Maintenance policies and buffer sizing: an optimization model

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Abstract: - In production, stops due to maintenance create imbalances within the system. Let's assume that you have a series of *n* machines and that the *i* stops. In this case the *i+1* would be able to continue to work only as long as stocks were available on the machine, while the *i-1* could continue to work only if there was the possibility that its production would be at least temporarily placed on the machine. Therefore it is normal in order to contain the system imbalances, due to maintenance stops, introduce some buffers. In this paper we propose a simulation model to define the optimal dimension of the buffer, with regards to the maintenance policy that is applied to the production system. The model can simulate a system of units that can have very different characteristics, such as productivity or reliability, and also we can simulate an inter-operational buffer between them. The model is based on the concept of thresholds which, when crossed by the parameter of wear, determine different maintenance interventions. The cost optimization consists in determining, by simulation, at what value the thresholds should be fixed to minimize the overall maintenance cost. We use the model to determine the buffer dimension trend depending on the cost of the buffer.

Key-words:- maintenance buffer, condition based maintenance, simulation, buffer, optimization

1 Introduction

In a production series system the stops due to failures or maintenance can generate high costs because during the MTTR (Mean Time To Restore) of one machine, all the machines of the series cannot produce. So, it should be convenient to put a buffer between the machines to let the system works for a while in case of a stop on just one machine. The model can simulate a system of units that can have very different characteristics, such as productivity or reliability. The CBM model that we have developed is based on the concept of thresholds which, when crossed by the parameter of wear, determine different maintenance interventions. The cost optimization consists in determining, by simulation, at what value the thresholds should be fixed to minimize the overall maintenance cost.

The model can calculate the cost of inspections, maintenance interventions, failures, production losses etc. At the same time it calculates the maintenance buffer cost as the product of an unitary buffer cost and the number of units being in the buffer while the system is off. We used the Optquest tool of arena to evaluate the optimal size of the buffer to have the minimum global system cost. Off course, we expect that the higher is the unitary buffer cost the smaller will result the buffer size.

1.1 Condition Based Maintenance (CBM)

CBM is a maintenance policy wich aims to prevent component failure in a system, by controlling certain wear parameters and activating maintenance intervention when these parameters pass pre-determined thresholds. Deciding what value should the thresholds be arranged at, the same thresholds that determine a maintenance intervention, requests that we know the law that describes the deterioration of the components and also an economic valuation of convenience. Let us remember that our final goal is to minimize the overall maintenance cost, considering that if we arrange the threshold at a low value, we will be more protected against accidental failure but such an arrangement will necessarily involve many maintenance intervention, which obviously have their costs. Instead if we were to place the thresholds at high values we would have limited maintenance intervention, with limited associated costs, but the risk of sudden and unannounced failures with costs that quickly become considerable.

The multithreshold CBM is a more complicated deciding system where the thresholds for each component indicate a different wear state of the unit and as a consequence different decisions. Let us start describing the models inspection method. This model does not consider a continuous control of the state of wear, but inspections at discrete time

every predetermined interval; in this way we can model the real act of inspection and associate to each inspection a determined cost and time consumption. In such a case the decision policy of the system can place one or more “alarm” thresholds between which the inspections become more frequent; in this way we would be able to keep under a better control the evolution of the components parameter of wear, trying to avoid unexpected failures.
A particularly interesting case are serial systems, because when a component of a serial system fails the whole system must be stopped, involving serious economic losses, except in the case inter operational buffers are present along the production line. In cases of a stop the cost is very consistent because it considers the unproductively of the production line, but also the costs to reactivate a normal flow of production, so it is typically convenient to use this time of inactivity for maintenance intervention on other components that in a close future would need preventive maintenance; this maintenance anticipating will be indicate such as “opportune” maintenance.

2. State of art

Dimensioning buffer size is a subject widely discussed in literature. In particular there is a study explicitly done considering as input the average times between failures and maintenance times (F.A van der Duyn Schouten and S.G. Vanneste, "Maintenance optimization of a production system with buffer capacity" [28]). This study is very interesting from an economic point of view, why faces with a problem of sure interest to the one is in charge of a production line.
Other articles, even more recently, have dealt with buffer size, using mathematical models in order to find its best and optimal size.
Particularly interesting it is the study conducted by Chelbi and Rezg: "Analysis of a production / inventory system with randomly failing production unit subjected to a minimum" [39]. In their work the optimal level of a given buffer and the threshold optimum value of preventive maintenance that minimizes the average total cost of a system subject to random failures has been found.
From there also to count a recent work (2007) produced by Zequira, Valdes and Berenguer entitled "Optimal buffer inventory and opportunistic preventive maintenance under production capacity availability" [37]. In this paper is determined, through a mathematical model, beyond the optimal maintenance production units policy also the optimal buffer level needed to meet demand during production stops due to maintenance actions on a system subject to faulty production.
In both studies the function cost to minimize includes as cost items apart maintenance cost and holding buffer cost, there is also the non-use buffer cost, unlike our model.

2.1 Literature review on CBM

We have examined 21 scientific articles regarding CBM highlighting their characteristics. A great part of these articles (Grall et al. 2002; Castanier et al. 2005; Kececioglu and Feng-Bin Sun 1995, Barros et al. 2003, Christer and Wang 1995, Ohnishi et al. 1986, Dieulle et al. 2001, Liao et al. 2004, Van der Duyn Schouten and Vanneste 1995, McCall 1965, Park 1988, Newby and Dagg 1999, Chiang and Yuan 2001, Dieulle et al. 2003, Van der Duyn Schouten and Vanneste 1993) formulate an analytic model determining a solution to the problem, while the other articles (Castanier et al. 2004, Barros et al. 2005, Barata et al. 2002, Guizzi et al. 2006) use a simulation approach to determine the best solution.
In all the works the state of deterioration of a component is determined by a parameter of wear which increases continuously with time. In every article the function of wear of each component is determined by a stochastic law such as a gamma process (Grall et al. 2002, Christer and Wang 1995, Dieulle et al. 2001, Liao et al. 2004, Park 1988, Newby and Dagg 1999) or an exponential process (Castanier et al. 2005). Some of the models consider a multithreshold decision process (Castanier et al. 2005, Kececioglu and Feng-Bin Sun 1995, Castanier et al. 2004, Chiang and Yuan 2001, Guizzi et al. 2006), even though only some models take in consideration the use of an opportune maintenance threshold (Castanier et al. 2005, Kececioglu and Feng-Bin Sun 1995, Guizzi et al. 2006). Almost all the models observed consider that inspections are perfect, except (Barros et al. 2003) and (Barros et al. 2005); this means that there is no error during the measuring or monitoring process of the components wear.
In this work we have decided to realize a model of a system of two elements in series governed by a multithreshold CBM policy. We decided to use simulation techniques, so a series of simplifying hypothesis would not be necessary, on the contrary of the analytic models, leading to more realistic results.

3 Problem definition

The problem of determining interoperational buffer optimal size is linked to total cost optimization of system maintenance.

A very large buffer size involves considerable costs for holding material stock, but it allows to reduce costs related to facility plant stop because of failure of a single machine. On the other hand, a buffer with smaller dimension is cheaper, but it can involve very high costs. It is obvious that the problem is much relevant in process industries or in the industrial processes in which there is a strong interaction among machines placed in series. As matter of fact, in such cases any stop due to failure may involve the stop of all production activities. Then it could be suitable to invest in interoperational buffers with an appropriate dimension so as to guarantee the production continuity also in presence of individual machines stops. Of course, the problem is also related to the type of maintenance policy adopted for the specific production system. The choice of a corrective or preventive maintenance policy also depends on economic assessment. In principle, greater is the frequency of breakdowns and stops value, or even the criticality of a given system component, the more convenient will be the preventive maintenance policy. Then it is clear that the economic optimization of maintenance system must take into account at the same time the mix maintenance policies applied to different system components and the opportunity to insert one or more buffer in order to mitigate the effects on the breakdowns system of single machines.

An integrated and comprehensive discussion of the problem has not been assumed in literature, because the used analytical mathematical approach involves the need to simplify some model choices in order to reach a solution. For these reasons, in this study has been chosen a simulation approach, which allows to simultaneously take into account all the complexity of integrated production-maintenance system.

4 Problem Solution

Through ARENA, a simulation model able to represent a number of machines placed in series has been defined. As our model created for scientific purposes, a placement of a single buffer of n elements in series has been foreseen. In this way the series can be regarded as broken into two sections, called sub-series, in part decoupled from the buffer. The upstream and downstream buffer machines instead will work in close series, with no buffer capacity. In this way, if a machine stops then shortly after would stop all those in the section belonging, or because the working piece in the works could not leave the machine since the next is occupied or since there aren't pieces to be loaded into the machine. The machines not belonging to the series of sub-machine into failure or in maintenance will instead run as long as the buffer is able of absorbing pieces or transfer them. The buffer ability is seen as highly limited. That is, its size will not be able to cover any maintenance intervention or failure, and even most of them. This buffer is essentially "imperfect" and will represent a limited possibility of decoupling, production but not a stable alternative.

This choice has been made because if an engineer had sized buffer in this way perfect, making its capacity as suitable to cover any eventuality, then it wouldn't make any sense to study the twos sub series together, but to optimize them separately could be expectable.

Obviously this is an economic optimisation, it could not be overlooked as WIP stockings as a source of production costs. In particular, the hourly cost is regarded as generated by a component stored in the buffer like a constant rate of its value. This model choice was made in order to make the buffer size optimisation according to maintenance processes. The presence of a buffer allows the storage of parts coming from a working machine when the subsequent processing ones don't work or even its picking, if it is not empty, when the upstream machines are under maintenance. Then the buffer is designed to decouple the facility plant and it has the advantage, offset by the holding cost, of limiting the time of non production.

4.1 Maintenance policies

Regarding the maintenance policy, it was suggested to adopt the on condition multithreshold maintenance. This policy provides that for every series element there is a wear parameter kept under control (through periodic inspections) in order to verify the achievement of three thresholds types:

1. **Warning Threshold (WT)**: in this case, the time between two subsequent inspections is shortened.

2. **Opportune Threshold (OT)**: in this case if another machine of the series is in maintenance, the maintenance intervention is done also on the machine that has reached the opportune threshold.

3. **Preventive Threshold (PT)**: the machine will be stopped in order to make the maintenance intervention.

The thresholds that form the basis for the decision policy are optimized on an economic basis. In essence, it is possible optimising the system total cost to get the optimal thresholds value as known the productive system parameters (times and costs), the probabilistic data on the failure times and the intervention times and the unit costs for the different inspection and maintenance operations, [46].

The event failure in this model is regarded as a random variable related to the wear parameter. Higher is the wear value, higher is the failure probability.

The system peculiarity is that, even if there is a condition maintenance policy, related to the effective system costs, this can also "degenerate" in a corrective policy. If, for instance, for one of the series machines the intervention time is very low or the cost related to the downtime is insignificant, as a result of the economic optimization the thresholds economic values can be at the top so as to avoid always the preventive maintenance. In essence, the machine will break down before the preventive threshold is reached. Then, the proposed integrated system is able to optimize both the maintenance policy and the interoperational buffer size.

4.2 Model features

This CBM model has to be representative of a real production system; each single resource can be modeled as deterministically or stochastically time consuming. The model keeps trace of the actual working time of a component. In fact a component will work only when it receives a work in progress from a precedent unit; in case the precedent unit is stopped (for failure or preventive maintenance) or in case of a temporary unbalance on the working line (caused by the stochastic working process), the following unit has to attend. After a discrete period of time the parameter wear, for each single component, will be increased for a value equivalent to the real operating time.

In all models based on CBM policy it is very important that inspections are correctly modeled. The models closeness to a real situation depends mainly on this aspect. All decisions that will be taken depend directly on inspection values, inspection errors will bring to corrupted maintenance decisions; in fact depending on the value of wear measured the system must decide what to do: preventive maintenance, opportune maintenance or delay in till the next inspection. Every single measurement is effected by uncertainty; this circumstance cannot be ignored because a casual event during a measurement can bring to wrong decisions. Therefore, in the model each measurement of wear will be considered to be not perfect, but affected by an error with a Gaussian distribution with null mean and standard deviation depending on the kind of measuring process.

The model considers three kind of threshold for each unit:

– preventive maintenance
– opportune maintenance
– alarm

The last kind of threshold can be present in a growing number, where they indicate a reduction of the period of time between inspections.

In most of the models examined, a component is considered to be in a state of failure when its parameter of wear passes a certain value, indicated as the failure threshold. This approach does not take in consideration the possibility that a unit can fail before it achieve a specific value of wear, for extraordinary events. Some of the models considered that the state of failure of a unit is noticed only with an inspection act. This hypothesis is unrealistic, except in cases where we define that a failure threshold is a value of maximum wear after which we necessarily must replace the component because it doesn't guarantee a proper function. Wanting to place the model with the most general non restrictive hypothesis possible, the hypotheses that we used are:

– failure of a component is possible at any value of the parameter wear;
– a wear limit which when is crossed by the wear parameter automatically brings the component in a state of failure does not exist.
– the probability of failure depends on the state of wear of each single component
– when a component goes in a state of failure, it is instantly acknowledged and automatically implies the stop of the production line.

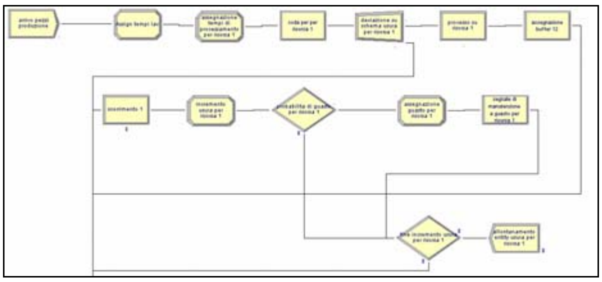

Fig. 1: The production/maintenance model

For this reason, we must build a continuous function defined in R+ , which must return the probability of failure depending on a certain parameter. In scientific field, time is commonly used as parameter of the probability distribution function. The probability function that has been used in this model is a Weibull, which is much more versatile then other, more common functions, such as the Gaussian or exponential. The parameter that describes the weibull function is wear, instead of the more commonly used time, depending on the fact that all units don't necessarily work continuously. This hypothesis is totally coherent with the CBM philosophy, which aims in measuring and controlling the state of wear of a unit to decide on eventual maintenance interventions. The fact that we have picked a weibull distribution does not compromises the model validity because in any case we can modify the probability density function used according to the components technologic characteristics.

In a series production line, stops caused by maintenance interventions on different components create an unbalanced situation along the production system. Wanting to have certain flexibility and contain different unit productivity, it would certainly be useful to insert along the line interpretational buffers. In this model we've considered only one buffer placed at the centre of the two units, in this way the line can be studied as if they were two distinct lines partially independent. Each machinery inside the two branches work as if between then there is a buffer with null capacity. When a unit stops, the other units of the same branch, once concluded the WIP, must stop too.

Instead, the units belonging to the other branch can work normally untill the capacity of the buffer allows it. The buffer capacity is not sufficient to cover the whole period of unproductively caused by a maintenance intervention or a failure. In fact the buffer that we've considered is "realistic"; it represents a limited possibility to separate the production line. If we would have considered a production line with an interpretational buffer that has an infinite capacity, it would not have sense to study the two branches together. In the sphere of economic valuation of our system we have considered the buffers costs as the buffers capacity for the unit storing cost per time for each component stored.

Unlike most article publication on this subject, whatsoever intervention is not considered instantly, every maintenance intervention (corrective or preventive), as inspections, are considered time consuming. The period of time considered for each act can be determined by deterministic formulas or stochastic parameters. All this in the intent to move the model closer to reality. The time for an inspection of maintenance act can also stochastically vary depending on different parameter for different causes such as employees, or kind of maintenance act.

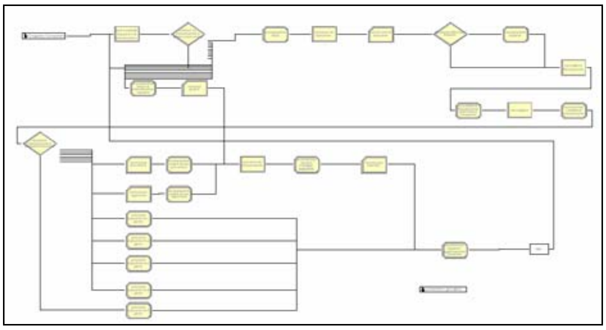

Fig. 2: The decision making model

5 Application of the model

It is been suggested a production model made up of only two machines with an intermediate buffer. The essential data needed to define the system are shown in the following table.

Table 1: parameters of the model

Parameter	Symbol	Type	Value
Number of machines	n		2
Wear		Gamma(□ □□)	(1.3,3)
Failure		Gamma(□ □□)	(3,6000)
Inspection cost	C_{insp}	fixed	100
Preventive maint. cost	C_{prev}	fixed	500
Opportune maint. cost	C_{opp}	fixed	500
Failure cost	C_{fail}	fixed	1500
Personnel cost	C_{pers}	variable	0
Setup cost	C_{setup}	fixed	250
Stop cost	C_{stop}	variable	100
Free machine cost	C_{free}	variable	100
Inspection time	T_{insp}		
Preventive maint. time	T_{prev}	deterministic	5 hrs
Opportune maint. time	T_{opp}	deterministic	5 hrs
Failure time	T_{fail}	deterministic	12 hrs
Pieces arrival interval		deterministic	5 mins
Processing time	T_{proc}	deterministic	5 mins
Buffer cost	C_{buff}	variable cost	0 - 1.2

It is believed that the variable cost item for buffer holding may influence the placement of thresholds maintenance in order to obtain the lowest total cost, and then to conduct the analysis of this hourly cost time on:

- Total costs
- Buffer size
- Maintenance policies

Our aim is to find, through Optquest (the application of Arena for optimizations), the optimal buffer size linked to maintenance policies. The system maintenance total cost to optimize is given by:

$$C_{tot} = C_{insp}^{tot} + C_{prev}^{tot} + C_{opp}^{tot} + C_{fail}^{tot} + C_{ind} \quad (1)$$

The system maintenance costs are represented by the first four addends of the (1) and are given by the following expressions.

$$C_{insp}^{tot} = [C_{insp} + (C_{pers} \times T_{insp})] \times N_{insp} \quad (2)$$

$$C_{prev}^{tot} = [C_{prev} + (C_{pers} \times T_{prev})] \times N_{prev} \quad (3)$$

$$C_{opp}^{tot} = [C_{opp} + (C_{pers} \times T_{opp})] \times N_{opp} \quad (4)$$

$$C_{fail}^{tot} = [C_{fail} + (C_{pers} \times T_{fail})] \times N_{fail} \quad (5)$$

Where N_{insp}, N_{prev}, N_{opp} and N_{fail} respectively represent the number of inspections, preventive maintenance, opportune maintenance and failures occurred in the simulation model at the end of the simulated time. The involved C_{ind} costs are those due to facility plant stops as represented in the following:

$$C_{ind} = [C_{stop} + C_{free} \times (n-1)] \times T_{stop}^{tot} + C_{setup} \times N_{stop}^{tot} \quad (6)$$

Where

$$N_{stop}^{tot} = N_{prev} + N_{fail}$$

represents the system whole stops number given by the sum of failure stops and preventive maintenance, while the inspection in the considered model is the online type monitoring and the opportune maintenance occurs by definition at a stop. Therefore these operations do not lead to a facility plant stop. The T_{stop}^{tot} total facility stop time is given by the number of stops for the required duration time and it generates a cost related to the downtime machine under repair (***C_{stop}***) and a cost related to the downtime machines not under repair but awaiting (empty machines: ***C_{free}***). Established the process parameters and the system costs, we proceed to analyze, through different optimizations, the buffer size changing according to buffer costs ***C_{buff}***. .

5.1 Input

The parameter that we are going to change in the different optimizations is ***C_{buff}***. Since we consider hourly costs for each component at buffer, this parameter will have very low values compared to other system unit costs. Indeed, the costs associated to maintenance are supported only in correspondence of the failure event or the scheduled maintenance, which are events "rare" in a healthy system. Conversely, the buffer cost is continually held up during the processing time since once WIP is stored it will remain continuously.

The optimizations launched with high ***C_{buff}*** returned in policies sizing buffer always making it inconvenient. Because our goal is to understand when the buffer cost assumes a value such as to advise not to use it, we started from a buffer cost equal to 0. This returns the maximum buffer size for the analysed system. Then, as we have done the optimizations with higher values in order to verify when it became no longer convenient the use of this buffer.

5.2 Results Analysis

The obtained results by individual optimizations are shown in the tables below. In **table 2** there are the optimal threshold defined by the optimization model and indicated as **WT 1** (Warning Threshold foe component 1), **WT 2** (Warning Threshold for component 2) and so on.

Table 2: Optimizations results: thresholds

Buffer cost	WT1	WT2	OT1	OT2	PT1	PT2
0	424	423	236	227	263	234
0,05	371	378	212	205	165	174
0,1	370	397	214	238	161	162
0,2	518	419	208	221	325	302
0,3	484	498	258	303	356	248
0,5	484	530	331	299	314	220
0,6	476	529	338	311	273	201
0,8	497	543	364	394	283	219
1	471	485	212	229	122	256
1,2	475	524	225	250	199	195

The fact that machine thresholds of a certain kind (warning, opportune or preventive) have quite the same value for each optimization confirms the efficiency of the model. In fact, being the two machines perfectly identical, we expect the same behaviour with respect to the values of wear and to the maintenance policy.

Table 3: Optimizations results: buffer size

Buffer cost	Buffer size	Total cost
0	108	124.816
0,05	85	124.550
0,1	63	125.646
0,2	31	132.347
0,3	22	131.358
0,5	16	132.187
0,6	12	131.178
0,8	4	131.751
1	1	131.448
1,2	1	131.379

In **table 3** for each buffer cost C_{buff} we have an optimal size of the buffer and the total cost of the maintenance system in a year.
Table 3 shows that after a certain C_{buff} value (C_{buff} = 1 in our case) the optimal buffer size is 0. Please note that buffer size is 1, corresponding to an absent buffer, as our model is built. As mentioned above, the first thing we analysed is the influence of costs on buffer size on its dimension. The buffer costs are calculated as product between a variable cost and continuance time in the buffer. Greater is the need to make independent the machines more convenient is buffer exploitation. But it will cost much more depending on piece permanence buffer. Then determine two forces: one related to the cost of car free, the other costs of maintaining a buffer. **Figure 3** shows how increasing C_{buff} buffer size decreases until zero since we lose the economical convenience to keep an interoperational buffer

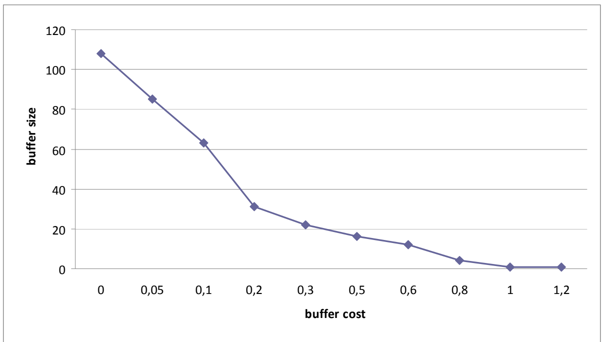

Figure 3: Buffer dimension depending on C_{buff}

Instead the influence of buffer cost on total costs is shown in **Figure 4**. In this graph, at buffer costs increasing the total costs at first remain almost constants and then there is a total cost "jump" (C_{buff} = 0.2) and after they remain more or less constant around this new value (higher than the previous one) is highlighted. This can be explained by the fact that since the "leap" of the total costs coincides with a drastic reduction in buffer size, the costs of the empty machine increase making the total costs higher.

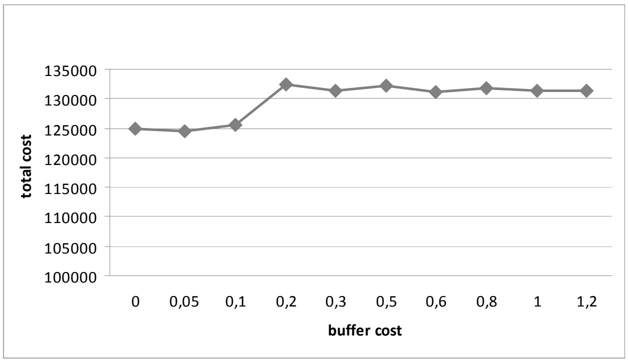

Figure 4: Total cost depending on C_{buff}

Finally we analyze the influence buffer costs on alarm thresholds, on opportune and preventive maintenance; as shown in **Figure 3**.

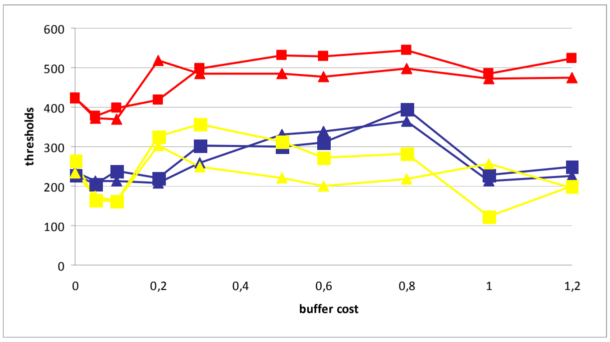

Figure 5: maintenance thresholds depending on C_{buff}

In the beginning it is highlighted that the different thresholds follow a very similar pattern for the two machines. In particular, from the **Figure 5** it is clear that the performance of the alarm threshold first decreases then, once achieved a minimum with buffer costs equal to 0.1, it grows (C_{buff}= 0.2) the after it remains almost constant with a tendency to decrease. It should be noted also that the threshold of preventive maintenance has the same trend.
As to concern the opportune maintenance threshold the graph shows that when the buffer size is 0, corresponding to C_{buff}= 1 and 2, the difference between the threshold of preventive maintenance

and opportune maintenance is maximum, therefore it is more opportune. This is because, in buffer absence, the system in series is rigidly connected and therefore more sensitive to downtime machines. And this makes it more convenient the opportune maintenance.

6 Conclusions

The study done on the simulation model allowed to integrate the analysis of the best maintenance policy in a production series system with the economic analysis of an interoperational buffer insertion. Essentially, through the simulation approach we are able to assess simultaneously both the good policies to be taken on a production system and the structure of the system itself. Taking both the cost parameters and the production costs, we could develop in the future an integrated approach to system design and maintenance engineering problem.
As we expected, the result of several optimizations we did are that the buffer size of the system goes from about 110 pieces, for a unitary cost of zero, to zero pieces for a unitary cost of 1,2.
The results confirm that the simulation model is useful to design the correct maintenance buffer size that minimize the global cost and also it can be implemented for a more complex system with several machines and buffers between them.

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