Influence of product variety on work allocation and server distribution of flexible manufacturing lines

A Arteaga1* and R Calvo1

1 ETS Ingeniería y Diseño Industrial, Universidad Politécnica de Madrid, Ronda de Valencia 3, 28012 Madrid, Spain

*Corresponding author: ag.arteaga@alumnos.upm.es

Abstract: Mass customization involves medium volume production of a high variety of products where flexible manufacturing systems can cope with it. The work allocation problem of assigning the work content of each workstation in a manufacturing line is formulated as the design problem of capacity allocation across the line by looking for the throughput maximization and/or simultaneous work-in-process containment or minimization. The bowl phenomenon refers to the distribution shape of work across the workstations in unpaced flow line (asynchronous flow) with buffers, experimentally observed and conjectured back in the 1960’s, but with theoretical roots not successfully established up today. The increasing value of flexible capability for mass customization makes worthy the research of the phenomenon in the presence of product variety, beyond the classical model of balanced dedicated flow lines. The three problems of workload, buffer, and server allocation are closely related, and they have been previously studied in queuing networks with meta heuristics. This paper faces the effect of product variety (service time variability) impact on the performance of the flow line, researching the bowl effect through experimental analysis. The results show a main influence of the coefficient of variation of the service times with the secondary effect of the buffer size.

Keywords: Bowl effect, Workload allocation, Flexible manufacturing lines, Stochastic manufacturing simulation.

1. Introduction

The increased demand for customized goods and services creates the need for change and adaptation in the manufacturing world. Production exists to satisfy a certain demand, and mass production of a common generic product fails to satisfy the now well connected and always changing market [1-2].

For a while the only measure of manufacturing performance was productivity, but since the implementation of lean manufacturing, it was clear that quality and flexibility in manufacturing processes and end products were gaining weight in the performance measure. Quality refers to the degree of perfection in making products, while Flexibility refers to the ability to adapt to change [3]. To study the behavior of a manufacturing production line and label it as good or better it is necessary to identify control parameters and some goal values or desired tendencies. In companies, these are usually called Key Performance Indicators KPI. The literature highlights the variables of flow factor, utility factor, work in process, and especially output rate or throughput rate as a reference value in form of their natural limitations [4]. In the mathematical world, this will be the optimization metrics. Taking into consideration the pressure to apply green manufacturing standards; the most obvious approach is to focus on the optimization of WIP throughput and utilization. A lot of research and time has been invested in finding efficient analytical methods to estimate throughput for manufacturing plants, other research
[5] does a good job summarizing these studies in this area for a system with unreliable machines and finite buffers. It also points out the importance of integration of productivity with quality and the flexibility to achieve demand satisfaction at low cost, along with the importance of a robust production design system able to respond to the variations of the manufacturing environment. It strengthens the motivations to study the applications of real-time data usage [5-7]. The bowl effect is an interesting result that is obtained by allocating the workload (service time at each workstation) following a concave function. To achieve this, a smaller mean time is assigned to the inner stations making them more powerful or faster. So, from the operator’s perspective, the workload allocation problem can be seen as a server time problem. In practical cases, a synchronous distribution of server time is highly complicated to achieve, increasing the value of finding a better performance in pre-defined unpaced line productions. [8]. Even when a lot of researchers have put their attention into proving and studying the existence of the bowl phenomenon as is shown in [8-12], where conclusions point out the relevance of server time and coefficient of variation (CV) when perfectly balanced workloads among stations is not possible. The lack of specificity and standardization of the results make it hard to find viable conclusive assumptions about the effect and its practical applications. Other studies, such as [13], conclude that the CV imbalance has a very small effect on throughput, and [14] where the server distribution becomes more influential when the CV is increased.

In this research, the experimental model of simulation of an unpaced flow line is created. The asynchronous flow line requires buffers to make the operations feasible. The parameters of influence in the throughput of the line are investigated looking for the bowl effect. The methodology is described in Section 2 and, in Section 3, the experimental setup and main results that are discussed. Finally, Section 4 summarizes the main findings and proposes further research.

2. Methodology
A complex system is characterized as being dynamic enough to respond to random demands. A five-station model with five buffers is set up to conduct the simulation experiments. No breakdowns were considered in this system with a set capacity and a set buffer size. Both the buffer capacity and the workload configuration are considered independent variables to conduct variance analysis.

![Figure 1. Line Simulation model in Simulink.](image)

The performance variables of throughput, wip, and utilization are evaluated. The code is programmed through MATLAB 2020a Simulink. The asynchronous flow is studied through a discrete event simulation, as shown in figure 1. The entity parts are generated into the system under an exponential distribution of mean 100 s. The exponential distribution is quite common in manufacturing systems because of its particular memoryless property that facilitates the study of the system. So, in the presence of random effects, the steady-state evolution of interest is not conditioned by the previous path. The control parameter was selected to study the influencing factor on workload allocation problem known as the bowl effect. The workload distribution in a workstation flow line can be, in theory, evenly distributed in a perfectly balanced line with the same mean service time at each workstation. This situation is ideal, but more properly utopic, since industrial processes associated with any product or products that are fabricated in the line hardly can be divided equally among the workstations. More often the work allocation will be unbalanced and the existence of buffers before each workstation provides the opportunity of maintaining an asynchronous transfer of the parts between stations. The need for a
buffer to decouple the different service times is the ordinary layout of unpaced lines. The work allocation problem of service time among workstations is formulated by (1).

\[
\max \{\text{Throughput}(w)\}; \sum_{i=1}^{k} w_i = W
\]

where \(w = w_1, w_2..., w_K\), denotes the vector of of workload \(w_i > 0\) allocation at each \(i\) workstation, \(i=1,2...,k\), with \(k\) being the number of stations equal to 5. Total work content \(W\) is constant across experiments and is set to 1500 s. The perfectly balanced line, one-level, is the solution with the bottleneck of 300 s, equally for each server. That is the arrangement with the maximum service time that is minimum. In consequence, the performance results for this ideal line are expected a priori superior to the rest. For the unbalanced distribution of unpaced lines, the mean service time adopts a two-level distribution profile of a three-level, see table 1. The service times form of the 5-workstation line is flat for one-level perfectly balanced line, increasing concavity or bowl profile distribution for two and three-level distributions.

**Table 1. Workload allocation distribution experimental setup.**

| Workload     | Service times (s)  |
|--------------|--------------------|
| One-level    | 300-300-300-300    |
| Two-level    | 310-293.3-293.3-293.3-310 |
| Three-level  | 310-293-295-293-310 |

The second set of experiments were conducted including the influence of product variety in demand mix. The variable of control and simulation designs are presented in table 2. Arranged as a design of experiments (DOE), the control parameters include the same CV for all workstations (ws). Demand mix was set at an 80% of the product used in former experiments and an additional second low runner with a share of 20% and a workload content of 1880 s following the three configurations of workload allocation: balanced, all at 300s, two-level \(ws1=ws5=380\) s, \(ws2=ws3=ws4=373.3\) s, and three-level \(ws1=ws5=380\) s, \(ws2=ws4=375\)s and \(ws5=370\) s.

**Table 2. Mix and workload allocation experimental setup.**

| #  | CV  | Demand mix | Workload |
|----|-----|------------|----------|
| 1  | 0.3 | 0.2 0.8    | One-level |
| 2  | 0.3 | 0.2 0.8    | Two-level |
| 3  | 0.3 | 0.2 0.8    | Three-level |

Some considerations made by Buzacott and Yao [15-16] can be taken into account for this research’s purpose, so a continuous supply into the system is assumed and, in consequence, the discussion is focused on the long-term behavior of the system. The simulations’ behavior was verified reducing the absolute tolerance and obtaining consistently similar results in each run. To measure the throughput, the departure number of pieces per simulation was calculated, inventory or work-in-process (WIP) was measured as the mobile average of the number of pieces in the system and the utilization as the average time the server was occupied. All measures are taken once the simulation is in a stationary state. The simulation had a run time of \(3.15 \times 10^7\) s, that is the approximate length of a year’s production with two shifts per day. An income rate of \(1/100\) s to the line assures proper continuous supply coping with its capacity. The system is modeled as a loss system, so parts that cannot enter the system, because the line is occupied, are discarded. Due to the use of the exponential distribution, it does not bias the entrance rate distribution.
Besides, the service times variability is characterized by the coefficient of variation (CV) and is studied at different levels. Different from other studies that considered only the exponential distribution for service times, those considered in this research follow a Gaussian distribution. They do not benefit from the memoryless property of the exponential distribution but are considered more realistic in the ordinary variation of service times variability, for instance, in assembly manual operations. Some former literature identifies realistic CV in manufacturing in the order from 0.2 to 0.5, while most of the theoretical studies based on markovian lines make use of exponential distribution with CV=1. Even when similar technologies or processes could be considered at front of similar CV, the variability in the performance of different workers (skilled or rookies) could present quite a different variability in task accomplishment. Many studies disregard the CV variability among stations, but this study will face it, identifying it as a main potential factor to observe the bowl effect.

3. Experimental results and discussion

As is set in the literature is possible to increase the throughput by unbalancing a line following the bowl shape, but a lot of components or variables can affect these results. The first batch of experiments pursuit evaluate the main influencing factor of design or operation. Initially and based on former research on unpaced lines, the size of the buffer and the unbalanced distribution of service times are expected to have significant influence. Note the ordinary approach of field research on the line bottleneck control for output control [1]. After results, the common approach of mean service time is extended to the distribution of CV in the second batch of experiments. Finally, and based on the former results the third bath of experiments confirms the main influences coupling the combined effect of the profile of service time distribution (bowl) with the natural variability of the service times in each workstation. These are commonly related to the differences in task time performance by an employee or related to unscheduled changes. However, to properly evaluate the bowl effect as a good parameter design other performance parameters must be considered. Therefore, we intend to evaluate the effect as a combination of their overall expected performances contrasted with an ideal lineal perfectly balanced scenario.

| Buffer size | Workload | Throughput (un/h) | WIP (un) | Utilization (%) | Lead time (h) |
|-------------|----------|------------------|---------|----------------|--------------|
| 1           | One-level| 11.45            | 7.04    | 0.98           | 0.62         |
| 1           | Two-level| 9.55             | 7.04    | 0.90           | 0.74         |
| 1           | Three-level| 10.21      | 6.90    | 0.90           | 0.68         |
| 3           | One-level| 8.72             | 11.23   | 0.87           | 1.29         |
| 3           | Two-level| 8.43             | 11.62   | 0.86           | 1.38         |
| 3           | Three-level| 8.51          | 10.47   | 0.86           | 1.23         |
| 6           | One-level| 9.75             | 16.67   | 0.91           | 1.71         |
| 6           | Two-level| 9.04             | 14.87   | 0.88           | 1.64         |
| 6           | Three-level| 9.30         | 16.69   | 0.89           | 1.80         |
| 12          | One-level| 10.61            | 23.78   | 0.94           | 2.24         |
| 12          | Two-level| 9.37             | 18.72   | 0.89           | 1.94         |
| 12          | Three-level| 9.87          | 18.72   | 0.91           | 1.90         |

3.1 Performance drivers of the asynchronous line

A first exploratory batch of experiments is performed, and the results are presented in table 3. All workload distributions have the same CV=1. The two main influence parameters of buffer size and workload allocation are evaluated. Work-in-process and utilization are also calculated, so they help to complement the evaluation. Thus, by the application of Little’s law, the lead time of production is also evaluated in the performance indicators.
By inspection of the quantitative results of table 3, the one-level or balanced line yield the maximum throughput under the different buffer sizes, but not the better lead time of production when the buffer size increases, suggesting that the unbalance service time distribution contributes to speed the flow across the line even when the bottleneck effect dominates. As expected, the rate of production or throughput is highly associated with the wider bottleneck of the one-level workload distribution, but the balanced line presents symptoms of congestion in its operational curve. The increase of the buffer size improves slightly the output at the cost of a higher lead time of production. For the small buffer size, the lead time is better in one-level configuration, but the size of the buffer decreases performance in throughput and lead time of production. It is also remarkable that a more pronounced bowl profile at three-level configuration improves the throughput more than the slight unbalance of two-level.

The results of the analysis of variance (ANOVA) are presented in table 4. Despite the quantitative results, surprisingly both the workload and the buffer size exhibit a marginal statistical influence on the variability of the throughput, because the p-test is clearly over 0.05, indicating no significant contribution to the observed variability.

| Principal effects | Squared sums | d.o.f. | Mean squared | F-ratio | p-test |
|-------------------|--------------|-------|--------------|---------|--------|
| Workload          | 1.70E-7      | 2     | 8.50E-8      | 8.93    | 0.159  |
| Buffer size       | 4.42E-7      | 3     | 1.48E-7      | 15.50   | 0.31   |
| Residuals         | 5.71E-8      | 6     | 9.52E-9      |         |        |
| TOTAL             | 6.70E-7      | 11    |              |         |        |

3.2 Factors of influence on the throughput of the asynchronous line
Looking for the hidden parameter influence, the coefficient of variation is incorporated into the study. The literature does not mention a special influence of former research by the CV. Only one previous research seems to indicate higher observation of the bowl effect when the CV among the different workstations is slight [2]. The experimental setup includes three levels of CV together with the three levels of workload and two levels of buffer size.

| Buffer size | CV  | Workload | Throughput (un/h) | Buffer size | CV  | Workload | Throughput (un/h) |
|-------------|-----|----------|-------------------|-------------|-----|----------|-------------------|
| 1           | 0.2 | One-level| 11.40             | 2           | 0.2 | One-level| 11.69             |
| 1           | 0.2 | Two-level| 11.35             | 2           | 0.2 | Two-level| 11.53             |
| 1           | 0.2 | Three-level| 11.36         | 2           | 0.2 | Three-level| 11.53             |
| 1           | 0.3 | One-level| 10.88             | 2           | 0.3 | One-level| 11.01             |
| 1           | 0.3 | Two-level| 10.50             | 2           | 0.3 | Two-level| 11.00             |
| 1           | 0.3 | Three-level| 10.50           |             |     |         |                   |
| 1           | 0.5 | One-level| 9.80              | 2           | 0.5 | One-level| 10.44             |
| 1           | 0.5 | Two-level| 9.81              | 2           | 0.5 | Two-level| 10.47             |
| 1           | 0.5 | Three-level| 9.81           |             |     |         |                   |

The analysis of variance of the experiments of table 5 is shown in table 6. Approximately 84% of the total variability is statistically associated with the CV and about 12% is assignable to the buffer size, both with significant influence because the p-test is <0.05. Conversely, the workload distribution does not influence in a significant manner the throughput, putting a quotation in the origin of the bowl effect or corroborating the difficulties in the observation of the phenomenon. The increase of the buffer size has significative influence, but in quantitative terms is the CV the origin of the foremost throughput variations.
Table 6. Factors of influence in throughput. Three factor ANOVA of table 5.

| Principal effects | Squared sums | d.o.f. | Mean squared | F-ratio | p-test |
|-------------------|--------------|--------|--------------|---------|--------|
| Workload          | 2.65E-9      | 2      | 1.32E-9      | 0.91    | 0.43   |
| Buffer size       | 5.88E-8      | 1      | 5.88E-8      | 40.37   | 0      |
| CV                | 4.20E-7      | 2      | 2.10E-7      | 144.25  | 0      |
| Residuals         | 1.75E-8      | 12     | 1.46E-9      |         |        |
| TOTAL             | 4.99E-7      | 17     |              |         |        |

3.3 The effect of CV distribution

Previous results suggest an overall outstanding influence of the CV combined with the underlying decoupling effect of buffers that enable the asynchronous flow between stations. To check this effect, an experimental setup of variable CV between stations is tested. Table 7 presents the results. The CV is established for two-level and three-level variables uniformly, when <0.2 denotes that the five workstations of the line have a variable CV during operation between 0 and 2. Either way <0.3 establishes variation up to 0.3. The effect on the rate of production benefits performance. Better results are obtained with a slight concave workload distribution (two-level) than when it is pronounced. The combined effect of CV variability and a slight concave distribution of service times surpass the ordinary bottleneck flow control. The reference line perfectly balanced, non-deterministic (CV≠0) but with the same variability in the workstations, underperforms the service time concave distribution (bowl service times) when the workstations CV presents variability.

Table 7. Influencing factors in throughput. Three factor ANOVA of table 4.

| CV   | Workload  | Throughput (un/h) | WIP (un) | Utilization (%) | Lead time (h) |
|------|-----------|-------------------|----------|-----------------|--------------|
| 0.2  | One-level | 11.4012           | 7.16     | 0.972           | 0.6281       |
| <0.2 | Two-level | 11.5632           | 7.16     | 0.981           | 0.6190       |
| <0.2 | Three-level | 11.5596         | 6.99     | 0.981           | 0.6045       |
| 0.3  | One-level | 10.8828           | 6.60     | 0.956           | 0.6065       |
| <0.3 | Two-level | 11.3796           | 6.05     | 0.975           | 0.5317       |
| <0.3 | Three-level | 11.3724         | 7.03     | 0.974           | 0.6183       |

The situation when the mean service times of a workstation is variable can be identified in a natural way when different products are processed in the same line. That is, a flexible line operating for a group of products might have a mean service time for each workstation with the non-uniform distribution. This distribution can be set up to have a concave profile along the line. Also, due to the variability of different products, the mean time in each workstation will oscillate with the product in fabrication, so oscillating the CV itself.

3.4 Input variety and workload allocation

Now we can observe the results including the effect of product variety in demand (mix) in the results of experiments in table 8, under the mix and workload allocation experimental setup. Experiments #1-3 show the performance reduction due to the perturbation introduced by the mix, so all workload configurations reduce their output. The behavior is basically by bottleneck and the perfectly balanced line (one-level) outperforms bowl distributions by 7%. These results are similar to those found in [3], where a set of buffer sizes, server mean times, and variability were combined and simulated obtaining the maximum throughput in the balanced scenarios. Nevertheless, while the balanced line has 300 s. bottleneck, two-level, and three-level is 376s, suggesting that the bottleneck effect in throughput is
compensated partially by the bowl workload distribution of two and three-level since $376/300 > 9.50/8.19$.

Nevertheless, the bottom section in table 8 is a replica of experiments with variable CV (<0.3). These show that a variable CV contributes to reducing the bottleneck effect when it is combined with a bowl workload distribution (two or three-level). More experimental work is needed to disclose the coupling between the workload distribution along the line and the possibilities of the service time variation (CV) to compensate through the bottleneck effect the unbalance of the line (real lines), including different mix-configurations for flexible lines, even perhaps the L-server station [8] which maximizes the possible combination to tackle the challenge of flexible manufacturing.

### Table 8. Results 2nd DOE.

| #  | CV  | Mix | Workload | Throughput (un/h) |
|----|-----|-----|----------|-------------------|
| 1  | 0.3 | 0.2 0.8 | One-level | 9.4968            |
| 2  | 0.3 | 0.2 0.8 | Two-level | 8.1864            |
| 3  | 0.3 | 0.2 0.8 | Three-level | 8.1864           |
| <0.3 | 0.2 0.8 | Two-level | 8.8092     |
| <0.3 | 0.2 0.8 | Three-level | 8.8128     |

4. Conclusions

The controversial existence of the bowl effect or understanding the circumstances where it appears is not well established. Literature is focused on the distribution of service times, but when the CV is the same in all workstations, the behavior of the flow line is dominated by the bottleneck. Besides, most of the research has been conducted under stochastic input and service times generally using the setup of markovian lines with the exponential distributions (CV=1), far from real variability of manufacturing processes. The present research has used exponential distribution only for line input, but the Gaussian distribution for the service times and CV in a more realistic range for process and assembly manufacturing times.

Former theoretical research on the bowl effect emphasizes reversibility, symmetricity, and the monotonicity properties of the distribution [9]. The profiles used in this research have followed those assumptions, but the improvement effect of a bowl distribution appears associated with the variability of CV across workstations. This situation can happen in a flexible flowline where a group of products is manufactured. This preliminary research points out the understanding of the variability as a source of potential performance gain in real imperfect unbalanced systems. Further efforts should be directed to understand the coupling of service time and their natural variation. A perfectly balanced line might be an unrealistic manufacturing system design alternative nowadays, where manufacturing lines require some degree of flexibility for product variety. Understanding the influence of the distribution of unbalance service times and/or their different variability (CVs) could be worthy for future research.

References

[1] C R P Narayan 2013 An Improved Methodology for Flexibility Desing in Production System of Manufacturing Firms 12 (2) pp 29-38
[2] A V Kapitanov 2017 Manufacturing System Flexibility Control Procedia Engineering 206 pp 1470-1475
[3] Y K and. P C S Son 1987 Economic measure of productivity, quality and flexibility in advanced manufacturing systems Journal of Manufacturing Systems 6 (3) pp 193-207
[4] A J 2006 General Motors Increases its Production Throughput pp 6-25
[5] J Li, D E Blumenfeld, N Huang and J M Alden 2009 Throughput analysis of production systems: Recent advances and future topics International Journal of Production Research 47 (14) pp 3823-3851
[6] S Ross 1980 *Introduction to Probability Models* (Academic Press)
[7] N N Y Viswanadham 1992 Stochastic modeling of flexible manufacturing systems *Math. Comput* 16 (3) pp 15-34
[8] D Spinellis, M J Vidalis, M E J O’Kelly and C T Papadopoulos 2009 *Analysis and design of discrete part production lines* (New York: Springer)
[9] F S Hillier and R W Boling 1977 Toward characterizing the optimal allocation of work in production line systems with variable operation times *Advances in Operations Research* (Roubens M) pp 109-119
[10] N P Rao 1975 Two-stage production systems with intermediate storage *AIIE Transaction* 7 (4) pp 414–421
[11] N P Rao 1976 A generalization of the ‘bowl phenomenon’ in series production systems *International Journal of Production Research* 14 (4) pp 437–443
[12] H S Lau 1994 Allocating work to a two-stage production system with interstage buffer *International Journal of Production Economics* 36 pp 281–289
[13] R Pike and G E Martin 1994 The bowl phenomenon in unpaced lines *International Journal of Production Research* 32 (3) pp 483–499
[14] N P Rao 1975 On the mean production rate of a two-stage production system of the tandem type *International Journal of Production Research* 13 (2) pp 207–217
[15] J A Buzacott and J. G. Shanthikumar 1993 *Stochastic Models of Manufacturing Systems* (Prentice-Hall)
[16] J A Buzacott and D Yao 1985 Modeling a class of state-dependent routing in flexible manufacturing systems *Annals of Operations Research* 3 pp 153-167
[17] W W Thompson and R L Burford 1969 Some observations on the bowl phenomenon *International Journal of Production Research* 26 (8) pp 1367–1373