INCREASING AVAILABILITY OF PRODUCTION FLOW LINES THROUGH OPTIMAL BUFFER SIZING: A SIMULATIVE STUDY

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ABSTRACT
In flow shop highly automated production lines the absence or undersize of inter-operational buffer between consecutive stations is an occurrence as frequent as detrimental for the productivity of the entire production line. A correct sizing of buffers mitigates or even eliminates the propagation, on the entire production line, of small inefficiencies due to stops and / or slowdowns of the single station. This paper describes a simulation approach to investigate the effect buffer between two successive stations and measure its effects in terms of change in the overall efficiency of the line. A wide range of typical production parameter is considered. This allows to extend the paper results to many different production system and to evidence some interesting analogies in production effectiveness behavior depending on buffer size. The introduction of an analytic experimental relation allows to describe the evidenced behavior and to size the buffer without need for further simulations.

1. INTRODUCTION
The increasing competition and attention of the market to the cost of the product have prompted the producers of goods to use more automated forms of production in recent years. This is pursued through more complex workstations that can perform many operations, with the aim of increasing productivity while ensuring the requested level of flexibility in production.

This issue is very important in flow shop dominant sectors (e.g. pharmaceutical, cigarettes, electronic, etc.) and has led to the development of production lines that complement many workstations (even over 20) in succession.

During several years of experience with some leading multinational companies, the authors have noticed that the design of these systems is often exclusively focused on the balance of workstations in ideal operating conditions. This approach neglects the effects of efficiency losses propagation between the workstations, that is dramatically important in this type of systems.

In particular the production rate of each workstation is often characterized by short but frequent interruptions and delays caused by minor stoppages (e.g. pieces stuck in the machines, block of mechanical parts, temporary reduction of workstations speed, congestion, minor stoppages). The effects of inefficiencies in the single work station can spread along the entire production line slowing down the other machines that otherwise would be able to operate properly. Therefore the lack of a minimum level of independence between workstations in series (belonging to the same production line) can get to stop the production lines (Spinellis 1999) also due to the temporary blockage of a single machine.

If the number of workstations is high, this effect may result in a reduction of the overall performance of the production line even over 30 %, also if the failure of a single work station is limited.
The loss of productivity of the production lines has a wide impact at a strategic organizational level, due to:

- Higher production costs;
- Delays in delivery (customer satisfaction)
- High inventory in stock (interest payable)

2. LITERATURE REVIEW
To ensure the desired performance it is necessary to determine an appropriate level of independence between successive work stations of the production line through the insertion of buffer of opportune size and suitably located. This issue has been widely debated in literature through two different paradigms:

- Buffer Allocation Problem (BAP)
- Buffer Size Problem (BSP)

The problem is studied by the scientific community in order to identify the location and/or the size of the inter-operational buffers, in order to minimize both cost and space, and maximize production line throughput.

2.1. Existing Problem approaches
Historically, there are different approaches to this problem, among which:

– Heuristic, typical of operations research (Hillier 1993, Lutz 1998 and Papadopoulos 2001);

– Survey followed by procedures for sizing (Tempelmeier 2003);

– Mathematics: (Hillier F. S. 1977 and Gutowski 2005);

– Simulation, (Malakooti 1994, Chiadamrong, 2003 and Yamada, 2003);

As stated from (D. Battini 2009)*"The optimal buffer size problem based on the machine availability is a very critical issue (50% of studies analyzed consider machine reliability parameters), but has not been yet sufficiently investigated.".* Furthermore there is a lack in the available literature of benchmarking analysis investigating the change in production line availability depending on the change of buffer dimension.
In particular, most of the literature available today does not provide an approach that fulfills the needs of industrial producers, i.e. an approach that is at the same time practical, operative and easily repeatable by the companies themselves. In fact:

(1) The mathematical approach is often too complex and too hard to repeat by the industrial producers;

(2) *"The dynamical simulation approach is often appreciated and applied by researchers to face the BAP problem under specific working conditions: otherwise, as (Chiadamrong 2003) underlines, no standard formulae or algebraic relations between line throughput and buffer sizes has yet been obtained to help practitioners in the fast and easy design and optimization of buffers, when time constraints avoid the use of simulation (which is often complex and time consuming);"* (D. Battini 2009).

(3) Furthermore, many existing approaches are not related to industrial standard parameters such as: Overall Equipment Effectiveness (OEE), Availability and Performance Efficiency (Samuel H. Huangt 2003).
All these aspects cause the inability to easily quantify the productivity lost in the production lines as a result of short failures due to an ineffective buffer sizing.

As noticed by the authors in their professional experience (e.g. pharmaceutical packaging lines, electrical components assembly line, etc.), this gap is strongly felt by the industrial sector, and it leads to buffers generally absent and/or under sized and/or misplaced. Thus, production lines present reduced OEE, which eliminate some of the benefits arising from greater speed automated lines.

Therefore authors believe that in literature there is the space to approach a second specific paradigm, already introduced by (D. Battini 2009) useful to study the function of buffers in production lines, which is the Buffer Design for Availability (BDFA).
Within BDFA, all the works available in literature up to now aim to assess the maximum buffer size depending on the production parameters. This approach could be comprehensive in flow shop industry if down-time production cost are more relevant than inventory cost, as stated by Gerwish and Goldin in their *"Efficient Algorithms for transfer line design"* (Gershwin 1995) (e.g. food, beverage, etc.).

Rather than maximum buffer size Authors, wants to investigate the trend of the OEE depending on the buffer size. In fact but in other flow shop production lines (such as electronic or pharmaceutical) where inventory cost can be higher than others to find the maximum size of the buffer could not be a sensible solution. Furthermore, not only costs affect the choice of the buffer size, but also others factors that may prompt to a smaller sizing, must be taken into account. For example:

- Operative production constraints.
  The value of Work in progress, or production line lead time may need to be under a certain value (Slack 1993Therefore maximum buffer of size could not allows to respect these constraints;

- OEE trend.
  The values of OEE, depending on the Buffer Size, assume an asymptotic trend on its maximum value after a certain value of the buffer. To chose the maximum buffer size, without analyze this trend could bring to increase the size of the buffer of more than 40% in order to obtain an improvement of OEE of only 1%.

By changing the value of the buffer size from zero to the maximum buffer size, Authors will show graphically and analytically the relation that connect the size of the buffer to the OEE of the entire production line.
Therefore this work aims to deliver a tool that give the possibility to estimate the OEE trend depending on the buffer size and to chose right size of buffer according to both inventory cost and all the others industrial factors
The resulting parametric curves obtained by Authors and the analytic model that will be propose in this study could certainly represent a significant step towards the needs of industry, since they allow both the buffer sizing in a simple and immediate way and provide to managers a greater sensitivity on the effects of buffer (in terms of OEE and productivity line), otherwise absent

2.2. The Buffer Design for Availability
The studies regarding the BDFA already available on literature aim to deliver the maximum buffer size that allow to achieve the maximum OEE, taking into account different performance parameters. This is a

very important result. In fact the bigger is the buffer, the highest is the OEE, but once achieved the maximum buffer size no improvement in OEE will be obtained by a further increase in buffer size. Therefore, the value of the max Buffer size depending on the process parameters (such as Availability, stoppage time, speed losses, etc) is a very important information that can allow to do not invest more money in buffer than necessary.
By the way is important also to consider the productivity trend of the production line depending on the buffer size.
In fact, considering synchronous flow shop lines with n series station (figure 1), if the buffers between the stations are null the global efficiency of the system will be the factorization of the single station productivity (P_1* P_2*…*P_i*…*P_n). The performance of each station depend on the performance on the other n-1 stations (Complete dependence).

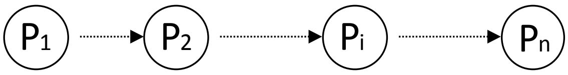

Figure 1: Stations in complete dependence

Instead, if the buffers between the stations are opportune sized with their maximum value (figure 2) the Productivity of the line will be the one of the bottleneck (*min*(P_1, P_2, P_i,.., P_n)).

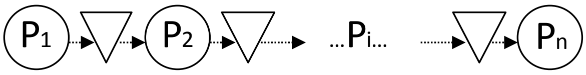

Figure 2: Stations in complete independence

The trend of the OEE between these two bound (Complete dependence and Complete independence) depend directly by the buffer size.

Therefore an enterprise can be interested to:

- size the buffers of the production line in order to maximize its overall availability and then its throughput;
- determine the minimal buffer size that allows to reach a desired level of real throughput, then minimizing buffer occupation, cost, etc.;
- easily know the lost level of efficiency due to absent/undersized buffers;
- know the expected growth trend of the overall production line productivity depending on the increase in buffer size.

Therefore the goal of this study is to investigate the behavior of the production line productivity depending on the buffer size, taking into account:

- Effect of cycle time variability;
- Effect of minor stoppages;

and to provide a tool that allows an experimental buffer sizing.

3. PROBLEM MODELING

The configuration of reference used in this paper consist of two consecutive work stations separated by a buffer, as shown in figure 1. The results could be extended to a line formed of more elementary units.

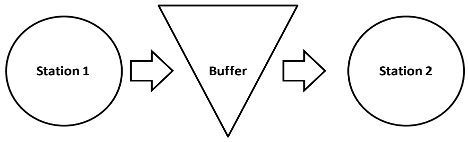

Figure 3: model configuration

The size of the buffer will be provided depending on different typical performance parameters of the line, such as:

- Randomness connected to reduction in Workstation speed;
- Mean Time Between Failures (MTBF);
- Mean Time to Repair (MTTR);
- Standard deviation (as a percentage of MTBF and MTTR).

3.1. Assumption

Authors have identified, considering evidence from literature review (D. Battini 2009), the simulation as the best approach to the problem in terms of robustness and validity of the output solution. The software selected by authors for the simulation model realization is “Rockwell Arena”. The model consist of different modules, already available in the software, that allow to simulate the process. Besides, the right definition of process attributes and variables allows to record the needed data for the further simulation analysis.
Data input of the simulation are typical of the industrial sector and are defined below.

3.1.1. Cycle Time

In automated production line the different station are usually balanced between them, therefore the station are characterized by the same ideal process time, Ti, within the range [0,01667; 0,25]. It does not take into account the inefficiencies.
Vi is the ideal throughput achievable in ideal condition (no inefficiencies) in one hour from the production line. It is defined as 60/Ti. All the time measures are expressed in minutes.
Loss in productivity are considered in the model according to the general notation of OEE (Samuel H. Huangt 2003).

3.1.2. Loss of Quality

In flow shop production line loss of quality due to defect in pieces are usually negligible. Moreover they affect the buffer size only if the detection of wrong units is done between the two stations. Consequently, the loss of quality have been neglected.

3.1.3. Loss of Performance

OEE theory includes in performance losses both the cycle time slowdown and minor stoppages. The latter are discussed within the Availability paragraph because of their feature to be simulated as a stop of the station. Regarding to cycle time slowdown distribution the goal has been to model it in the most general way.

The production stations can be modeled according to the principle of queue theory.(H.T. Papadopoulos 1996). Exploiting the link to this mathematical formulation of the problem is possible to identify the statistical distribution that allows to model cycle time slowdown in order to obtain result with highest general significance.

According to Kingman equation (or VUT equation) (Kingman, 1966) exponential distribution of cycle time (M/M/1) can be used as an upper bound of general distribution in cycle time (G/G/1) for specific range of variability. In accordance to theirs experience in flow shop sector Authors argue that real variability in cycle time is include within this range.

To model the Cycle time variability with an exponential allows to obtain an Upper bound for Buffer size and therefore to gain a more robust size of the buffer.

Performance index P(i) can vary within [0,8;0,00].The performance of the two stations can be different from each other.

3.1.4. Loss of Availability

Availability depend on failures and set up. Set up usually require the stop of the entire production line, therefore it is not considered in this treatment. Also significant failures usually stop the entire, hence only failure till 30 minutes (minor stoppages) are included in this study

The BDFA aim to eliminate the effect of the unpredictable minor stoppages that may occur during production in one or twice stations , (that can be frequent in a production line). Therefore only this kind of losses will be take into account. When a minor stoppage occurs on the second station a correct size of buffer between the two stations allow to complete all the maintenance with no influence to the first station performance. In presence of minor stoppages in the first station a correct size of buffer allows to feed the second station while maintenance regard the first

Scientific literature(Lawless 1982) provides many models of statistical distribution that can represent different kind of minor stoppage, such as Lognormal (fatigue and material strengths and loading), Weibull (material strength, times-to-failure of electronic and mechanical components, equipment, or systems), Exponential (behavior of units that have a constant failure rate) or Normal (complex mechanism)

Therefore the variable that require to be modeled for availability are:

- Up-time distribution (Mean Time Between Failures of the station i);
- Down-time distribution (Mean Time to Repair of the station i).

Availability index vary within [0,8;0,99] (lower value of availability in automated lines are infrequent).

Mean Time to repair of stations are supposed within the range [0,01; 30] minute. Because greater downtime are uncommon in automated production lines.

The MTTR of first station is at most equal to MTTR of the second

$$MTTR(1) \leq MTTR(2) \qquad (2)$$

Mean Time Between Failures (MTBF) is expressed as function of Availability (table 01).

Both up-time and down-time are assumed as normally distributed.

Standard deviation is expressed as a percentage of respectively Up-time and Down-time average. The range is from 5% till 100%.

All these losses affect the overall productivity of the line reducing the reliable throughput in the time unit. Therefore in the model the OEE have been measured as the Ratio between the Real line throughput and the ideal line throughput.

3.2. Simulation Plan

The simulation is composed of two phases:

1. The first for the definition of Bmax, the minimum buffer size that ensure complete independence between the two stations.
2. The second to study the effect on OEE for a buffer of a size minor then B max.

Both phases have been repeated in two different scenario: The first scenario consider only the losses due to the effect of cycle time variability. It wants to investigate how, in absence of opportune buffer size, the cycle time variability of one station can affect the performance of the other station and so of the entire production line.

Second scenario considers also the effects of failures and theirs variability.

The first phase was was carried out by changing the data input (Ti, Ai, Pi) within the range defined above, with an infinite buffer size.. 50 repetitions of the production period of more than 160 hours for each configuration case was carried out.

All the simulation parameters are briefly reported on table 1.

Table 1: Simulation Parameters

Parameter	Description	Range
Bfix(j)	The chosen buffer size for the specific (j) simulation.	[0;Bmax]
Ti	Ideal Cycle Time to process a piece (min)	[0,01667; 0,25]
Vi	Ideal line throughput in one hour of production (pieces/h)	-
P(i)	Performance represents the speed at which the station (i) runs as a percentage of its designed speed	[0,8;0,99]
A(i)	Availability represent the percentage of scheduled time that the station (i) is available to operate	[0,8;0,99]
MTTR (i)	Mean time to repair of the station i	[0,01;30]
MTBF (i)	Mean time between failures of the station i. It is a function of Availability, where A(i) = MTBF/(MTBF +MTTR)	-
σ (mtbf, mttr)	As percentage of MTBF or MTTR	[5%;100%]
B Max	The maximum buffer size that allow to decuple globally the two stations	
Throughput	Total number or processed pieces	

In this phase the output data was the maximum buffer size(for all 50 replications) and it is called Bmax.. This value assures the real maximal throughput of the production line (complete independence between the two stations).

The second phase was carried out by using the same data input (Ti, Pi, Ai) configuration, increasing step by step the buffer size Bfix(j) within the range [0; Bmax).

In this phase the output data was the line throughput and the corresponding OEE for each set of parameters Ai, Pi, Ti, Bfix(j). OEE have been measured as the Ratio between the Real line throughput and the ideal line throughput

3.3. Model Validation

Before to start any kind of analysis the model was validated by comparison of the second simulation scenario (more complete) with a work already available in literature. Specifically, the chosen work for validation was the simulative study proposed by (D. BAattini 2009).

The Output Parameter used for the validation of the simulation model was the maximum buffer size obtained under a specific simulations conditions.

The output results of the model in comparison with the available results in literature (once fixed same configuration and same statistical distribution) are briefly showed in table 2.

Table 2: Model Validation

A(a)	A(b)	Mttr(a)	Mttr (b)	Model Result	Difference (%)
93%	95%	0,03	14,00	71	1,43%
92%	96%	0,05	12,00	61	0,00%
97%	92%	0,50	20,50	105	0,96%
92%	97%	0,50	20,50	105	0,00%
99%	95%	1,00	26,50	135	0,75%
99%	92%	1,00	25,50	130	0,78%
99%	92%	1,50	21,50	112	2,75%

The statistical significance of the model is high. The obtained R^2 is of 99,88%.

The Analysis of Variance (ANOVA) on the regression test in order to validate the regression test indicate a P-value of 0,000. Therefore the model is statistically validated.

4. SIMULATION RESULTS

4.1. First Scenario: Effect of cycle time variability

This scenario considers an equal value of the ideal cycle time for the two stations. Ideal cycle times data are distributed as an exponential distribution within this range [0,01667; 0,25]. The performance index is included within the range [0,8;0,99].

investigates how speed losses can affect the OEE of a production line in absence of opportune buffer between stations.

Lack of opportune buffer between the two stations can affect dramatically the availability of the system. In fact also if the ideal cycle times of the two stations are equal, the variability of speed that affect the stations are not necessarily of the same entity because depend on different factor. Furthermore Performance index is an average, therefore it could happens that machine present sometimes reduced speed and sometimes an highest speed. The presence of this effect in two consecutive stations can be mutually compensate or add up.

The simulation of this phenomena In order to evidence the effect of the cycle time variability is useful to express the performance of the production line as the percentage of the maximum achievable value of the OEE. This value is obtained when the losses of one station don't affect the performance of the other. In this situation the OEE of the production line is equal to the minimum OEE of the two stations. obtain general results, the Overall effectiveness of the system could be expressed as a related measure.

For example is possible to express it like the ratio between the achievable performance in terms of OEE for the selected buffer size (OEE(j)) and the OEE ideally achievable with the max size of the buffer: OEE(B max)

Therefore we can introduce the parameter

$$Rel.OEE(j) = \frac{OEE\ (j)}{OEE(Bmax)} \quad (3)$$

Where:

- OEE(j) is the value of the OEE corresponding to the buffer size (j).
- OEE(Bmax) is the maximum value of OEE(j) and it is achievable with a buffer size equal to Bmax.

Hence:

- in worst condition Rel.OEE (0)= $\frac{\text{OEE (0)}}{\text{OEE(Bmax)}}$= OEE(1)*OEE(2)/min(OEE(1);OEE(2));
- in ideal condition, with Buffer size equal to B max the Rel.OEE (B max)= $\frac{\text{OEE (Bmax)}}{\text{OEE(Bmax)}} = 1$

Figure 4 shows the trend of Rel.OEE(j) depending on the buffer size. The two curves represent the minimum and the maximum simulation results. All the others simulation results are included between these two curves. Maximum curve represents the configuration with the lowest difference in performance index between the two stations, the minimum the configuration with the highest difference.

By analyzing the figure 4 it is clear how an inopportune buffer size affect the performance of the line and how increase in buffer size allows to obtain improve in production line OEE. By the way, once achieved an opportune buffer size no improvement derives from a further increase in buffer.

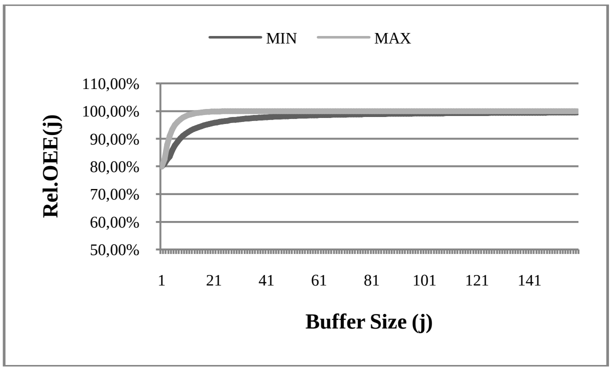

Figure 4:Rel OEE depending on buffer size in system affected by variability due to speed losses

It is important to evidence how the trend of Rel.OEE by change in simulation parameters is really similar between the different cases. Figure 5 shows the deviation between different simulation cases and the value of the curve of the min represented in figure 4.

Figure 5 shows how the gap between the different simulations is negligible. A first assessment of the loss of OEE, depending on buffer size, could be done using the curve of minimum, and the difference with the specific curve of the specific simulation would be negligible in first approximation.

For a example, with a buffer of 17 pieces the Rel.OEE(17) obtained with the simulation with this input parameters (Ti=0,01667; P(a)=0,85; P(b)=0,8) is s 97,1%, corresponding to an effective OEE of 77,68%. The value of the Rel.OOE for the same size of the buffer Rel.OEE(17) with the curve of minimum is 94,9%. The deviation between the real curve and the minimum curve of Rel.OEE is 2,2%. To use the curve of minimum as a proxy of the Rel.OEE would bring, in this case, a value of effective OEE of 75,92% with an underestimation of OEE of 1,76%. Then, different curves within all the defined ranges of simulation parameters are available after this study, however the deviation by the specific curve and a first assessment, done by referring to the curve of the minimum is reduced, by increasing the buffers size.

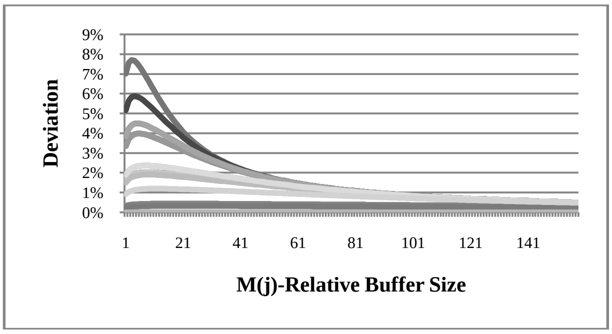

Figure 5:Deviation between the curve of the minimum and other simulation curves

4.2. Second Scenario: Effect of Minor Stoppages

Minor stoppages of the two stations can stop the flow of material processed by the line.

Considering the ratio: $MTTR(2) / \frac{Ti}{P(1)}$ it represent the maximum amount of material produced by the first station when a failure in second station occurs (P(1) supposed constant and equal to its average) .

Likewise the ratio $MTTR(1) / \frac{Ti}{P(2)}$ represents the maximum amount of material that must be stored on the buffer in order to not affect the second station when a failure in the first occurs.

The maximum of these two ratio could represent a proxy of the buffer size but it does not take into account the effect of variability in MTTR, MTBF, the effect of cycle time speed losses and the moment in which the first failure occurs. Simulation allows to take into account also this effect.

Hence, the buffer size fixed in the specific simulation is expressed as percentage of these ratio

$$M(j)= \frac{B\ fix(j)}{max\left({MTTR(1)}/{\frac{Ti}{P(2)}} ; {MTTR(2)}/{\frac{Ti}{P(1)}} \right)} \qquad (4)$$

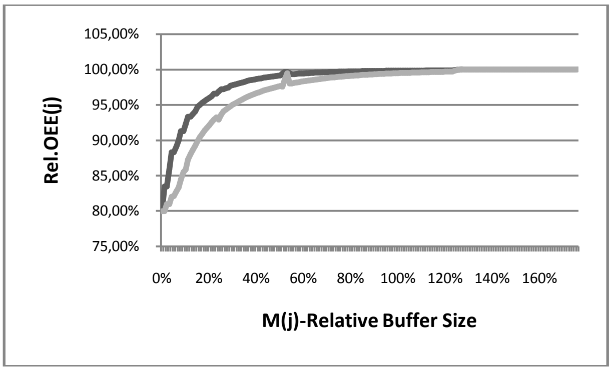

Figure 6: Relative OEE depending on relative buffer size M(j) for a defined value of availability

Authors analyze the behavior of the OEE depending on the buffer size, taking into account all the different configurations of cycle time, different performance yield, and minor stoppages value within the defined range (table 1).

Figure 6 show an example of relative OEE trend depending on the M(j) ratio. The curves represents a configuration where the level of availability is defined, but MTTR and therefore MTBF vary properly within the defined range (table1). For simplicity it reports only two extreme different configurations: Maximum curve represents the configuration with the lowest ideal cycle time (0,01667 min) and minimum curve the configuration with the highest (0,25 min).

Trend like those represented in figure 6 have been developed by authors for each combination of simulation parameters within the defined range (table 1).

The obtained trend are similar for all the Availability level. In fact, Figure 7 shows the deviation between different curves with same level of availability from the curve of the minimum. The proposed figure represent the simulation case with the highest variance between the curves. Hence, considering that simulation results take into account also the effect of variability on MTBF and MTTR (5%), the behavior of the Rel.OEE depending on the relative buffer size is even so regular.

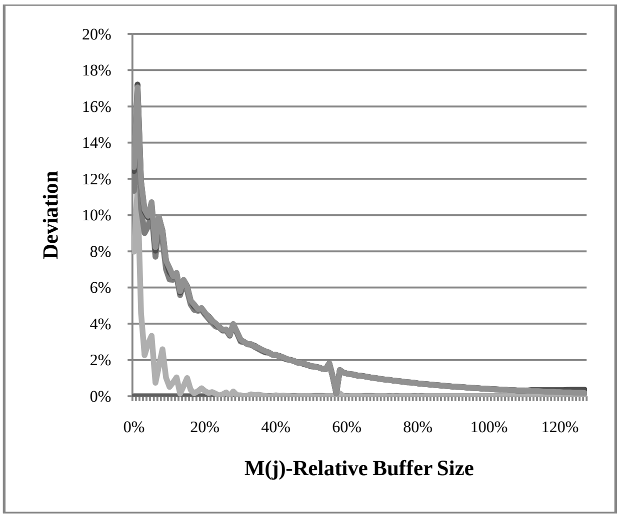

Figure 7: Error in confounding the specific curve

To express the Buffer as a ratio between the chosen buffer size and the amount of material necessary to feed a station during the stoppage of the other evidence how the uncertainness in Performance, and availability affect the buffer size requiring oversized buffer.
Nevertheless the frequency of cases in which the Bmax is required is reduced. The differential between different buffer sizes are the cost.

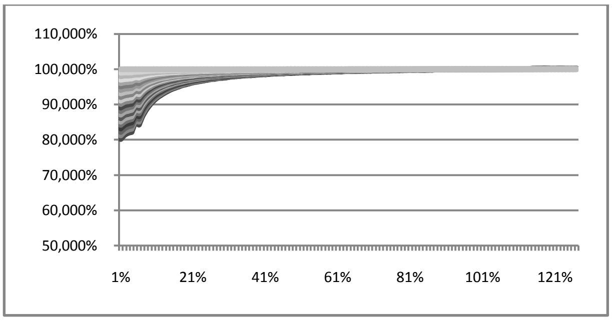

Figure 8: Resume of Rel.OEE depending on M(j) for all the analyzed availability level

The regularity in behavior of the Rel.OEE depending on the M(j) allow to express the evidenced relation between Rel.OEE(j) and M(j) in an analytic way.
Trends obtained with simulation analysis (figure 6, 8) are similar to an hyperbole, but more flattened.

Any kind of analytic relation must take into account that in limit configurations, as evidenced in figure 8, the Rel.OEE of the production line is independent from the buffer size. It happens when OEE(station 1) or OEE(station 2) or both tend to 100%) .

The analytic relation, obtained by authors to describe properly the considered relation is:

$$\begin{cases} \dfrac{1-Rel.OEE_j}{1-Rel.OEE_0} = \dfrac{K_j * (1-M_j)}{M_j} \\ 0{,}05\% \leq M_j \leq 100\% \end{cases} \qquad (5)$$

That can also be expressed as:

$$\begin{cases} Rel.OEE(j) = 1 - \frac{[1-Rel.OEE_0]*[K_j*(1-M_j)]}{M_j*100} \\ 0{,}05\% \leq M_j \leq 100\% \end{cases} \quad (6)$$

where:

- $Rel.OEE_j$ is the relative value of O.E.E. obtainable with a (j) size of the buffer (equation 3)
- $Rel.OEE_0$ is the relative value of OEE when buffer size is zero (complete dependence)
- M_j is the percentage dimension of the buffer (equation 4). For values of M_j>100%, as seen in figure 8, the increase in Rel.OEE is negligible. Therefore this experimental formula is meaningful only for value of 0,05%≤M_j≤100%. If M_j≤0,05% buffer can be considered null, therefore condition of complete dependence occurs, and than OEE = OEE(station 1) * OEE (Station 2)
- K_j is a experimental coefficient that allow to take into account that the behavior of the curve is not a real hyperbole. The value of K_j depends by the value of j and they are reported in Table 4.

Table 4: K_j Value

M_j value	K_j value
0,5%	0,005
1%	0,01
2%	0,019
3%	0,028
4%	0,037
5%	0,039
≥ 6%	0,05

Equations (5) and (6) are the same, but their representation want to evidence two different aspects:

Equation (5) represents the inverse relation between OEE and M_j. When M_j is 100% the buffer is maximum, the second term is null, and the first is null because REl.OEE = 100%, therefore maximum buffer cause maximum REL.OEE.

Equation (6) is easier to use in order to calculate the Rel.OEE(j) for a chosen size of buffer.

For each analyzed configuration the analytic results of the analytic relation (equation 5 and 6) have been compared with simulation result.

The obtained R square index are vey high, and vary, from case to case within [0,945;0,993]. The relative ANOVA output on the significance of regression test produce a P-value of 0,000. Therefore the formula is statistically validated

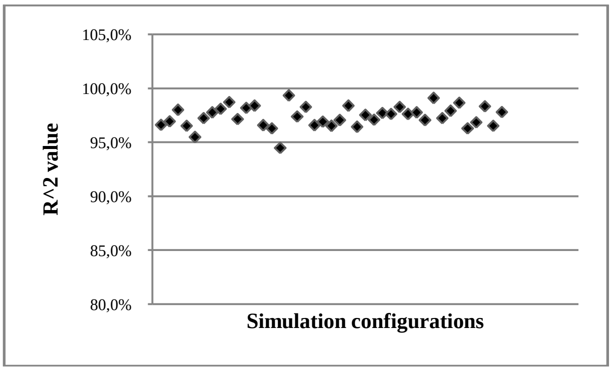

Figure 9: R-square index between Analytic value and simulation results

The formula (5) or (6) allows the buffer size without need for any further simulation.

Two different application of the formula (6) to real industrial cases are summarized in table 4..

Table 4: Formula parameters of two example cases

Cases	MTTR A	MTTR B	T a (Sec)	P A	P B
Case 1	20	30	7	0,9	0,8
Case 2	18	23	15	0,85	0,8

Starting with case 1 we want to show how the Rel.OEE change depending on buffer size, and what are the value assumed by the equation parameter (table 5).

When the buffer size is zero the two station are completely dependent. Therefore the value of the OEE will be the equal to the product of the two performance index (Pa*Pb=0,8*0,9=0,72). With a buffer of 3 units Mj is 1,33%, therefore once chosed the right Kj value (0,01) the formula output is Rel.OEE=92,39%, corresponding to a OEE of 73,9%. Hence, a buffer of three unit increase the OEE of the system of 1,9%. For a buffer of 12 units, corresponding to an Mj of 5,19%, once selected the right Kj (0,039) the Rel.OOE is 92,87%, corresponding to an OEE of 74,3%. It means a further increase in OEE of 0,4%. Further increase in buffer size generates increase in OEE.

Table 5: Result description of Formula (6) for Case 1

Buffer size	Mj	Kj	Rel OEE	OEE
0	0%	-	90,00%	72,0%
3	1,30%	0,01	92,39%	73,9%
12	5,19%	0,039	92,87%	74,3%
22	9,51%	0,05	95,24%	76,2%
32	13,83%	0,05	96,88%	77,5%
42	18,15%	0,005	99,77%	79,8%

The same consideration can be done for the case two, and results are briefly shown in Table 6.

Table 6: Result description of Formula (6) for Case 2

Buffer	Mj	Kj	Rel OEE	Oee
0	-	-	85,00%	68,0%
1	1,28%	0,01	88,42%	70,7%
4	5,12%	0,039	89,15%	71,3%
6	7,67%	0,05	90,98%	72,8%
15	19,18%	0,05	96,84%	77,5%
25	31,97%	0,005	99,84%	79,9%

5. CONCLUSION AND FURTHER RESEARCH

The goal of this study have been to deliver an operative tool that allows an effective, but easy sizing of the buffer in flow shop industries also considering all the necessary information regarding the OEE trend.

The wide range of values that have been simulated allows to include in the study a significant amount of different production systems and to evidence some analogies in the behavior between them. Pharmaceutical sector, where authors have already applied this study, is also included. the simulation range.

Big effort in simulation analysis in conjunction with deep knowledge of the physical problem of the buffer design allow the introduction of a analytic relation. The added value of the analytic relation is the possibility to assess immediately, without the need for further simulations, and with strong statistical significance the optimal buffer size for a chosen level of availability. This relation is valid within the wide range of simulated value, and that proximally will be even wider.

In fact studies to obtained a further more general analytic relation has already begun. Many other area of research are possible, such as a deeper analysis on the effect of time variability on buffer size, or the introduction of a analytic method that allows, once define the required OEE; to obtain an estimation of the required buffer size en a easier way, and without recourse to the recursive computation.

Further research could be also carried out by changing the statistical distribution and the method of analysis

Keywords: Availability, Buffer, Buffer Design for Availability, Flow Shop, Simulation.

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