A condition based maintenance simulation model for controlling the yield of Pick and Place machines

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Abstract: The scope of this work is to improve the production yield of a series of Pick and Place machines, the process is characterized by a high value of basic components, and therefore, eventually obligating rework of all refused units caused by defective assembling, causing high costs for the reworking. In literature **t**here are models that base themselves on calculating the probability of different factors that vary the yield. The differnent studies conductied in this sense have not given positive results, since none of these models have considered technical parameters of the machines condition correlating it with the defectiveness of the assembled units at the end of the process. In this work we have proposed a condition based maintenance simulation model, which is able to determine when it is economically conveinent to make a preventive maintenance intervention on the machine in function of the number of refused units per unit of time produced by the process. The model that we have considered is a multi-threshold model, which means that it consideres the possibility, once that the process line is stopped for preventive maintenace, to intervenue even on other machines, these interventions will be called opportune maintenace. The proposed model has clearly demostrated to improve the efficience of the process respect the nowaday, experienced based, management, but also respect a model based on the optimizing of the processes yield present in scientific literature.

Key-Words: - condition based maintenance, simulation, yield, pick & place

1. Introduction

This work has been accomplished in a plant that produces instruments for mobile radio networks, both with 2G and Edge technology, and also microwave systems. This plant has a large capacity, which is estimated in 900.000 circuit boards per year, with 500 million assembled components. The plant is composed of several assembling lines, Surface Mount Technology (SMT), with different configurations.

In this work, we have focalized our attention on the assembling line which produces components for indoor microwave network apparatuses. The study regard the series of Pick and Place (P&P) machines of the specific line, this because the company had specifically required assistance, since the lines yield was quite low, due to continuous maintenance interruptions.

The line considered is multi-product, the boards produced can mount from about 400 to almost 2000 components. The process line configuration is as following:

- Board Unloader
- Serigraphic MPM AP25S
- Conveyor + Lent 4x
- Siplace S25 HM
- Siplace 80 F5 HM
- Oven Omniflo 10
- Board Loader
- X-Ray Inspection Station (not in line)

On this line five Pick and Place (P&P) machines are present: the first three have the same configuration, mounting all two revolver heads with twelve segments each. The forth, also a S25, mounts one head with twelve segments and another head with six segments. The last P&P machine, F5, which has one IC head with six segments, which carries out a single assembly for every withdraw, for every Pick and Place cycle, necessary for the larger components.

Each one of these machines have an entrance or mouth, where in each of them are mounted feeders which introduce the necessary components for the assembly: this components are hosted in containers, which are substituted when the product changes.

As normally happens with this kind of manufacturing process, an important share of the costs are caused by reworking, in fact considering the high number of components which each board mounts and the fact that even a single component that is missing or incorrectly placed determines malfunctioning of the circuit. The eventual weldings that are missing, are discovered by the X-Ray station or along the next inspections, such as the "In Circuit Test". The following functional inspections, must be realized by an operator, this operation needs much more time if compared with a correct welding made on line. In case a component results crooked, first it must be disconnected and then correctly rewelded.

For these reasons it is essential that we contain the P&P's defectiveness. The scope that we have is to introduce and optimize a condition based maintenance policy on the series of P&P along the process line.

Before our studies the P&P's are maintained following the recommendations of machine producers, which prescribe a scheduled preventive maintenance. But the process line has evidenced a low yield, caused by frequent non-scheduled interventions: such interventions, in absence of any pre-determined criteria, are entrusted to the operators, whose limited experience, limited quantity of data and subjective valuations are used for the decision making. Analysis takes place only when the processes' yield becomes particularly low such to attract the managements attention.

The yield of the process line depends on countless factors, since, at the moment there aren't any intermediate tests, and therefore the intervention that are carried out, aren't always correctly aimed in the best direction, for this reason we want to determine a series of physical parameters that once monitored can indicate whether an intervention should be made or not. P&P machines are extremely complex and sophisticated, they supply a vast quantity of outputs, from which it is quite complicate to obtain significant data.

Once we've found which parameters best indicate the state of a P&P machine, we must determine the values of the thresholds that when crossed indicate the necessity of an intervention: the evaluation of this threshold will obviously be a point of equilibrium of a trade-off, seeing at one side the direct, indirect costs, and production lost regarding a maintenance intervention and at the other side, costs regarding a products defectiveness, a considerable share of this cost is in reworking the product.

2. State of the Art

The subject regarding SMT production yield and costs deriving from eventual reworks of defective products is very important under an economic point of view, for this reason it has been widely studied and analyzed. Particularly interesting for our specific study case result the works of Kamen, Goldstein [7] and others [9]. Their scope in one case was to analysis the relationship between the SMT process and the associated yield, in the other case it was to study the causing of mistaken placement of the components in a SMT process.

The approach is based on the concept of probabilistic network which defines the relationship between causes and effect of the machines state and quantitative inspections and measurements, such as the quantity of welding paste applied, precision in placing the component on the board, and the processes yield. The general form of this network is shown in the following figure.

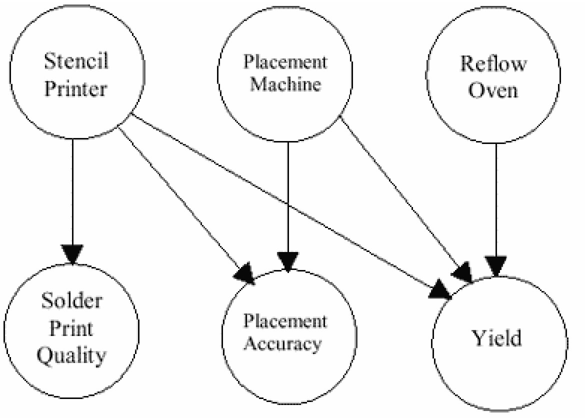

Fig. 1: Probabilistic network for evaluating the yield

The superior nodes indicate the states of the machines, the inferior nodes are parameters that can be objectively measured, while the arrows represent cause effect relationship. This network is able to indicate the state of a machine, measuring the three parameters indicated in the inferior nodes. To work, the network needs a previous evaluation of the conditioned probabilities. Particularly important is to determine the effect of different states of failure of the machine on the quality of the screen-printing, component placement and on the processes yield. For this we need to measure the different parameters during the different states of the machine. The experimental data was obtained by tests made on the machine Siplace analogue to the machine encountered in the plant of this study. Till now, we have examined:

- Intentional offset added on the P&P, corresponding to a calibration error
- Pads volume and height
- Nozzles pressure values, during functioning intervals

When we estimated the correspondence of the above factors with the placement accuracy of the components, only the first of them indicated a significant correlation. Let us note the significance of the non correlation between the quality of the screen printing, which, as we've seen, is calculated by measuring the volume or height of the welding paste placed on the circuit board, the evaluation is made by an optical instruments, and obviously measuring the components placement on the board. The components placement depends exclusively on the P&P's performance, neglecting accidental factors such as the detaching of a component due to human manipulation, aspects which are of limited importance.

The Siplace supply innumerous parameters related to it's functioning state: in particular, it registers the difference of pressure in presence or absence of a component on the machines nozzle (the nozzle is a pipette that is mounted on a segment, depending on which component must assemble on the board), in case the pressure difference results low for three times in a row, the machine automatically stops, but typically an operator starts the machine without a whatsoever intervention or even inspection. Problems of this type seem principally correlated with the malfunctioning of the same nozzles, which should by substituted at every board change and cleaned every work shift. Other gathered data regards the share of defective components, which is calculated as the quantity of refused components that the machine does not recognize, placing these components in a specific container. This problem, which is cause of immense expenses, has already been studied by the company, and it appears that such problem is not caused by the Siplace but by the feeders that supply the components for the Siplace. For this reason the feeders are replaced as soon as the percentage of refused components is more then 1%. A factor which appears to be significantly correlated with the P&P's placement errors, from the studies of Goldstein, Kamen and Asarangchai, and experimentally demonstrated on the Siplace S series, is with the segments offset, as a direct consequence it seems natural to monitor its value, to obtain information regarding the machines state. Unluckily this was not possible, the segments value of offset of each machine is accessible only in maintenance condition using the Siplace software Sitest [10]; the value of the segments offset is measurable when calibrating the head of the machine, or calibrating a single segment, operation which takes place after the disassembling and cleaning of the segment. In case this parameter results to be out of the prefixed range, calibration must be repeated. It is clear that his parameter can not give us any information regarding the functioning state of the machine, since this parameter is measured after a maintenance intervention: the cited study after all was formulated for correlating the segments offset with the placements offset, giving in this way a indirect measurement. Unfortunately, on this line we don't have an AOI instrument which is able to measure the placement offset on the output of the P&P; the only information that we have come from the X-Ray station, besides the fact that currently it isn't on line.

3. The proposed approach

3.1 Selection of the controlling parameter

Non of the data at hand seems to be a good parameter for indicating the P&P's state: The technical data proposed by the machine doesn't seems to be correlated with the machines performance, as indicated by various academic and industrial studies. The will to apply a condition based maintenance policy (CBM) based on one or more parameters, results to be frustrating, due to the fact that it is complicated to define a stress parameter corresponding to our scope [11].

On the contrary, to follow a maintenance policy based on time scheduling doesn't seem to be suitable, because of the limited results and often unscheduled intervention necessary. These intervention are implemented by evaluating, in a non-systematic way, the products' yield increases: but the yield depends also on the differences between the countless components, by errors generated along the whole production line, and therefore not only by the P&P. From the types of errors that are present in the table of troubleshooting of the SMT line:

- Open
- Solder balls
- Cold welding / voids
- Short
- Missing component or misaligned

Only the last seems to be caused by the P&P machines.

We decided to formulate another index, in terms of Defect Per Million of Opportunities (DPMO). Where we considered only the boards with a component missing or misaligned, noticeable by the report on the ABC analyses on refused circuit boards.

Considering only the refused boards of our interest, we considered the number of opportunities to generate a defect, which varies from board to board depending on the number of components on each of them. Furthermore, we must be able to determine which P&P machine, of the five in the process line, committed the error, this because our intent is to develop a model for interventions on the single machine. The necessary information has been obtained by accessing the NC assembly files: these files contain the assembling sequence for every product. The files are loaded on the processes line central computer, which programs the P&P's activity, by indicating for each machine the components and the segment that mounts each component, the position on the board is obtained by the CAD file of the board, also the set of nozzles that each head must use for the different products.

From these file we've obtained:

- The number of components mounted by each machine for each product
- Knowledge of which machine to associated a missing component

Information regarding processing time, are acquired from files, relative to each P&P, that contain data regarding running time, waiting time, stop time and also information on the product that has been processed. Using an electronic data sheet we've been able to calculate the daily DPMO's of the five machines, based on samples of the four principal products processed by the line, with various dimensions and composition. The expression used is the following

$$\mathrm{Dpmo} = \frac{\mathrm{E}}{\sum_{\mathrm{i}} \mathrm{Ci} \cdot \mathrm{Ni}} \times 10^{6} \qquad (1)$$

Where
E = number of errors committed by the machine in the samples that we have considered
Ci = number of components per board referred to product i
Ni = number of circuit boards of the product i considered

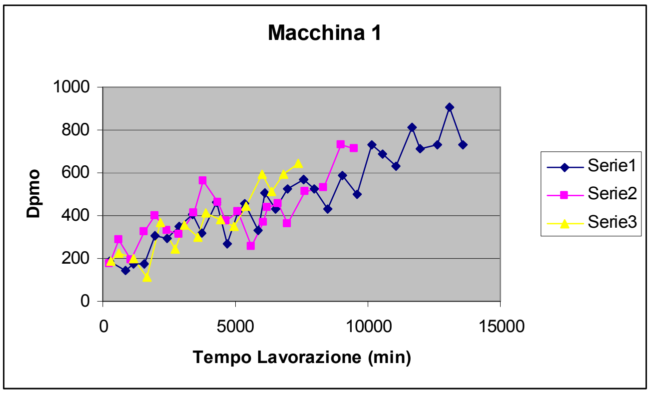

Fig. 2: DPMO for machine 1

All the data has then been gathered in another sheet where information is inserted for each machine regarding processing time expressed in minutes, the cumulated function of processing time starting from the last maintenance intervention held (intervention of cleaning and calibration of the revolver heads are also considered as maintenance), and the DPMO. In this way we were able to study how the DPMO varies when the processing time grows, this for each single P&P. The information in our hands, however, is limited, it appears evident that the performance has a certain trend, as we can observe from figure 2 which reports the performance of machine 1.

3.2 The simulation model

Once that we determined the parameter that will guide us in deciding if or if not to carry out maintenance, we need to have an objective criteria so to determine the values of the thresholds: for this reason, we've decided to implement a simulation model of maintenance on the P&P series. Once modelled the process line it will be possible to optimize it by using the cost function built by considering all maintenance costs, production loss and expenses due to the non quality of the products. We decided to use for simulating or model a event driven simulator, in particular Arena.

A model that well adapt to our needs must consider two fundamental aspects: it must simulate the process line, this is accomplished by modeling the PCB (printed circuit boards) as entities that flow through the different blocks in the simulated environment, each block represents elementary tasks or logic steps, while this is done the simulator must note the deterioration of the P&P performances. The simulator must also contemporary replicate maintenance processes, since the two processes are linked together: the DPMO, factor which determines whether or not to carry maintenance, will depend on the number of PCB's processed by all machines, while a maintenance intervention will influence the availability of the machines and therefore on the possibility of them working.

Given the vast heterogeneity of the two processes, where in the first case we have entity/product, and in the other entity/machine, or better, opportunity of a maintenance intervention, it is convenient to develop two distinct model that interact through global variables and *Signal* modules that send signals to other modules *Hold* situated in the first sub-model.

The sub model production is roughly built as following: The model starts with six *Create* modules, which generate the batches of the different products; then there is a logical structure that determines if two following boards are of the same kind, in this way, as soon as the first machine receives a new batch, the process stops for a time adequate for the setup process. Next we have five sub sectors which represent the five P&P's: in each one of them, the simulator occupies the resource/machine for a period of time imitating the processing time. The period of time for each machine referred to each product is extracted from a probability distribution which has been determined from real process data. We also simulate casual micro-stops which are not correlated with DPMO values. At the end of the process line, we will separate the products depending on the kind, once separated the products they have to pass through a *Counter*, in all six, one for each kind of product, these counters register the number of products and they are annulled on a daily basis, continuing along our model there are also six *Record* modules that account the value generate by the P&P process line, such calculation is made for each single circuit board on a zero defect basis.

The logical structure of the model that is oriented to maintenance aspects must respond to the following necessities:

- Evaluate the opportunity of accomplishing maintenance on all machines depending on the thresholds, fixed on consideration from the DPMO, in this why we can exploit the process stop to anticipate a maintenance intervention, saving on inducted maintenance costs.
- Simulate when necessary, maintenance processes by activating and shutting down the process line in the model

- Account the costs deriving from maintenance intervention and also reworking defected products
- Restore the machine to a functioning state after the process has had a micro-stop

We've decided to model these aspects with a closed loop. In this loop, at time zero, there will be created a series of entities representing each single P&P, these entities will never be disposed, they will circulate in the model for the entire time of the simulation.

For each entity the modules *Assign* will provide them with a series of factors such as hour cost of the personnel, the thresholds (*sogliemac,* is a five per two matrix where each row is associated to a machine and the two columns indicate the two thresholds that we've considered, one indicating the necessity of a preventive maintenance, the other is an opportune maintenance thresholds which allows a maintenance intervention only if at least another machine needs a preventive intervention), and other parameters useful for simulating maintenance time. In particular, the last parameter announced will be read from the matrix *ptman* where each row is associated to the intervention time of each machine: in this way we can associate different maintenance intervention time to each single machine (in our particular case, the fifth machine, Siplace F5, has different maintenance times, because it has a IC head and not a revolver head as the first four).

Once the entities are create they'll queue themselves in a module called *Hold,* of the kind "wait for signal". A specific signal will come once a day from the sub model "daily chronometer", and every time it is necessary to restore the process model following a micro-stop. When the signal is emitted, the *Hold* module releases all five of the entities, sending them to the following module *Decide* that will appropriately direct them along the model. This module determines if the signal is determined by breakdown or if it's the daily inspection that evaluates the prospect of a maintenance intervention. In the first case, the functioning machine (entities) will be sent again to the module *Hold*, while the machines in breakdown will be sent to the restore sub model. In this sector the machine will employ the resource operator for a certain time, after that the parameter *on* is restored to the value of 1, the entity returns to the module *Hold* where it came from.

Instead if the signal is associated to the "end of the day", the entities will all be addressed to the module " time allocation": here the entities will be associated to a maintenance time that will be casually extracted from a probability distribution. The following module *Record* will register the data in the module *Set*, costs for each machine, day by day, deriving from reworks by using the function DPMO and also considering the number of boards produced, this aspect will be explained letter on.

Next we have the module "if to stop process": here the simulator compares the variable *DPMO* with the attribute *spre*, with is the value of the threshold that once is crossed by DPMO, starts the maintenance process. The value of the attribute spre is obtained from the matrix *sogliemac*. The module "maintenance decision" will evaluate the machines conditions, and consequently address the entities to:

- Preventive maintenance
- Opportune maintenance
- The module *Hold* at the beginning, waiting for a new signal

3.3 The input data

Once concluded the structural modeling, it is necessary to proceed with a quantity modeling, determining the values of parameters and the form of the probability distribution so to be able to simulate the P&P's process line that we want to study. In particular we will need:

1. Time
    - Production time of all products on every machine
    - Setup time
    - Maintenance time for each machine
    - Restore time in case of micro-stops
2. Costs
    - Maintenance costs
    - Reworking costs
3. Generated value for product
4. Variations of the DPMO
5. Resources
6. Buffer

To analyze the data that we've gathered obtaining the distribution that will be used in the model, we have used the software Minitab and a component of the simulator Arena, Input Analyzer, which can be used to determine the quality of adapting the data to a probability distribution function, carrying out for this scope a Chi-square and Kolmogorov – Smirnov test.

One of the most important factors of this model is given by how the DPMO index varies, because it is on this factor that the maintenance decisions are made. For this reason we are interested in determining an aleatority function which describes the DPMO's increments in function of the working time per machine. To determine this function we proceeded as following:

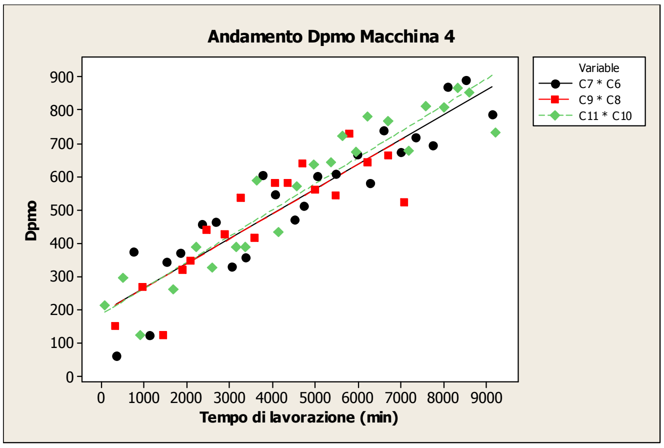

Fig. 3: DPMO machine 4

In first place, we've observed that after cleaning and calibrating the segments, the DPMO values would not tend to zero, but to a significant value, similar after every intervention.

Since we could have the value of the DPMO only at the end of a day (we've chosen to use a daily basis in evaluating the DPMO variations, since the line produces a couple of hundreds PCB per day; a smaller time interval would bring to have a limited number of samples from which we can gain information), we operated with a linear regression of the data, so to estimate the value of the DPMO at time zero; we have observed that there aren't many differences between different series of data form similar machines, as indicated in the example figure 3, referred to machine 4.

We proceeded in estimating the researched value using a linear regression of the generalized series of data for every machine. The results indicate similar DPMO starting values for the first four Siplace S25 Hm, therefore we decided to fix the starting DPMO value for all four at the average starting DPMO, different case regards the fifth machine, which is a F5 Hm.

Continuing with the first four machines, we have that the linear regression calculated has this expression:

$$\text{DPMO} = 186 + 0{,}0766\ \text{T}$$

With a value of R^2=84,9%

The mean value of the first four P&P machines result to be 185, which will be the value placed, after every maintenance intervention, to the DPMO variable. For the fifth machine (different to all the others) the mean that has been calculated is 450. These values have been considered as deterministic and not aleatority given the limited deviations of the samples, the limited number of samples, in particularly regarding the Machine 5, but more important then all because of the fact of the limited sensibility demonstrated by the model regarding these values; fact that has been confirmed by various simulated runs of the model that we have made.

After determining the starting value for the DPMO's, we've gathered in separated tables data relative to each machine. From these tables we calculated the increment per minute per every day, using the formula brought below:

$$\frac{\mathbf{Dpmo}_{k+1} - \mathbf{Dpmo}_{k}}{\mathbf{T}_{k+1} - \mathbf{T}_{k}} \qquad (2)$$

The values obtained have then been analyzed using the Input Analyzer, so to adapt them to a distribution. As the results we have obtained that some are better described by a Weibull while others by a Gaussian. This fact may depend on the limited quantity of the samples at hand. Given the nature of the phenomenon's that are responsible for the deterioration of the P&P performance, it is logical to consider a Gaussian distribution. In any case, we preferred to maintain the distributions that we have determined with the samples available.

At this point we must specify that as we said, the data available derives from a daily production basis, the numerosity of the sample is variable, and in the same way, also the time of authentic production is variable between a measurement and another.

The way we formulated the increment values by the minute are to intend as constant between each interval, which in this case is a day. For this reason the function results to be a step function.

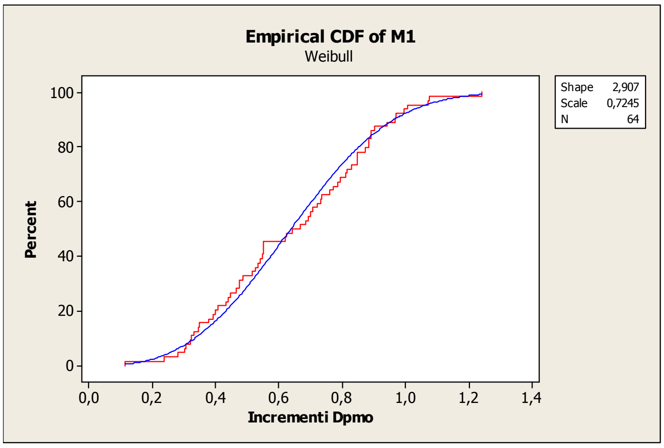

Fig. 5: CDF for machine 1

If we would use the distributions obtained, in our model, Arena would casually extract an increment of the DPMO for every simulated minute, we would have hundreds of extractions every day, this would sum up as an almost constant increment at the end of the day, since the mean would stochastically converge to the mean of the distribution that is given.

To reproduce the same conditions with which we calculated our functions, for each machine, Arena will extract only one casual value from the distributions that we feed to the program, this value will be the increment of every minute during that day, in an analogues way of how we treated the samples that were available.

The cost deriving from the rework of the defected boards is essentially caused by the fact that the missing or misaligned component must be, once found by the X-Ray station (and after the operator has correctly confirmed the investigation, which not always happens) removed and rewelded by an operator. We don't consider the cost of the component because it should have been present on the card and therefore it is already accounted. Remains to be evaluated the cost of the operators time and the cost of the occupied station for the interval of time necessary to correct the faulted board.

The hour cost of the reworking station is estimated by the firm to be 78,65€. So now we must calculate the average time to correct a defected board, for each product. The company has collected the reworking time for each single product, this data considers the time necessary to correct different kinds of errors per circuit card.

To estimate the value of our concern we simply divided the average time of reworks for the number of defects per board, considering only the defected circuit boards. Obtaining in this way a mean value of the time necessary to correct a generic error for all the different products. This value that we've acquired must by related to the different DPMO's of each machine.

Table 1: error opportunity per product or machine

Prod.\mach.	M1	M2	M3	M4	M5
36	202	60	46	80	42
50	223	196	130	160	58
68	348	218	174	148	80
92	346	371	307	268	48

We built a matrix product/machine, where in every cell are indicated the corresponding number of components mounted per each board. So these are the number of components that can generate errors, since at the X-Ray station we don't verify the correct functioning of the component but only its placement. The expression used to evaluate the reworking costs will be:

$$\sum_{m}\sum_{p}\frac{C \cdot T_p \cdot N_p \cdot Dpmo_m Opp_{pm}}{10^6} \qquad (3)$$

Where:
C = Hour cost of production
T = Time for reworking a defected board, expressed in hours
N = number of produced boards
Opp = number of components projected per board
m,p = machine and product index

Once built the model, we economically optimized it by using another tool of Arena, which is Optquest. As control variables, which are the variables that Optquest varies while optimizing, we obviously have chosen the opportune and preventive maintenance thresholds.

The objective function, which is to maximize, is defined as Net Generated Value, given from the difference between Gross Generated Value (obtained from SAP data, which calculates the value of every product on the basis of a production cycle with zero defects) and the reworking and maintenance costs.

4. The results

The optimization has indicate a series of values of the preventive and opportune maintenance threshold quite close, this is comprehensible given the fact that setup costs following a machine stop are insignificant if compared with other costs, but also the limited number of technicians limiting the maintenance interventions to maximum two at a time.

The processes first optimized solution has been casually chosen, since simulated logic it not implemented in the plant.

Subsequently we made a simulated run with the optimized solutions. Using a procedure developed in two phases, we first evaluated the length of the run with 50 replications, so to obtain the mean of the objective function with a confidence semi-interval not more then 1%. The results obtained presented an increment of the net generated value of 7.98% respect the net generated value of the line during the period of gathering the data, thanks to a very important reduction of the reworking costs.

To verify that this improvement is associated to the using of a DPMO metric, and not only caused by the optimization, we built an alternative model where the logical and cost structure remained the same, and we changed the logic in maintenance decisions basing ourselves on the processes yield (the same logic that the process line used). To do this, we calculated the values of the yield from the DPMO's, which remained in the background of the model, for each product we would foresee the maintenance thresholds, the expression used is:

$$Dpu_{pm} = \frac{Dpmo_m \cdot Opp_{pm}}{10^6} \qquad (4)$$

$$Y = e^{-DPU} \qquad (5)$$

Even this model has been optimized, neither the less, as we can see from the following results, the model based on the DPMO's presents a net generated value +4.19% respect the yield optimized model.

$$YIELD = Y_{P\&P} \cdot Y_{nonP\&P} \qquad (6)$$

The data that has been actually observed in the plant, when simulated for an equal period of time of the other two models, generates the following results:

Net generated value	67921.26
Gross generated value	96233.47
Rework costs	27042.27
Maintenance costs	1269.94

While the DPMO model generates these values:

Net generated value	73340.44
Rework costs	18955.54
Gross generated value	94581.40
Prev. maintenance costs	2106.20
Opp. Maintenance costs	179.22

The comparing model based on the processes yield, has given:

Net generated value	70392.88
Rework costs	25608.30
Gross generated value	96926.20
Maintenance costs	925.02

In conclusion, the model that we have built appears to be in grade, using the DPMO metric, to offer more precise information regarding when to carry a maintenance intervention.

Furthermore, the models flexibility will allow in future, as done here with the other model, to compare different decision processes with limited changes.

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