FIRST STUDY ON MANUFACTURING FLOW LINES WITH SHARED BUFFER

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Abstract: the paper addresses the problem of properly using buffer spaces in manufacturing flow lines. The idea is to exploit recent technological devices to move in reasonable time pieces from a machine to a common buffer area of the system and vice versa. In such a way machines can delay their blocking since they can send pieces to the shared buffer area. The introduction of the buffer area shared by all machines of the system leads to an increase of throughput as demonstrated by simulation experiments. Also, a preliminary economic evaluation on a real case has been carried out to estimate the profitability of the system comparing the increase of throughput obtained with the new system architecture with the related additional cost.

Keywords: flow lines, buffer allocation, system design.

1 Introduction

A manufacturing flow line is defined in literature as a serial production system in which pieces are worked sequentially by machines : from the first machine, in which pieces are still raw parts, to the last machine in which the process cycle is completed and finished parts leave the system. If parts are loaded on pallets and the number of pallets is constant during the production, these systems are also called closed flow lines (see Figure 1 where rectangles and circles represent respectively machines and buffers of the system) to distinguish them from open flow lines (see Figure 2) where the number of parts is not maintained constant. Gerhswin gives in [2] a general description of flow lines in manufacturing. The production rate of manufacturing flow lines is clearly a function of speed and reliability of machines: faster and more reliable machines are and larger the production rate is. However, since machines can have different speeds and may be affected by random failures, the part flow can be interrupted at a certain point of the system causing blocking and starvation of machines. In particular, blocking occurs when one or more machines cannot move to the next station the parts that they have just machined (BAS, Blocking After Service) or they have still to work (BBS, Blocking Before Service). In open production lines blocking of a machine can be caused only by a long processing time or a failure of a downstream machine. Analogously, starvation occurs when one or more machines cannot be operational because they have no input part to work; in this case machine cannot work and it is said to be starved. In open production lines the starvation of a machine can be caused only by a long processing time or a failure of an upstream machine. If there is no area where to put pieces between two adjacent machines, behavior of machines is strongly correlated. Indeed the state of a machine affects that of the other machines because of blocking and starvation that propagate respectively upstream and downstream the source of flow interruption in the line.
In order to decrease blocking and starvation phenomena in flow lines, buffers between two adjacent machines are included to decouple the machines behavior. Indeed, buffers allow to adsorb the impact of a failure or a long processing time because (a) the presence of parts in buffers decreases starvation of machines and (b) the possibility of storing parts in buffers decreases blocking of machines. Therefore, production rate of flow lines is also a function of

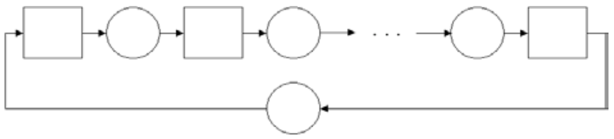

Figure 1: Scheme of closed flow lines.

Figure 2: Scheme of open flow lines.

buffer capacities; more precisely, production rate is a monotone positive function of the total buffer capacity of the system.

Traditionally, flow lines or transfer lines have been deeply investigated in literature. Researchers' efforts have been devoted to develop new models for evaluating performance of transfer lines and for optimizing their design and management in shop floor. Operation research techniques like simulation and analytical methods have been widely used to estimate system performance parameters such as throughput and work in process level. Performance evaluation models are currently used in configuration algorithms for finding the optimal design of transfer lines taking into account the total investment cost, operative cost and production rate of the system. In synthesis, academic innovation has been mainly focused on the development of performance evaluation and optimization methods of transfer lines without entering in mechanical details. See also the review [3] of Dallery and Gershwin on performance evaluation model of flow lines and a recent state of the art on optimization techniques applied in practice [1]. Indeed, most of scientific works is at system level as they deal with optimization of macro variables such as number of machines in the transfer line, buffer capacities and machine speed. On the other hand, engineers of firms have had to face the complexity due to the fact that transfer lines are designed in practice with all their mechanical components. Innovation from builders of manufacturing flow lines has been mainly dedicated to increase machines reliability and to reduce system costs by improving the design of specific mechanical components such as feed drives, spindles, transporters, etc.

It is worthwhile to notice that advancements in transfer line evolution does not regard the main philosophy of the system. Parts are loaded into the system at the first machine and, after having been processed, they are moved into the first buffer waiting for the availability of the second machine. Blocking phenomena is limited by buffers, larger is their capacity and higher the throughput of the line is. However, buffers in transfer lines are dedicated to machines; this characteristic implies that a buffer can contain only pieces worked by the immediately upstream machine. Therefore, when a long failure occurs at a machine of the line, the portion of the system upstream the failed machine is blocked but upstream machines continue to work until their corresponding buffers are full. On the other hand, the portion of the system downstream the failed machine is starved because downstream machines cannot work since they do not have any piece to work. In that case the buffer area downstream the failed machine cannot be used to store parts worked by machines that are upstream the failed machine since empties buffers are dedicated and cannot be used for pieces coming out from other machines. It appears that buffer spaces are not fully exploited when needed. The problem of properly using all the available space in transfer lines has never be faced in scientific literature and it is first addressed in this paper.

The paper presents a new concept of transfer line characterized by two different types of buffers: traditional dedicated buffers and a common buffer shared by all the machines of the

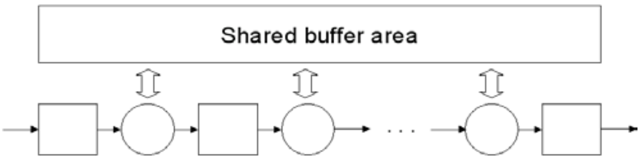

Figure 3: Scheme of the proposed system architecture.

system. The common buffer allows to store pieces at any point of the system thus increasing the buffer capacity of each machine (see Figure 3). The main advantage is related to the fact that whichever interruption of flow is in the system, the common shared buffer can be used by all machines. In the new system architecture the probability of blocking is lower than that of classical transfer lines thus allowing an increase of throughput at constant total buffer capacity.

However, profitability of the new system architecture depends on costs incurred for the additional shared buffer. The main goal in the design phase of transfer lines is to find the system configuration at minimum costs constrained to a minimum value of production rate. Large efforts in practice are dedicated to optimize in details all system components satisfying a minimum value of throughput provided by user and trying to decrease their costs. In this context, the introduction of shared buffer in transfer lines is possible only if the time necessary for moving parts from shared buffer to machines is small and the relative investment for additional mechanical components is reasonable.

Indeed, costs are the main reason for which shared buffers have not still be adopted in practice. Designing shared buffer in transfer lines implies to have additional components, and thus larger costs, for carrying pieces from machines to the central buffer and vice versa. However, technology is now mature to be used for this scope at affordable costs. Several manufacturers can now provide at low costs a wide set of transport modules for part movements. These modules can be assembled in a flexible way to move parts through the system; actually speed of conveyors is around 20 m/min on average depending on the weight of parts. Parts can follow linear paths, as usual in transfer lines, and circular paths with small rounds. Furthermore in order to save floor space, parts can be moved up or down for reaching different heights. The cost of transporter modules is now affordable allowing their intensive usage in practice at the same productivity level, defined in the paper as the amount of output obtained for one unit of input. We consider the production rate of the system as the output and the total cost of the system as the input. It is rather difficult to increase productivity of manufacturing systems since a specific action that can increase the production rate of a system is normally balanced by the effort required. Actions that can improve system productivity should reduce the total costs (reduction of machines and fixtures cost, reduction of adaptation cost, etc.) without reducing the production rate or should increase the production rate (shorter system set–up times, reduction of unproductive times, improvement of system availability, etc.) without increasing costs. The proposed system can be considered interesting for practical exploitation if its productivity remains constant or increases in comparison with traditional systems.

The article is organized as follows. Section 2 contains a detailed description of the system proposed in the paper. Section 3 reports preliminary assessments based on test cases. Conclusions and future developments are then drawn in the last Section.

2 System description

The proposed system architecture is a transfer line composed of K machines separated by limited buffers. In case of open systems the number of buffers is equal to $K-1$ while for closed systems is equal to the number of machines. We denote with M_i and B_i (with $i = 1, ..., K-1, K$) respectively the i-th machine and the i-th buffer.

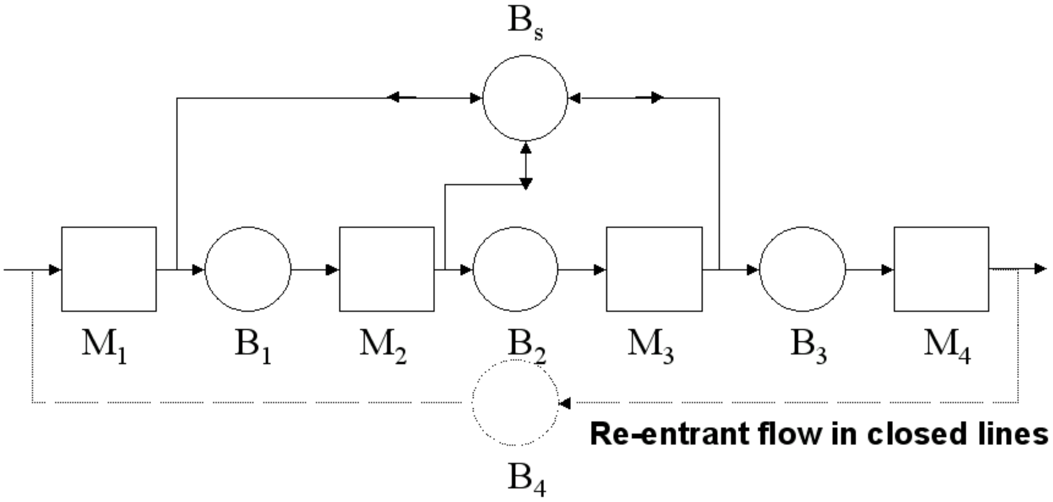

Figure 4: Example of proposed system architecture with 4 machines.

Machines are unreliable and their efficiency depends on their failure and repair distributions. The $K-1$ buffers (or K) are dedicated to their corresponding machines: buffer B_1 contains only pieces already worked by first machine M_1, buffer B_2 contains only pieces already worked by second machine M_2, and so on (see Figure 4). If buffer B_i is full, i.e. buffer level is equal to buffer capacity, machine M_i can send worked pieces to buffer B_s that is located in a specific area of the system, shared by all the machines, where it is possible to put pieces independently by their process status. The presence of shared buffer decreases blocking phenomena in the flow line. Indeed, a generic machine M_i is blocked only if both dedicated and shared buffers, i.e. B_i and B_s, are full. Therefore, if dedicated buffer is full, pieces worked by machine M_i can be moved to the shared buffer until the part flow resumes at machine M_{i+1} and the level of buffer B_i decreases. However, a certain amount of time is necessary for physically moving parts from a dedicated buffer area to the shared buffer area and viceversa; in the remainder of the paper we call this time the *travel time.*

Profitability of the system depends on the value of travel time and its impact on system performance. If travel time is reasonably small, then the penalty time incurred for using the shared buffer does not deeply decrease the system performance since, after resumption of flow, the time spent by parts for going from shared buffer area to the dedicated one is covered by the pieces already present in the dedicated area and processed in the meanwhile by machine M_{i+1}. If travel time is large, then the penalty time incurred for using the shared buffer can strongly decrease the system performance since machines are frequently starved. Next Section reports a numerical analysis for assessing productivity of flow lines with shared buffer in different conditions.

3 Preliminary experimentation

The objective of the Section is to evaluate the gain in terms of productivity due to the introduction of shared buffers in production lines. To do this, the experimentation has been carried out by simulating flow lines on simple test cases, created ad hoc to understand the system behavior in different conditions, and on a real transfer line.

3.1 Test cases

We consider a closed production line composed of five machines, each one with a buffer immediately downstream. Machines are unreliable and have the same efficiency. In particular machines are characterized by the same type of failure. Failures are time dependent and have mean time between failures (MTBF) and mean time to repair (MTTR) exponentially distributed with means 1000 s and 100 s respectively. Also the cycle time of each machine of the system is the same and is denoted with t_c. The number of parts circulating in the system is maintained constant during production and equal to P. For simplicity, dedicated buffers have the same capacity N_i with $i = 1, ..., K$.

The goal of this first experiment is to evaluate by means of steady state simulations the impact of variations of specific factors on the performance of both systems with only dedicated buffers and with shared buffer. In the comparison between proposed and traditional system architecture the total buffer capacity is maintained constant but allocated in different ways. Factors taken in consideration are: machine cycle time t_c , total buffer capacity N_{TOT}, percentage of dedicated buffer capacity α, travel time t_t and number of parts that circulate in the system P. Table 1 reports levels of factors chosen in the experiment. In each simulated scenario the capacity of dedicated buffers is calculated in the following way:

$$N_i = \frac{N_{TOT} \cdot \alpha}{K}, \quad i = 1, ..., K \tag{1}$$

while the capacity of the shared buffer is equal to $N_{TOT} \cdot (100\% - \alpha)$. Since a traditional flow line has only dedicated buffers, coefficient α is equal to 100%.

Factors	**Levels**
Cycle time (t_c)	5, 15, 30, 45, 60
Total buffer capacity (N_{TOT})	50,150,200,250
Percentage of dedicated buffer capacity (α)	20%, 60%, 100% of N_{TOT}
Travel time (t_t)	0,0.5t,t,2t
Number of parts (P)	20%,40%,60%, 80% of N_{TOT}

Table 1: Test case: factor levels of the experiment.

Figures 5 and 6 show the throughput obtained from simulation with a half 95% confidence interval equal to 2.5 pieces/h. In particular graphs in Figure 5 show the throughput of the system depending on the number of parts circulating in the closed flow line for cycle time and travel time respectively equal to $5s$ and $10s$ and for different values of α and N_{TOT}. The throughput of the system with only dedicated buffers (i.e. $\alpha = 100\%$) is always smaller than that with shared buffer and the relative difference is larger in those systems with small total buffer capacity. Indeed the difference between the throughput of systems with shared buffer and that of traditional systems decreases as the total buffer capacity increases. This is due to the fact that the probability of blocking of machines decreases when system buffers are enlarged. Notice also that, for the same reason, the maximum value of throughput curves related to flow lines with shared buffer is shifted to the right direction in the diagram respect to that of traditional flow line; also for values of $\alpha = 20\%$ the throughput is always increasing in the analyzed diagram region and it is reasonable to think that the maximum value is closer to the total buffer capacity of the system.

Graphs in Figure 6 show the maximum throughput of the system depending on the total buffer capacity for different values of α and t_c with travel time $t_t = 2t_c$. These graphs show as the increase of throughput obtained by the introduction of shared buffer becomes not significative when the total buffer capacity is large and blocking of machines does not occur frequently. This behavior is more evident when the cycle time of machines is long; indeed in Figure 6d all systems can be considered equivalent because the half–confidence interval on average throughput

is around 2.5 pieces/h.
Finally graphs in Figure 7 show the maximum throughput obtainable by the system with total buffer capacity equal to 50 for different values of cycle times. It can be noticed that the performance of systems with shared buffer decreases as travel time increases. Indeed it is possible to find the threshold value of travel time after which the system performance strongly decreases. It is worthwhile to point out also that systems with smaller capacity value of the shared buffer can be used with good performance also if travel time is large; the reason is that large dedicated buffers allow covering long travel times because there are more pieces in dedicated buffers that avoid the starvation of machines. Indeed the threshold value for α=20% is greater in Figure 7b (with $t_c = 15$) than that in Figure 7a (with $t_c = 5$).

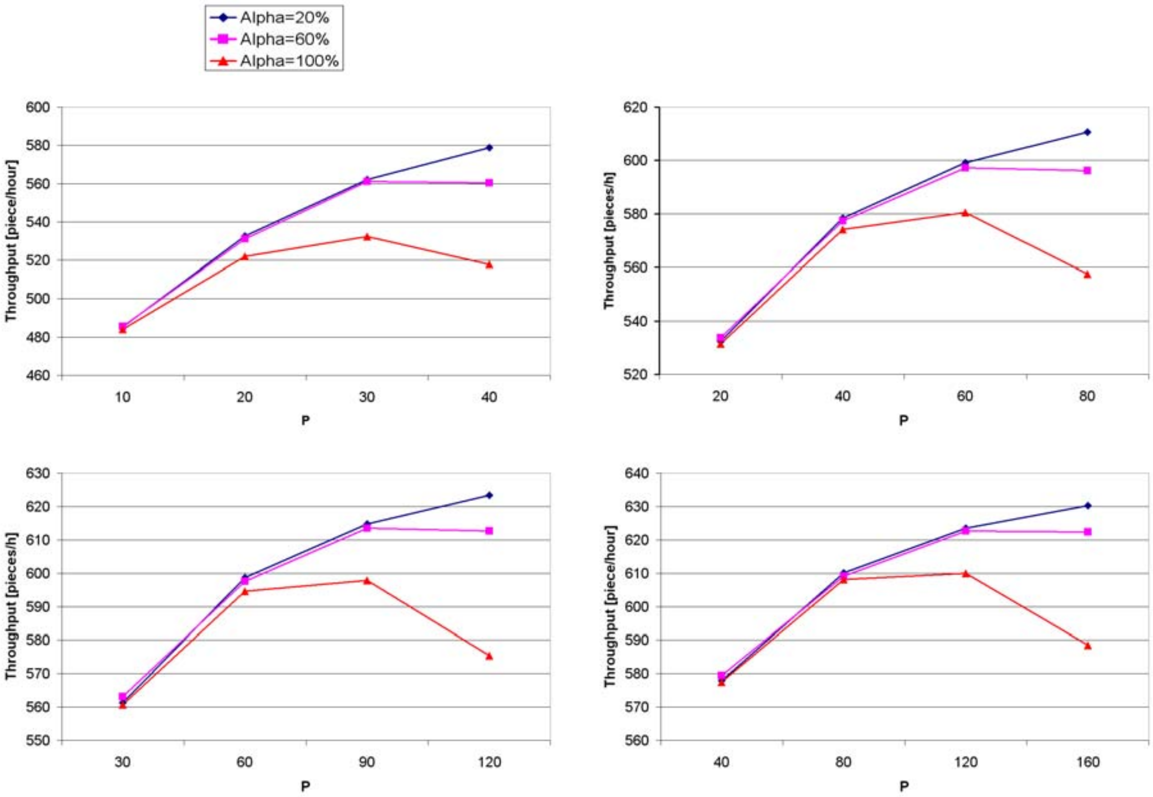

Figure 5: Test case: throughput as a function of P; (a) $N_{TOT} = 50$, (b) $N_{TOT} = 100$, (c) $N_{TOT} = 150$,(d) $N_{TOT} = 200$.

3.2 Real case

In the second experiment we consider a real system composed of five machines separated by buffers. The system is an assembly line in which parts are loaded on pallets and the number of pallets remains constant during the production. Machines are unreliable and characterized by different types of failures and repairs exponentially distributed with means as reported in Table 2; the table contains also processing rates of machines, assumed deterministic in the developed simulation model, and capacities of buffers in the original line. The real system already uses in the traditional way flexible transport modules for moving parts through the system at a speed of 18 m/min. The capacity of dedicated buffers in the proposed system is equal to $N_i \cdot (\alpha)$ while the capacity of the shared buffer is equal to $N_{TOT} \cdot (1 - \alpha)$.

The graph in Figure 8 shows the throughput of the system depending on the number of pallets that circulate in the closed line. Throughput curves in the graph are obtained for values

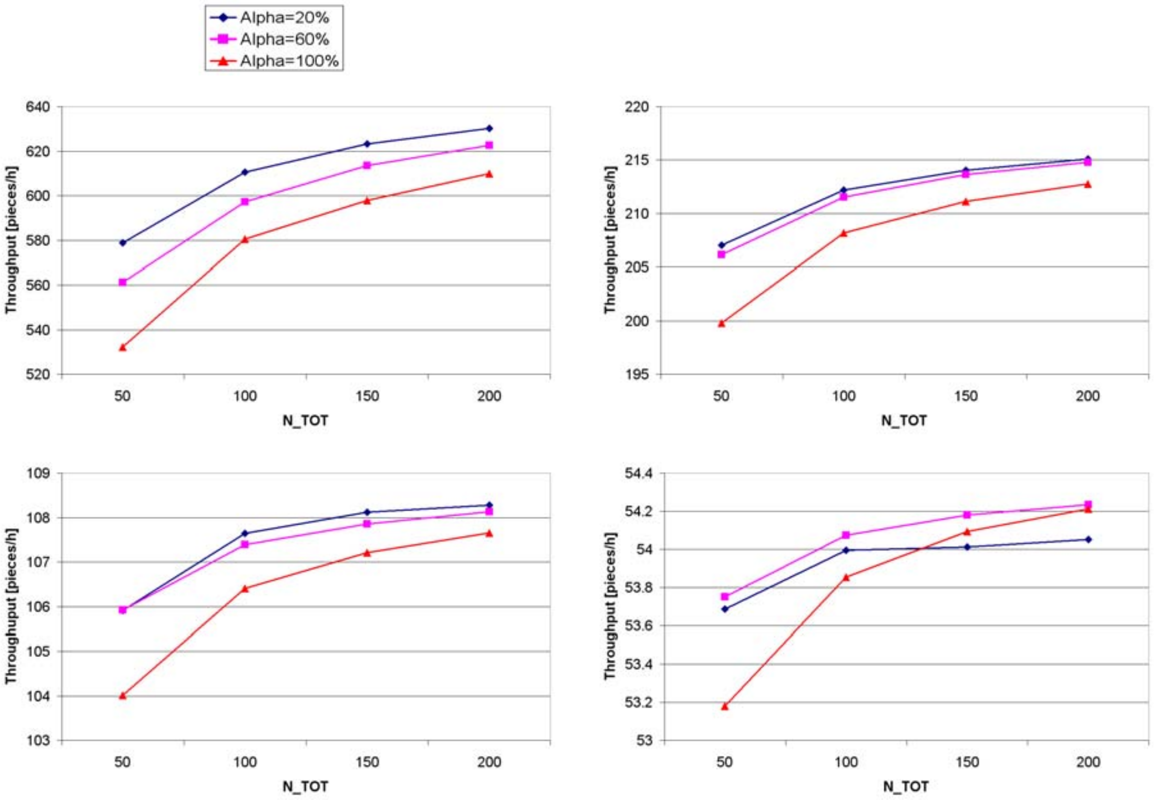

Figure 6: Test case: throughput as a function of N_{TOT}. (a) $t_c = 5$, (b) $t_c = 15$, (c) $t_c = 30$,(d) $t_c = 60$.

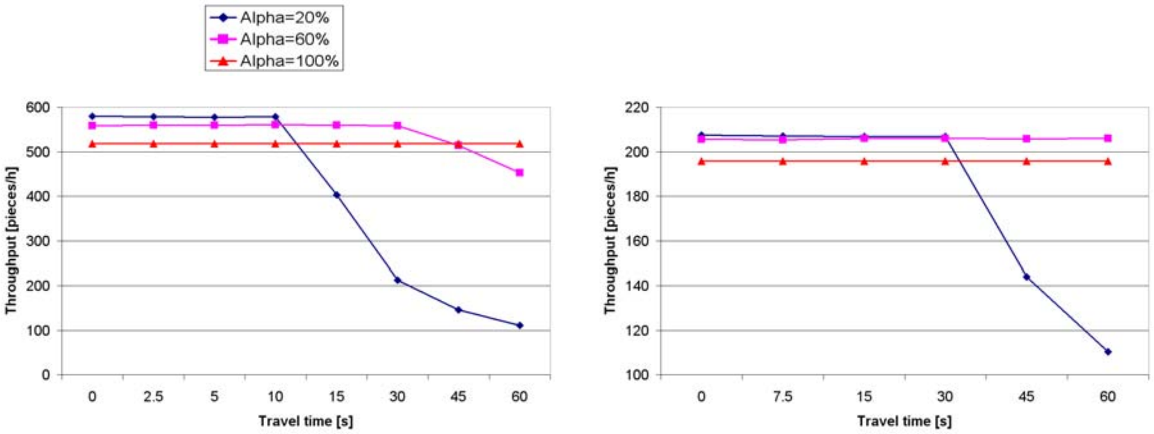

Figure 7: Test case: maximum throughput as a function of travel time t_t ($N_{TOT} = 50$). (a) $t_c = 5$, (b) $t_c = 15$.

of travel time equal to 30s. Notice that the system with smallest percentage of dedicated buffers (i.e. $\alpha = 25\%$) are not profitable in practice because travel time is too long in comparison with processing times thus causing the starvation of machines. However, systems with larger dedicated buffer capacity performs better than traditional flow line. The average increase of throughput is equal to 7.2% and 4.5% for systems with $\alpha = 50\%$ and $\alpha = 75\%$ respectively. Table 3 reports average throughput values and relative 95% confidence interval obtained by simulating the system in steady state.

Machine	Cycle time	Buffer capacity	MTBF 1	MTTR 1	MTBF 2	MTTR 2	MTBF 3	MTTR 3
1	20	40	5.64	0.8	500	4	120.5	7
2	17.3	36	2.9	1.1	95.2	5.2	70.9	5.2
3	16.5	20	5.6	0.6	-	-	-	-
4	15.7	22	21.3	0.5	-	-	-	-
5	16	76	10.6	0.6	250	5.2	-	-

Table 2: Real case: processing rates [pieces/min] and MTBFs and MTTRs [min] of machines.

α	t_t [s]	N_{TOT} 50	N_{TOT} 75	N_{TOT} 100	N_{TOT} 125	N_{TOT} 150	N_{TOT} 175
10%	0	589±7.1	615±6	621±6.2	637±5.3	637±8.4	638±6.2
	15	422±2	427±2.4	433±3	435±2.2	438±1.9	439±1
	30	225±1.4	225±1.1	225±0.8	225±0.8	225±0.7	224±0.3
	60	116±1	115±0.3	115±0.2	115±0.1	115±0.2	115±0.1
	120	59±0.2	58±0.1	58±0.1	58±0.1	58±0.1	58±0.1
25%	0	584±6.2	611±6.4	622±5.1	628±3.9	636±5.9	610±5
	15	587±6.2	608±6	627±5.3	625±7.2	638±4.4	609±7.5
	30	511±3.9	520±4.8	526±3.3	531±3.4	536±3.2	584±5.3
	60	305±2	302±3	295±2.9	292±2.4	289±1.6	395±3.5
	120±	173±3.8	162±3.1	150±2.8	148±2.4	146±0.7	230±2.6
50%	0	579±5.2	608±8.1	624±7.7	633±4.6	607±6.6	606±4.9
	15	576±7	608±6.6	621±8.1	632±6.8	612±5.4	607±7
	30	581±5.8	609±4.3	619±7.8	629±5.9	609±6.3	608±4.4
	60	541±5.5	544±5.3	552±3.5	578±3.7	594±4.4	588±4.6
	120	373±4	354±4.4	342±5.4	386±4.7	445±5.7	367±6.8
75%	0	575±5.8	604±7.2	614±6.7	608±4.4	607±7	594±4.3
	15	571±6.7	608±5.4	610±6.4	608±6	608±7	590±7.3
	30	577±4.3	605±7.2	614±5	607±6.9	600±4.9	594±3.4
	60	577±5.3	607±4.7	606±5.7	607±5.4	608±6.8	590±5.5
	120	542±6.9	520±6.2	558±5.3	573±4.6	566±6.8	540±6.1
100%	-	562±5.3	578±6.2	587±5	585±7.3	584±5	545±4.2

Table 3: Real case: average throughput [pieces/h].

If we consider a reasonable system with $\alpha = 50\%$ and $t_t = 30s$, the total estimated cost necessary to introduce shared buffer in the existing system goes from 41,000 to 58,600 Euro depending on quantities of modules acquired in the year by the firm. However, the increase of throughput due to the introduction of shared buffer is around 7% respect to that of the original system. Since investment cost of the system is equal to 2,250,000 Euro, we can calculate its productivity as the ratio throughput over cost. The productivity of existing system is equal to 0.261 while that of the proposed systems goes from 0.272 to 0.274 depending on investment costs. The increase of productivity related to the new system is from 4.4% to 5.2%. Therefore, the introduction of shared buffer in analyzed existing system allows in the analyzed real case an increase of throughput without decreasing the system productivity.

4 Conclusions and future developments

The paper addresses the problem of fully using buffer spaces in transfer lines. The idea is to exploit recent technological devices to move in reasonable time pieces from a machine to

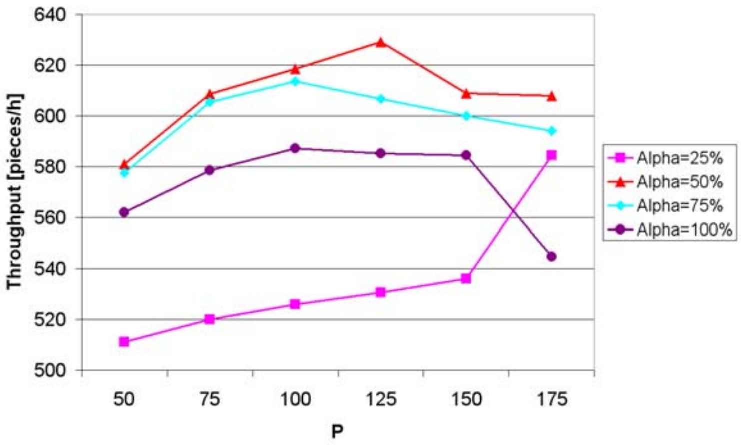

Figure 8: Real case: throughput as a function of P ($t_t = 30s$).

a common buffer area of the system and vice versa. In such a way machines can delay their blocking since can send pieces to the shared buffer area. Decrease of blocking in transfer lines has a positive impact on their production rate. The numerical analysis reported in the paper demonstrates the validity of the idea pointing out also factors that affect the gain of proposed system architecture in terms of productivity. Additional experimentation will be carried out in future to identify application areas of the new system architecture proposed in the paper.

This work represents a first study in this field and further research is needed. Indeed, the introduction of shared buffer in transfer lines introduces new key-issues never addressed in literature:

- Mechanical design of transfer lines with shared buffer. It is necessary to design accurately a solution that has to be valid in practice and exploitable by system builders.
- Allocation of dedicated and shared buffers. Traditionally only capacities of dedicated buffers have been considered in design of transfer lines.
- Performance evaluation of transfer lines with shared buffer. New analytical methods are necessary to estimate performance of new system architectures.
- Management of transfer lines with shared buffer. New dispatching rules could be necessary to avoid deadlock in new system architectures when pieces converge to the same area coming from different positions.

Future research will be first dedicated to propose the mechanical solution for moving pieces from machines to the shared buffer and vice versa. Then potential areas for a practical application will be identified both with test cases and real cases.

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