disappears while ABL’s advantage declines.
- The best pattern consistently exhibits significantly lower ABL levels over the balanced line for all factor levels considered.

6. SUMMARY

Several unbalancing policies and methods were examined in three single-source imbalance investigations. None of the policies were noticeably better or worse than any of the others in broad terms, but there were particular patterns within each policy that showed improvements of performance either in idle time or in average buffer level when compared to the balanced line counterpart. Table 16 (see next page) summarizes the best performing configurations in terms of IT and ABL for the three investigations:
Best Performance Configurations

<table>
<thead>
<tr>
<th>Mean Operation Times (MT)</th>
<th>Idle Time</th>
<th>Average Buffer Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bowl pattern</td>
<td>Descending order</td>
<td></td>
</tr>
<tr>
<td>Variability (CV)</td>
<td>Bowl pattern</td>
<td>Bowl pattern</td>
</tr>
<tr>
<td>Buffer Capacity (BC)</td>
<td>Close to balance</td>
<td>Ascending order</td>
</tr>
</tbody>
</table>

Table 16. The influence of single source imbalance patterns on idle time and average buffer levels

It should be noted from Table 16 above that for the CV investigation the best pattern in terms of both idle time and average buffer level results is the bowl shaped pattern. This is of great interest to those manufacturers who, within the constraints of lean buffering need to keep down buffer levels and increase output rates at the same time.

It was found that for all the three investigations, as BC/MB increases, IT goes down but ABL rises, suggesting that BC/MB exerts an opposite influence on IT and ABL. In the case of the MT investigation, increasing DI raises IT, but ABL declines. Also, when DI is increased, the % saving in IT over the balanced line decreases, but in terms of ABL it increases.

In addition, it was observed that the best configurations result in a significantly smaller ABL levels than those of corresponding balanced lines at all the factor levels considered.

As regards the influence of the various factors on IT and ABL, Table 17 below summarizes ANOVA findings:

<table>
<thead>
<tr>
<th>Investigation</th>
<th>Performance Measure</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT</td>
<td>IT</td>
<td>DI</td>
<td>BC</td>
<td>MT pattern</td>
</tr>
<tr>
<td>CV</td>
<td>IT</td>
<td>BC</td>
<td>CV pattern</td>
<td>----</td>
</tr>
<tr>
<td>BC</td>
<td>IT</td>
<td>MB</td>
<td>BC pattern</td>
<td>----</td>
</tr>
<tr>
<td>MT</td>
<td>ABL</td>
<td>BC</td>
<td>MT pattern</td>
<td>DI</td>
</tr>
<tr>
<td>CV</td>
<td>ABL</td>
<td>BC</td>
<td>CV pattern</td>
<td>----</td>
</tr>
<tr>
<td>BC</td>
<td>ABL</td>
<td>MB</td>
<td>BC pattern</td>
<td>----</td>
</tr>
</tbody>
</table>

Table 17. Ranking of the independent variables in their effects on IT and ABL

Moreover, the best patterns found have resulted in various degrees of savings over the balanced line counterpart for the three investigations, as is shown below in Table 18.

<table>
<thead>
<tr>
<th>Investigation</th>
<th>% Saving in IT</th>
<th>% Saving in ABL</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT</td>
<td>-3.46</td>
<td>-87.56</td>
</tr>
<tr>
<td>CV</td>
<td>-43.08</td>
<td>-53.75</td>
</tr>
<tr>
<td>BC</td>
<td>-16.14</td>
<td>-56.13</td>
</tr>
</tbody>
</table>

(-) indicates saving

Table 18. Highest obtained % savings in IT and ABL
7. DISCUSSION AND CONCLUSIONS

The main purpose of this study was to assess the effects that unbalancing service mean times, coefficients of variation, or buffer sizes have on the efficiency of a production line. One of the main conclusions of this research is that the decision of how to allocate different sized buffers between workstations, where to place operators with different average working times and variability will depend on the particular conditions of the production facilities.

It may be a priority to keep the amount unfinished goods in storage as low as possible, for example fresh produce where hygiene and safety issues are important. In this case, a manager would opt for reductions in average buffer levels. To do this, one might allocate more buffer capacity to the end of the line. If worker average times are known to differ, it could be advantageous to put the fastest workers towards the end, and when workers vary in their average speeds to a great degree, one might consider placing the steadiest workers in the middle. This is especially the case where just-in-time and lean buffering strategies are in place where operations managers are facing enormous pressure to reduce expensive inventory, and so to decrease production lead times.

In contrast, if we are looking at a sector where labour costs are high, for example the automobile industry, then it could be advantageous to move towards bringing idle time down and either distributing buffer capacity as evenly as possible along the line or again considering placing faster workers towards the middle.

We should remember, however, that the best and other good patterns are specific patterns among numerous possibilities, and that imbalance directed in the wrong way could lead to the opposite effect, i.e. increases in average buffer levels and/or idle times.

Companies spend billions of dollars every year on the design, installation, operation, and maintenance of production lines. Even the slightest improvement in efficiency or reduction in inventory costs can result in substantial savings over the lifespan of a line. Since a balanced line is virtually unattainable in practice and that most lines suffer from a certain degree of imbalance, it would make sense for production managers to examine the benefits of deliberately unbalancing their lines in the right way, particularly as unbalancing can be done at no extra cost.

The study showed that in many cases substantially superior performance to that of the balanced line in terms of IT or ABL, or sometimes both is attainable (see Table 18 above).

The scale of the potential reductions in IT and ABL, when calculated over the lifecycle of a production line means that purposely unbalancing the buffer sizes and operators with different variability and speeds could lead to real benefits for the manufacturer and so might be a strategy to take into account when designing the production line.

It is hoped that this research has contributed to the total body of knowledge of production lines in giving new insights into how to fine tune unbalanced lines in order to improve performance. There is still scope for a considerable amount of research based on this study, for example experiments on the effects of the single source imbalance for merging (assembly) lines as well as for unreliable lines, will enrich knowledge in this area and give managers a more accurate picture when designing their production lines.
REFERENCES


