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Effect of discrete batch WIP transfer on the efficiency of production lines

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In this paper, the effect of discrete batch transfer of WIP between workstations on the efficiency of asynchronous production lines is analysed via a simulation model. The processing times are assumed to be random variables distributed according to specific distribution functions. The WIP transfer design problem involves determining the number of containers to allocate to each buffer location and the container capacity. Interesting and valuable information for practitioners has been obtained. It is found that loss in capacity occurs in the first few stations. Another finding is that an important portion of the lost capacity can be regained by allocating two containers to each buffer location, and if it is impossible to assign two containers to each location, then no single-container location should be adjacent to another single-container location.

1. Introduction

The analysis and design of production lines have been studied in the research literature for a long time. Although several aspects of the problem have been analysed both analytically and via simulation, the problem of WIP transfer design still remains an open question. In addition, there is very little in the technical literature to guide practitioners on the role and amount of buffers (Conway *et al.* 1988).

A production line consists of serially arranged stations and all items pass through these stations in the same sequence. After being processed in a station, items are disposed to the buffers between the stations and picked out of the buffer as soon as the downstream station becomes idle. Note that a line can be designed with no buffers between stations.

There are two major types of buffer design: in the first type, buffer inventory resides on a tray or in a container between the stations within a small distance of the operators. The upstream operator can place an item into the container as soon as work on the item is completed, if an available space is present. The downstream operator can take an item out of the container as soon as he becomes idle, if an available item is present. Another type of design involves stations separated from each other; the container is filled by the upstream operator and is moved to the downstream operator who takes the items out of the container one after another to complete the required work. As soon as all the items in the container are taken out, the container is again made available to the upstream operator. This design may involve more than one container betwen stations. A more general design is a combination of the two designs described above; while the operators of several adjacent stations can reach the container simultaneously, a discrete batch WIP transfer is done between the other adjacent stations. All the research performed on production lines, to the best knowledge of the author, assumes the first type of buffer design. This study aims to provide information about the effect of discrete batch transfer of WIP between stations on the efficiency of production lines.

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The fundamental operating assumptions of a production line are as follows:

(1) The first station has unlimited input available.
(2) The finished goods are collected at the end storage with infinite capacity.
(3) No station breakdowns occur.
(4) No non-conforming unit is produced.
(5) The processing time of an item in a station is distributed according to a specific distribution function with known parameters.

The first four assumptions above allow us to isolate the line from the disturbing factors of raw material input and finished goods output, machine breakdowns, and non-conforming unit production; in other words, the analysis is conducted only on the WIP transfer design problem. If these assumptions are relaxed, then the decrease in efficiency may be significant, but it would be impossible to examine the effect of the design problem on the line efficiency. The fifth assumption above is especially valid with human operators/assemblers due to the inherent variability in the operation times.

Capacity utilization of a typical line is seldom 100% and loss in line efficiency arises from stations being blocked or starved. A station is blocked if the completed item in the station cannot be disposed to the buffer due to insufficient space. Thus, the station stays idle until a space in the buffer becomes available. A station is starved if there are no available items to start processing. Considering the assumptions above, the occurrence of these two events is attributable to the variability of the processing times.

A line is balanced if the expected processing times of the stations are equal to each other. In a synchronous line, each item is held at its station until all the items are ready to proceed to their next operation. Note that synchronous lines are unbuffered lines. In an asynchronous line, each item proceeds to the next operation after processing in the station is completed.

The distinctive characteristic of the production line considered in this study is that WIP inventory is stored in containers that move between stations. The conceptual space between two adjacent stations in which the containers move will be called a buffer location. For each buffer location, the WIP transfer design problem has two variables: number of containers and container capacity. There might be some floating containers which are allowed to move to any buffer location if a need for a container arises. Let C and n_i denote the container capacity and the number of containers in buffer location i. If there are S stations, then the design with n_i containers at buffer location i will be represented as $n_1 - n_2 - \ldots - n_{s-1}$. The system considered has the following assumptions in addition to the fundamental operating assumptions given above:

(1) Items are stored in standard containers that move between the stations.
(2) A container moves to the downstream station only when it is completely filled and it moves back to the upstream station when it is completely emptied.
(3) Items are taken out of the containers one at a time.
(4) The flowtime consists of processing, waiting and transportation times; the relative weight of transportation time is negligible compared with the weights of the other factors.
(5) Floating containers, if available, are used only when a station is unable to unload the item into a regular container.

The first assumption imples that only one type of container is utilized along the line and the capacity of the container, in terms of the number of units carried, is fixed. The second assumption prohibits partially filled containers from moving between stations.

The third assumption imples that a station can hold at most one item at a time, and the items waiting to be processed stay in the containers. The fourth assumption implies that the sum of processing and waiting times comprises a major portion of the flowtime. The transportation time constitutes a negligible portion of the flowtime. Note that for $n_i = b$ and $C = 1$, the buffer location i reduces to the one considered in the literature with a buffer capacity of b.

The system considered in our paper represent a majority of the production lines encountered in manufacturing industry in which a process layout is utilized to locate the stations. The system considered in the literature is restrictive in the sense that the stations are located close to each other such that the operators of adjacent stations can reach the buffer location simultaneously. Although this situation can exist for some systems, it can be quite restrictive for some production lines or for some of the buffer locations along the line. The motivation for this study stems from the needs of practitioners working in an environment in which WIP is transported in containers between the stations.

2. Previous research

The problem of production line design has been examined by many researchers over many years. Most of the research has focused on analytical models for small systems simplified by restrictive assumptions (Chow 1987, Hillier and Boling 1966, Muth and Alkaff 1987). For larger systems, analytical approximations or simulation models have been utilized (Baker *et al.* 1990, Conway *et al.* 1988). Some studies deal with the effect of buffers in the presence of station breakdowns (Altiok and Stidham 1983, Wijngaard 1979). In all the studies above, the production line is assumed to need no material-handling container-type equipment to transfer WIP between stations.

Although the design considered in this study differs significantly from the ones in the literature, there are a few studies in which some similarities exist in the methodology and the results. Hillier and So (1991) have examined the effect of the variability of processing times on the optimal allocation of buffers between stations. They have concluded that the centre stations should be given more buffer space, especially for processing times with high variability. Smith and Daskalaki (1988) have developed a heuristic procedure for buffer allocation within balanced and unbalanced assembly lines with series, merging and splitting topologies. They have obtained a counterintuitive result that buffer allocation should favour the stations close to the end of the line. This result is attributable to the objective function utilized in which both WIP and buffer capacity holding costs are considered (McClain and Moodie 1991). Conway *et al.* (1988) have examined serial production systems via a simulation model with the objectives of determining where WIP is most effective and measuring the benefit of WIP as a function of quantity. They have found interesting and counterintuitive results, such as buffers are more essential in balanced lines than in unbalanced lines. Baker *et al.* (1990) have examined the effect of buffers on the efficiency of lines in which two serial processes merge, via a simulation model. They have concluded that small buffers are sufficient to regain most of the lost capacity, and buffer space should be allocated equally among the locations. A computerized scheduling system called optimized production technology (OPT) developed by Goldratt is gaining in popularity. The books written to illustrate the effects of OPT by Goldratt and Cox (1986) and Goldratt and Fox (1986) provide the basic features of the proprietary software package. The essential idea is to first identify bottlenecks in the system and then to design a schedule to maximize their output.

There is almost no work reported in the literature to explore the WIP transfer design problem considered in our study. Furthermore, the existing studies provide little help due to the significantly different buffer design.

3. Method of investigation

The configurations of different line designs are examined via a simulation model. The model operates in a push-mode which is characterized by the movement of the item, upon completion, to the succeeding station. The performance measure is taken as the average throughput, defined as the long-run average output per unit time. The mean processing time is taken as 1·0; thus, the maximum achievable throughput is also 1·0. With this scaling, throughput can be interpreted as efficiency (Baker *et al.* 1990). Data is collected during the production of 100 000 units, which is higher than the figures utilized in other simulation studies (Baker *et al.* 1990, Conway *et al.* 1988). This high simulation length eliminates the need to make long simulation runs for resolving anomalies (Baker *et al.* 1990).

The distributions of processing times used in the study are shown in Table 1. The coefficient of variation in the table is the ratio of the standard deviation of the processing time to its mean; in other words, it reflects a relative measure of the variability of the processing time. The level of variability represented by the first three distributions can be encountered in practical manual operations. The last distribution is included to explore how bad things could be for wildly changing processing times (Conway *et al.* 1988, Lau and Martin 1987).

In the sequel, production lines with identical buffer locations are examined in the following sections; each buffer location can consist of a single container or multiple containers and these cases are considered in sections 4 and 5, respectively. Most of the findings in these sections are trivial and could be reasoned without any simulation study, but they provide an important background for the findings in subsequent sections. The effect of floating containers is then analysed in section 6. Lines with non-identical buffer locations are examined in section 7 and finally a summary of the findings and future areas of research are given.

4. Single-container buffer locations

The production line with identical, single-container buffer locations is the simplest system to analyse. An analytical model has been developed for this system for two stations, with exponentially distributed processing times with unit mean, and the following throughput formula was developed by Hunt in 1956 (Baker *et al.* 1990):

$$\text{Throughput} = (C+2)/(C+3)$$

where C represents the buffer capacity. The above formula is valid for our analysis only for $C=1$, since for $C>1$, the design is different from the one considered in this study.

Processing time distribution	Mean	Range	Coefficient of variation (CV)
Uniform $U(\pm 0{\cdot}2)$	1·0	0·4	0·115
Truncated normal $N(\pm 0{\cdot}5)$	1·0	1·0	0·167
Uniform $U(\pm 0{\cdot}5)$	1·0	1·0	0·289
Exponential $E(1)$	1·0	Infinite	1·0

Table 1. Distributions of the processing times.

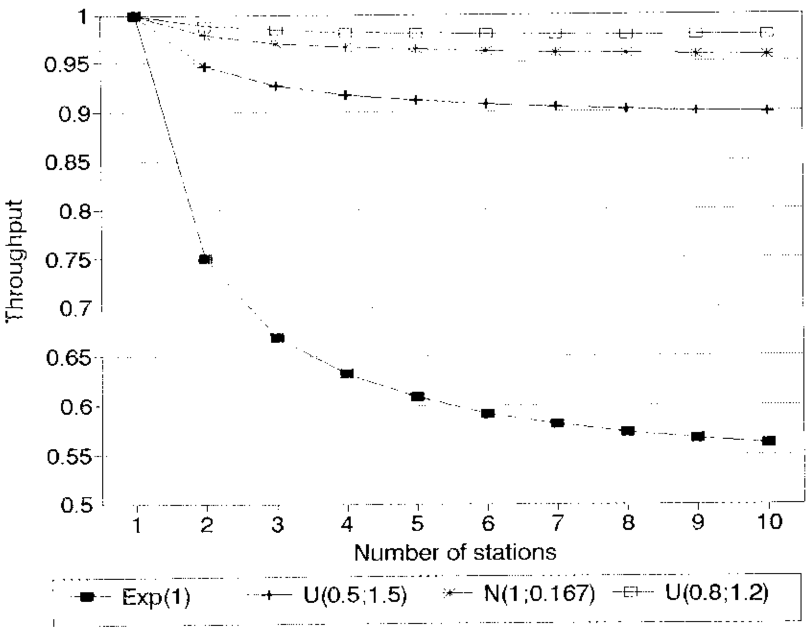

Figure 1. Effect of line length on throughput.

Variability in processing times decreases throughput due to the two events described earlier; namely, station blockage and starvation. For lines with a large number of stations, the decrease is expected to be more pronounced, since more stations will interfere with each other and a larger portion of the line capacity will be lost. Figure 1 depicts throughput values for lines with various numbers of stations (line lengths). It is observed that longer lines are less efficient, but the loss in capacity occurs in the first four or five stations and no significant loss is observed for additional stations, especially for processing times with small *CV*s. For the exponentially distributed processing time, throughput decreases at a decreasing rate as the line length is increased; the majority of the loss is again occurs in the first five stations. Experiments made with other values of container capacity and numbers of containers at each buffer location also result in a similar behaviour. Based on the above observation, we will draw conclusions about the behaviour of lines by analysing a six-station line. Accordingly, hereafter a line is assumed to have six stations unless stated otherwise.

In Fig. 1, it is also shown that throughput and variability of processing times are inversely proportional for all line lengths. This observation supports the claim that the variability of processing times is responsible for the decrease in throughput.

Throughput decreases for all the processing times considered as the container capacity, C, increases, as shown in Fig. 2. However, the decrease almost stops for $C > 4$ and the throughput values stay below the value of 0·6 for all processing times. Consequently, the decrease in throughput is larger for processing times with small variability.

Based on this observation, we can conclude that the container capacity must be minimized (set to 1 if possible) in order to maximize utilization of line capacity. This conclusion is more pronounced for processing times encountered in practice (processing times with low *CV*s). On the other hand, lines with single-container buffer locations with $C = 1$ do not exist in practice since the ignored transportation cost outweighs the

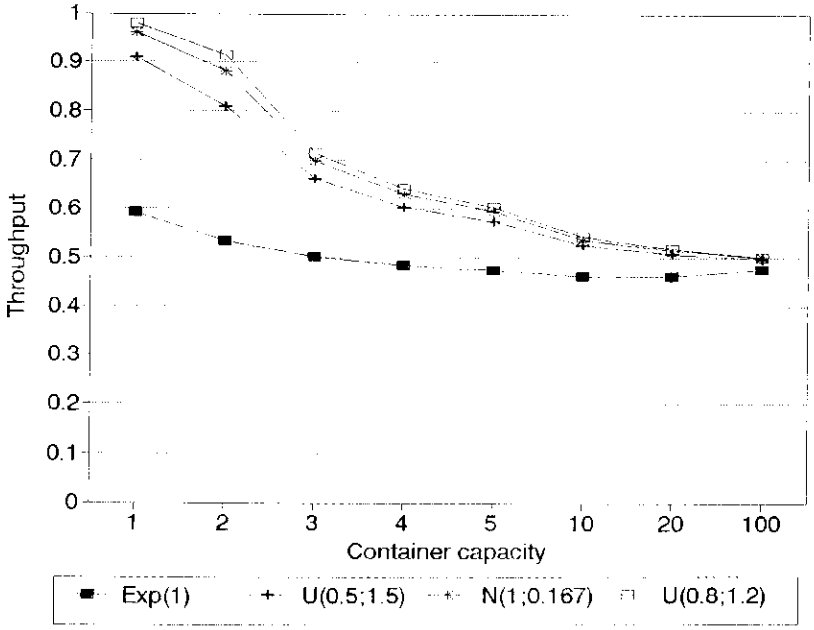

Figure 2. Effect of container capacity on throughput.

cost savings. However, in the case of bulky units or long processing times, utilizing unit capacity containers becomes mandatory.

Since the increase in container capacity decreases throughput, the other alternative is to increase the number of containers between stations. The effect of container capacity on throughput in a multiple container buffer location design is examined in the following section.

5. Multiple-container buffer locations

The negative effects of variable processing times on throughput are expected to be diminished by assigning more than one container to the buffer locations. The lost capacity is expected to be further recovered by assigning several small-capacity containers rather than a smaller number of large-capacity containers. The change in throughput as the number of containers increases for the exponentially distributed processing time is shown in Fig. 3. A substantial increase in throughput is observed when the number of containers is increased from one to two especially for large C values. For example, when $C = 10$, increasing the number of containers from one to two recovers 63% of the lost capacity due to the variability of processing times. Another observation is that the capacity of the containers should be maximized when there are multiple containers in the buffer locations; note that this observation is the opposite of that in the single-container case. Figure 3 also shows that if the total buffer allocated to a buffer location is fixed, then a larger recovery of the lost capacity is achieved by assigning several small-capacity containers rather than a smaller number of large-capacity containers. For example, five containers each with a capacity of four at each location (a throughput of 0·9035) is preferred to two containers each with a capacity of ten (a throughput of 0·8011), as shown in Fig. 3.

The percentage of the lost capacity recovered by increasing the number of containers for the uniformly distributed processing time ($U(\pm 0{\cdot}2)$) is shown in Fig. 4. A

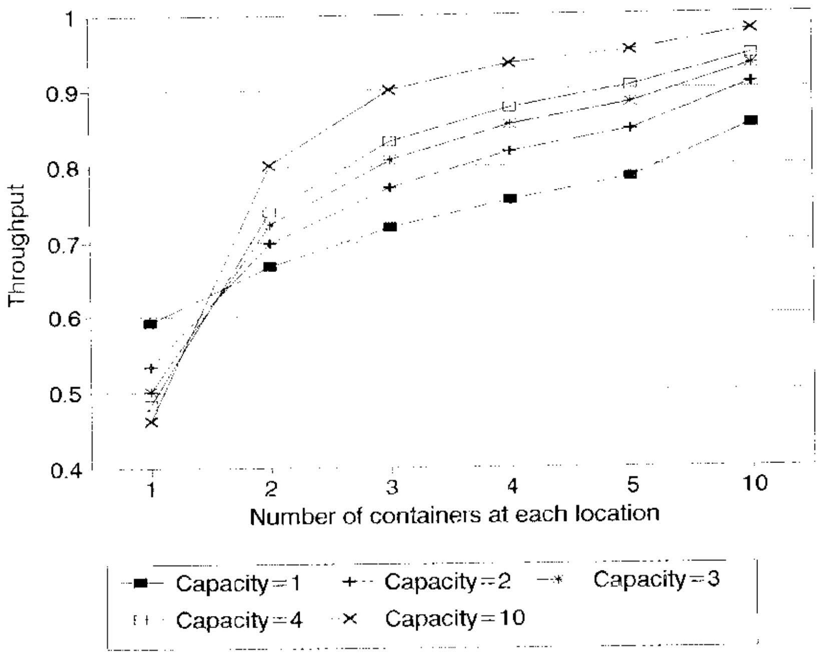

Figure 3. Effect of the number of containers at each location on throughput for $E(1)$.

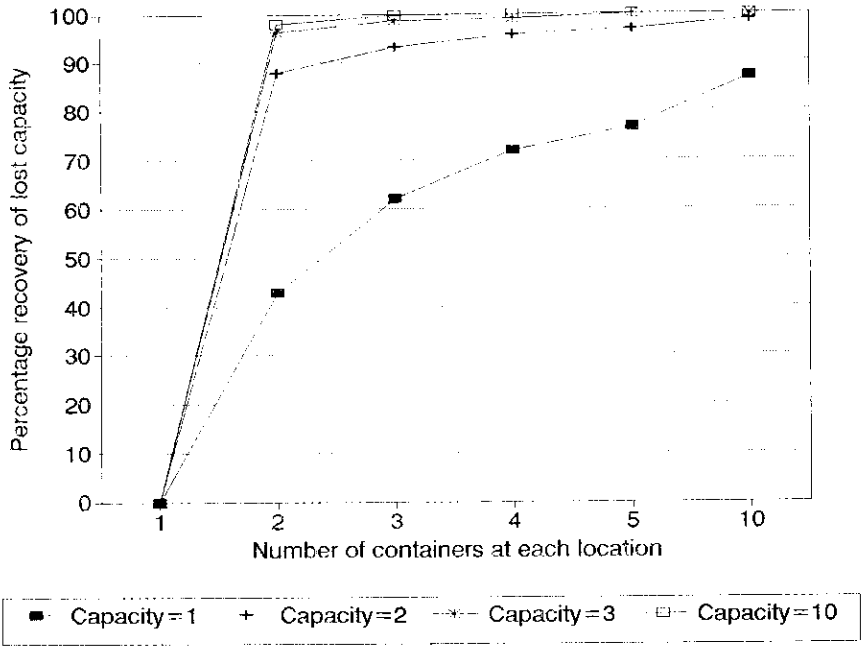

Figure 4. Recovery of the lost capacity when the number of container at each location is increased for $U(\pm 0{\cdot}2)$.

significant portion of the lost capacity is recovered when the number of containers is increased from one to two for this more frequently encountered processing time. The recovery is almost 100% for $C > 1$. For $C = 1$, the recovery is slower, since the initial capacity utilization is already high (e.g. for $C = 1$ and $n_i = 1$ for all i, throughput is 0·9795). The same behaviour is observed for the other low CV processing time distributions considered.

These experiments indicate that assigning two containers to each buffer location has vital importance in recovering the lost capacity due to variable processing times. Further increase in the number of containers improves throughput very little, especially for low CV processing time distributions and high container capacities.

Throughput is shown to improve significantly as a result of assigning an equal number of additional containers to the buffer locations. If these additional containers are not assigned to specific locations, but allowed to move to any buffer location which needs a container, it is expected to further improve throughput. The effect of such floating containers on throughput is analysed in the following section.

6. Effect of floating containers

Assigning more than one container to each buffer location is obviously an effective method of recovering lost capacity. On the other hand, this method creates cost factors such as inventory holding cost, container purchase and maintenance cost, storage cost, etc. A compromise solution is to provide extra (floating) containers to buffer locations only when a need for a container arises. A pool of floating containers is kept ready along the line; when a station faces blockage, a floating container is rushed to the buffer location to eliminate the problem and the container returns to the pool as soon as it becomes idle.

Figure 5 shows the effect of the number of floating containers on throughput for various container capacity values and for the processing time distribution of $U(\pm 0{\cdot}2)$. For $C = 1$, the presence of floating containers does not seem to affect throughput since the throughput associated with zero floating containers is already high (0·9795). For $C > 1$, the change in throughput is highly erratic up to a specific number of floating containers and no pattern is recognizable, as shown in Fig. 5. Beyond these specific points, almost all of the lost capacity is regained. In order to explain this counterintuitive observation, an analysis to explore the buffer locations in which the floating containers were utilized was conducted. It was found that the containers were mainly used in the locations close to the beginning of the line; the first buffer location using them with the highest frequency. This phenomenon results in higher rates of blockage of the stations close to the beginning of the line and the advantage of the unlimited input available to the first station is lost. On the other hand, a much faster recovery of lost capacity can be achieved by positioning some floating containers at specific locations (acting as regular containers) as will be discussed in the following section.

Based on the above observation and the experiments made with the other processing time distributions and line lengths, we can conclude that floating containers do not help to regain lost capacity unless a significant number of them are provided. Considering the various associated cost factors, assigning the floating containers to specific locations as regular containers is a much better means of improving throughput, especially if at least one floating container can be assigned to each buffer location.

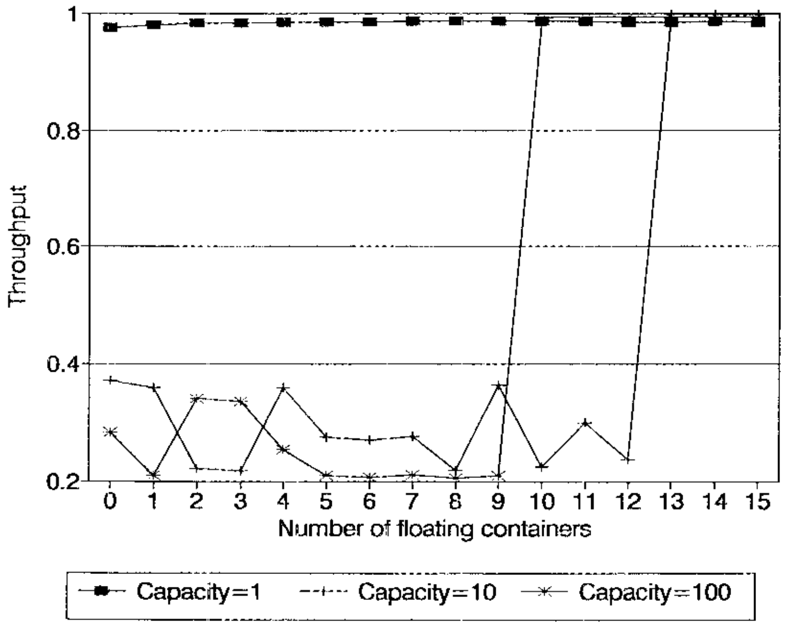

Figure 5. Effect of the number of floating containers on throughput for $U(\pm 0{\cdot}2)$.

7. Non-identical buffer locations

Increasing the number of containers in the buffer locations has been shown to recover the lost capacity due to variable processing times. The increase in the number of containers does not need to be the same over the buffer locations; assigning containers to some specific locations may yield higher throughput than assigning the containers uniformly through the line.

Considering a six-station line with five buffer locations, there are several different ways to assign the containers to the buffer locations. The numbers of different designs we can have with 6, 7, 8 and 9 containers are 5, 15, 35 and 70, respectively. The design with two containers at each location is obtained with ten containers and, as shown in Fig. 4, the recovery of lost capacity is almost 100%, especially for low CV processing time distributions. Accordingly, we will restrict the analysis to designs with at most nine containers.

The results of the experiments conducted with the 125 different designs associated with nine or less containers, two levels of container capacity values (for $C=1$ and $C=10$) and four processing time distributions (a total of 1000 experiments) are as follows: a subset of the designs results in throughput values which are superior to those obtained with the remaining designs. In addition, the superior throughput values are almost equal to each other regardless of the design or the processing time distribution. Table 2 shows the designs resulting in superior throughput values for $C=5$. Note that with six containers, no design is found to result in a superior throughput value. The last row in Table 2 shows the throughput values obtained by assigning two containers to each buffer location.

Examining the designs given in Table 2 and comparing them with the excluded ones reveals that no single-container buffer location is adjacent to another single-container location. As long as this condition is satisfied, neither the design nor the processing time distribution affects the throughput. For example, with 8 containers the total number of

Total number of containers	Design	Processing time distribution $U(\pm 0{\cdot}2)$	$N(\pm 0{\cdot}5)$	$U(\pm 0{\cdot}5)$	Exp(1)
7	1–2–1–2–1	0·6238	0·6222	0·6170	0·5552
8	1–2–2–2–1	0·6247	0·6247	0·6231	0·5887
	1–2–2–1–2	0·6221	0·6241	0·6221	0·5826
	1–2–1–3–1	0·6241	0·6229	0·6189	0·5662
	1–3–1–2–1	0·6240	0·6229	0·6190	0·5645
	1–2–1–2–2	0·6240	0·6234	0·6194	0·5704
	2–2–1–2–1	0·6242	0·6229	0·6195	0·5706
	2–1–2–1–2	0·6242	0·6230	0·6196	0·5702
	2–1–2–2–1	0·6245	0·6241	0·6223	0·5825
9	1–4–1–2–1	0·6240	0·6231	0·6191	0·5714
	1–2–1–4–1	0·6240	0·6231	0·6195	0·5706
	1–2–1–2–3	0·6240	0·6234	0·6194	0·5702
	1–2–2–1–3	0·6243	0·6241	0·6221	0·5840
	1–2–2–3–1	0·6247	0·6243	0·6235	0·5967
	1–2–3–2–1	0·6249	0·6249	0·6234	0·5961
	1–2–3–1–2	0·6247	0·6242	0·6231	0·5919
	1–2–1–3–2	0·6240	0·6234	0·6194	0·5721
	1–3–1–2–2	0·6246	0·6242	0·6221	0·5885
	1–3–2–1–2	0·6247	0·6245	0·6232	0·5908
	1–3–2–2–1	0·6249	0·6246	0·6235	0·5950
	2–1–2–1–3	0·6242	0·6230	0·6196	0·5710
	2–1–2–3–1	0·6245	0·6243	0·6230	0·5920
	2–1–3–1–2	0·6246	0·6239	0·6220	9·5871
	2–1–3–2–1	0·6248	0·6246	0·6234	0·5900
	3–1–2–2–1	0·6245	0·6240	0·6220	0·5810
	3–1–2–1–2	0·6239	0·6230	0·6195	0·5724
	2–3–1–2–1	0·6241	0·6229	0·6197	0·5708
	3–2–1–2–1	0·6239	0·6230	0·6193	0·5718
	2–2–2–2–1	0·6250	0·6254	0·6248	0·6088
	2–2–2–1–2	0·6251	0·6251	0·6251	0·6073
	2–2–1–2–2	0·6252	0·6248	0·6247	0·6074
	2–1–2–2–2	0·6248	0·6250	0·6258	0·6054
	1–2–2–2–2	0·6248	0·6248	0·6252	0·6109
	1–3–1–3–1	0·6243	0·6237	0·6211	0·5773
	2–2–1–3–1	0·6246	0·6240	0·6223	0·5875
10	2–2–2–2–2	0·9898	0·9804	0·9526	0·7550

Table 2. Throughput values of the designs for $C = 5$.

designs is 35 and 8 of these designs contain no single-container location adjacent to another single-container location. For the processing time distribution of U($\pm 0{\cdot}5$), the mean throughput value of these 8 designs is 0·6205, whereas the mean throughput value of the remaining 27 designs is 0·5925. The mean of the former group is statistically superior with $p < 0{\cdot}0005$.

This observation seems contradictory to the findings reported in the literature that the allocation of buffer capacity should have a centre-weighted spread (Conway *et al.* 1988). For example, a centre-weighted spread with seven containers with $C = 10$ results in designs 1–2–2–1–1, 1–1–2–2–1 or 1–1–3–1–1, and the throughput values associated with these designs are 0·6136, 0·6137 and 0·6135, respectively, for the processing time distribution of $U(\pm 0{\cdot}2)$. Note that all of them are lower than the one associated with 1–2–1–2–1 (0·6238) (Table 2). This discrepancy is due to the design considered in our paper; namely, WIP is stored in containers that move from station to station, and a station surrounded by two single-container buffer locations consitutes a bottleneck.

In order to verify the result above, some experiments have been conducted on a seven-station line and a similar behaviour has been observed. Based on the observation above, we can conclude that no single-container buffer location should be adjacent to another single-container location. Furthermore, if the total number of containers is less than $2N-2$ (e.g. it is impossible to assign two containers to each buffer location), then it is sufficient to utilize $\lfloor(3N-3)/2\rfloor$ of the containers, where $\lfloor x\rfloor$ is the largest integer smaller than x. The expression $\lfloor(3N-3)/2\rfloor$ follows from the fact that there should be at least $\lfloor(N-1)/2\rfloor$ multiple-container locations. For example, if $N=10$ and the total number of containers is less than 18, then 13 containers would be sufficient to make better use of the line capacity. Utilizing 14, 15, 16 or 17 containers would improve throughput negligibly and considering the cost factors of utilizing a container, the best policy would be to utilize exactly 13 containers. The configuration associated with these 13 containers would be 1–2–1–2–1–2–1–2–1. Note that utilizing 12 or less containers (up to a minimum of nine containers) would decrease throughput significantly.

8. Summary and conclusions

The results of this study may be summarized as follows:

(1) The loss in capacity occurs in the first four or five stations in an asynchronous production line in which WIP is transported in standard containers. The amount of loss is proportional to the variability of processing times.

(2) If only one container is placed in each buffer location, then container capacity must be minimized in order to maximize the utilization of the line capacity. This conclusion is more pronounced for processing times with small variability.

(3) A significant portion of the lost capacity is regained by assigning two containers to each buffer location. Assigning more than two containers to each location improves throughput only slightly. The capacity of the containers should be maximized when there are multiple containers between the stations.

(4) Floating containers do not improve throughput unless a significant number of them are made available. A much faster recovery of lost capacity can be achieved by assigning these containers to specific locations.

(5) If at least two containers cannot be assigned to each location, then no single-container buffer location should be adjacent to another single-container location.

Although some interesting results have been obtained as listed above, there are several questions remaining to be addressed. The assumptions of insignificant transportation time of the containers and a container waiting until it is completely filled or emptied originate interesting questions. If partially filled containers are allowed to move and the transportation time constitutes a major portion of the flowtime, how is the efficiency of the line affected? Will the above policies stay valid for an unbalanced production line? The only performance measure considered in our study is throughput; other measures such as the average amount of inventory in the system or a measure based on average profit per unit time as developed by Altiok and Stidham (1983) can also be of interest.

References

ALTIOK, T., and STIDHAM, S., 1983, The allocation of interstage buffer capacities in production lines. *IIE Transactions*, **15**, 292–299.

BAKER, K. R., POWELL, S. G., and PYKE, D. F., 1990, Buffered and unbuffered assembly systems with variable processing times. *Journal of Manufacturing and Operations Management*, **3**, 200–223.

CHOW, W., 1987, Buffer capacity analysis for sequential production lines with variable process times. *International Journal of Production Research*, **25**, 1183–1196.

CONWAY, R., MAXWELL, W., MCCLAIN, J. O., and THOMAS, L. J., 1988, The role of work-in-process inventory in serial production lines. *Operations Research*, **36**, 229–241.

GOLDRATT, E. M., and COX, J., 1986, *The Goal* (New York: North River Press).

GOLDRATT, E. M., and FOX, R. E., 1986, *The Race* (New York: North River Press).

HILLIER, F. S., and BOLING, R. N., 1966, The effect of some design factors on the efficiency of production lines with variable operations times. *Journal of Industrial Engineering*, **17**, 651–658.

HILLIER, F. S., and SO, K. C., 1991, The effect of the coefficient of variation of operation times on the allocation of storage space in production line systems. *IEE Transactions*, **23**, 198–206.

LAU, H. S., and MARTIN, G. E., 1987, The effects of skewness and kurtosis of processing times in unpaced lines. *International Journal of Production Research*, **25**, 1483–1492.

MCCLAIN, J. O., and MOODIE, D. R., 1991, A comment on 'Buffer space allocation in automated assembly lines'. *Operations Research*, **39**, 857–860.

MUTH, E. J., and ALKAFF, A., 1987, The throughput rate of three-station production lines: A unifying solution. *International Journal of Production Research*, **25**, 1405–1413.

SMITH, J. M., and DASKALAKI, S., 1988, Buffer space allocation in automated assembly lines. *Operations Research*, **36**, 343–358.

WIJNGAARD, J., 1979, The effect of interstage buffer storage on the output of two unreliable production units in series, with different production rates. *IIE Transactions*, **11**, 42–47.