"MAINTENANCE MODELS AND SYSTEM DYNAMICS"

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ABSTRACT

This paper presents a complete study of quantitative models to optimize maintenance decisions in a company. The corrective, preventive maintenance with and without previous test are modeled and implemented for several cases. This is a new contribution within the field of maintenance, introducing the possibilities associated to the utilization of these models as a support for the maintenance planning decision making process.

INTRODUCTION

In the new complex industrial systems using high technologies, the manintenance function development is playing an strategic role (Ruiz Usano, 94). The planning of this function must be simultaneous to the production fuction planning and therefore has to take into account several factors becoming essential (Furlanetto,94) as lean-flexible operation and organizational structure simplification.

The role of the planning function must be (Escuredo, 73) to support/push the introduction of substantial changes in the system. The goal of these changes will be to improve operations performance and methods in use. With this purpose, this function will introduce new strategies, procedures and resources assignment modifications.

The process of analysis, design and implementation of the mentioned modifications is generally slow and can be influenced by many short term issues needing urgent solutions at the same time. There are several options in order to support this process:

- the introduction of new methodologies. A good example of this is the TPM (Nakajima, 89), which approach the problem under the perspective of all company employees involvement. Some more methods can also be found (Crespo & Usano, 94) focusing mainly on the creation of a proactive maintenance culture in the company. This culture tries, through the consecution of a learning organization, to obtain robuster systems, much less affected by the difficulties generated by the failures (Senge, 90 ; Sterman,Bonahan & Gorman, 92).
- the possibility of an evaluation of the optimal strategies to be adopted through the real system validated models .

The reasons previously mentioned completely justify the opportunity of a much deeper investigation in the details of the maintenance planning, as well as the development of tools to support this mid/long term important function.

PHASES TO ESTABLISH A MAINTENANCE STRATEGY.

1. SELECTION OF CRITICAL EQUIPMENTS.

Among all the equipments to maintain, critical equipments have to be analyzed with priority. Criticality is a measure of the equipments failures' importance within the production system. If this feature becomes important for an equipment, a much more detailed FMEA (Failure Modes Effects Analysis) should be required in order to ensure future equipment reliability with the most economical maintenance methods (Henley E.J. & Kumamoto H., 92)(Smith D.J., 92).

The aspects to take into account when evaluating the equipment's criticality could be: safety in case of failure, environmental effects, production required availability, stand-by equipments available, etc.

2. CRITICAL EQUIPMENTS. FMEA.

The FMEA is an inductive analysis where all possible modes of failure and their effects over the system, are component to component detailed.

A mode of failure can be casued by an individual element of a system or a consequence of misadjustment of several elements forming a subsystem, even if each one of these elements maintains a good operating condition by itself.

The FMEA will lead to a particular maintenance method for each mode of failure.

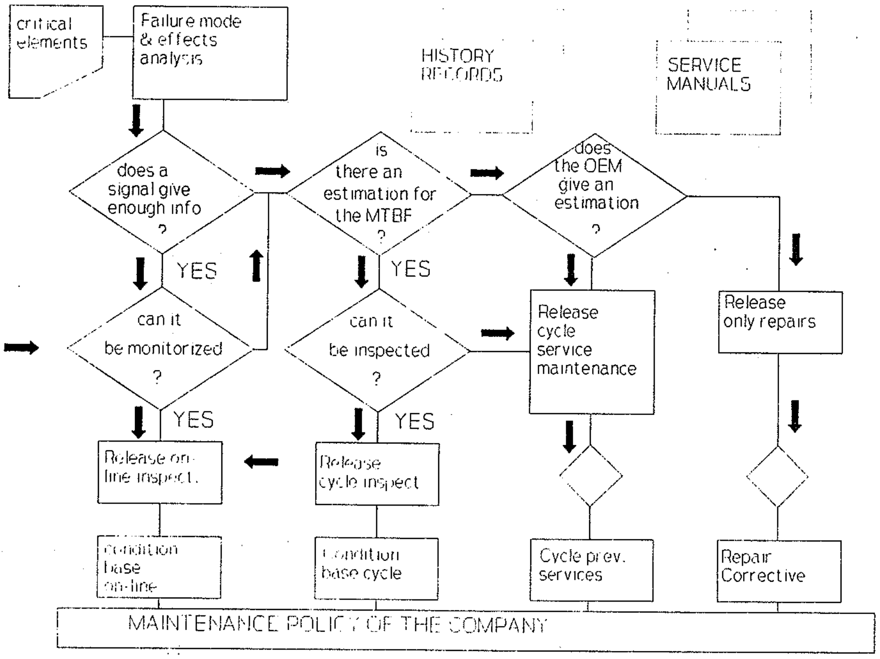


Figure 1

3. MAINTENANCE STRATEGY FOR CRITICAL EQUIPMENTS.

The Figure 1 shows the steps to follow in the selection of the maintenance strategy for a critical equipment. This diagram should be completed with a technical/economic study to evaluate the convenience of the preventive service versus the equipment replacement. This study will deal with two main variables: maintainability and replacement cost.

MAINTENANCE QUANTITATIVE MODELS

The study of the industrial systems behaviour concerning failures can lean on disciplines like statistics, computer science or operations research.

There are different ways to pattern an industrial system depending on technique chosen for the simulation process control. At present, using continuous simulation like System Dynamics(Crespo & Usano, 93), the evolution of a production system can be reproduced through the utilization of a convenient computer simulation program (Ventana System, 91). In the same way, discrete simuylation centered in events or in process, allows a deep knowledge of the evolution of each element of the system (Pedgen, 86).

In this paper we use probability models to analyze the evolution of the system considering discrete periods of time. These models focus their attention on the moment when the system reaches stability, in that time, the behaviour of the system is repetitive every period or cycle of periods. The calculation of the mean maintenance cost in case of stability is very simple, after determining the number of inspections, services and repairs to do in that moment.

MAINTENANCE METHODS ANALYZED

Four different maintenance methods are analyzed in this paper.
- Repair, corrective maintenance
- Total service, preventive maintenance to all equipments.
- Service according to equipment periods of time since last failure (TSLF)
- Service according to previous inspection and TSLF of the equipment.

In the following paragraphs these methods are detailed:

- **Repair, corective maintenance.** The system evolves from one period to next one reparing failed equipments. After a transitory period, which will last according to equipment features and its starting point, the system reaches stability and the same number of repairs are released by period.

- **Total service, preventive maintenance to all equipments.** The system evolves like in the previous case but now each certain number of periods, called cycle, a preventive service to all equipments is carried out. In this case the system trends towards a repetitive cycle of periods.

- **Service according to equipment periods of time since last failure (TSLF).** This is the same case than the previous one except for the number of equipments to be serviced. Now those with a certain number of periods of TSLF will be serviced. There will be different policies depending on these factors:

- possible cycle sizes
- age (TSLF) of the quipment to be serviced

- Service according to previous inspection and TSLF of the equipment. This model suposes the existence of an inspection procedure which is able to determine, with a certain level of confidence and for those equipment to be maintained, which ones should be serviced. This decision will be taken in the case of a bad result in the inspection of the equipment. For this case, and like in the previous one, after a transitory period the system reaches repetitive cycles.

HYPOTHESIS OF THE MODELS

- These models will be applied to an homogeneus set of equipments anf for an specific mode of failure.
- The time to repair, service or inspect a mode of failure in an equipment is small compared to the mean time between failures for that particular mode (MTTR< <MTBF).
- The quality of the function performed by an equipment does not depend on the TSLF of the equipment. However, this time affects the instant failure rate of the equipment for a given mode of failure.
- Once any equipment has been serviced or repaired, is considered "new" regarding its instant failure rate.
- The probability of having more than one failure of an equipment in only one period is minute.

SYSTEM STATUS DESCRIPTION

The condition of a system is determined by the number of existing equipments with different TSLF. One equipment evolves from one status to another (one period later) in one of the two possible directions:

- failing, it is then repaired and set to its first period of TSLF
- running, going then to its next period of TSLF

Mathematically, the status of the sistem is represented by means of a Vector which has as many components as periods of TSLF are admissible for the selected set of equipments.

The component "i" ,$N_i(t)$, represents then the number of equipments which are in their i period of TSLF.

$$E(t) = [\,N1(t), N2(t),\ldots, Ni(t),\ldots,N_{T1}(t)]$$

here, there are two remarks to mention:

- T1 is the maximun admissible number of periods of TSLF.
- The sume of all components is equal to the total number of equipments.

SYSTEM EVOLUTION

Departing from an instant t, the system evolves towards the next period:

$$E(t+1) = E(t) * P$$

Where P is called transition matrix, defined using the equipment mode of failure probabilities. As previously mentioned, when an equipment fails, it is repaired instantaneously an set to its first period of TSLF. This fact is included in matrix P.

In case of preventive services, after each time cycle selected, there is an instantaneous update of the status vector. This effect is traduced mathematically as follows:

$$E(t, \text{after maintenance}) = E(t, \text{before maintenance}) * M$$

Where M is called maintenance matrix. This matrix will be defined according to the particular preventive policy adopted. P & M (see Figure 2) are, therefore, matrices which model evolution in the system each time the condition system vector is multiplied by one of them. However there is an important different between both of them:

- P implies a "time consumption" transition.
- M implies instantaneous transition.

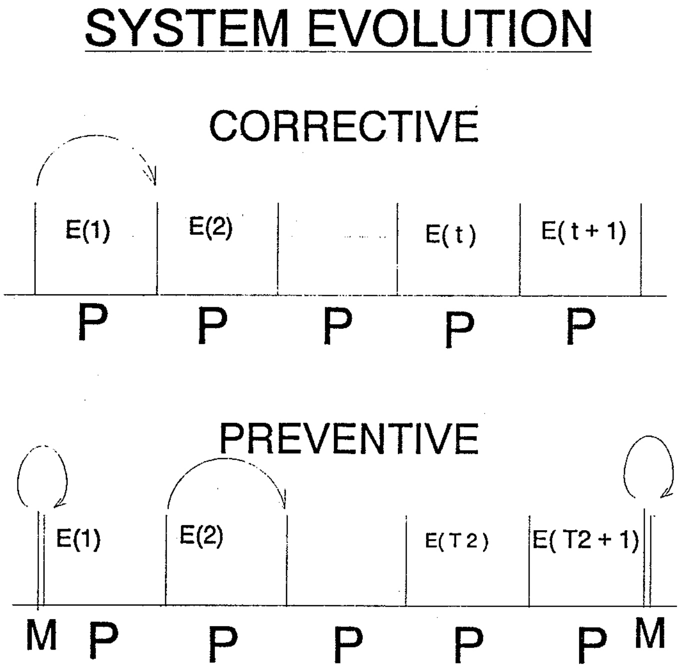


Figure 2

STUDY OF THE SYSTEM UNDER STABILITY

Doing a system analysis under an external point of view, the model can be represented as a black box receiving some inputs and generating some outputs, as depicted in Figure 3.

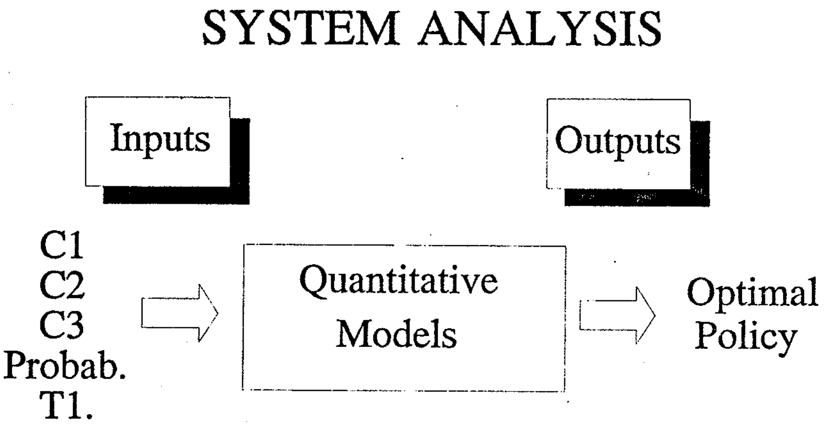
In the following paragraphs a more delailed inputs description is given:

- **C1**, is the mean total cost of the repairs done over an equipment for the mode of failure being analyzed. Direct and indirect cost resulting of induced problems are included.

- **C2**, is the mean total cost of the preventive service applied for an specific equipment mode of failure. This cost also includes the proportional cost of the information system to control the maintenance program.

- **C3**, is the cost of an inspection operation to observe the appearance of the mode of failure.

- **T1**, is the maximum number of periods of TSLF. A period is the amount of time in which a mode of failure can be reproduced in an equipment. This interval can be variable: hours, weeks, months, ... or any other time unit.



C1	Mean repair cost
C2	Mean preventive service cost
C3	Mean inspection cost
Probab.	Instantaneous of failure
T1.	Maximun TSLF

Figure 3

- **Failures instantaneous probabilities of an equipment.** From previous analysis, the percentage of the equipments failing or surviving in each period can be determined. With this data, the values of the probabilities required for the model are obtained for each period t. The instantaneous probability of failure of an equipment for a given mode of failure in the period t means the probability of an equipment to fail in the period t [t-1,t] once it has survived t-1 periods. In Figure 4, it is shown how to build the probabilities needed for the models. The output of the black box determine the most adequate maintenance method to apply for a given mode of failure. Besides this, some other results can enrich the knowledge of the system, for example:

- optimal policies to aplly under conditioned situations
- comparison among all strategies, number of repairs, etc...
- transitory periods
- status vector behaviour
- ...

COMPUTER PROGRAM DEVELOPMENT

All ideas and models commented on before would not be of help for the maintenance manager if there is not a way to put them into praxis for their daily utilization. With this criteria the informatic resolution of the problem is approached.

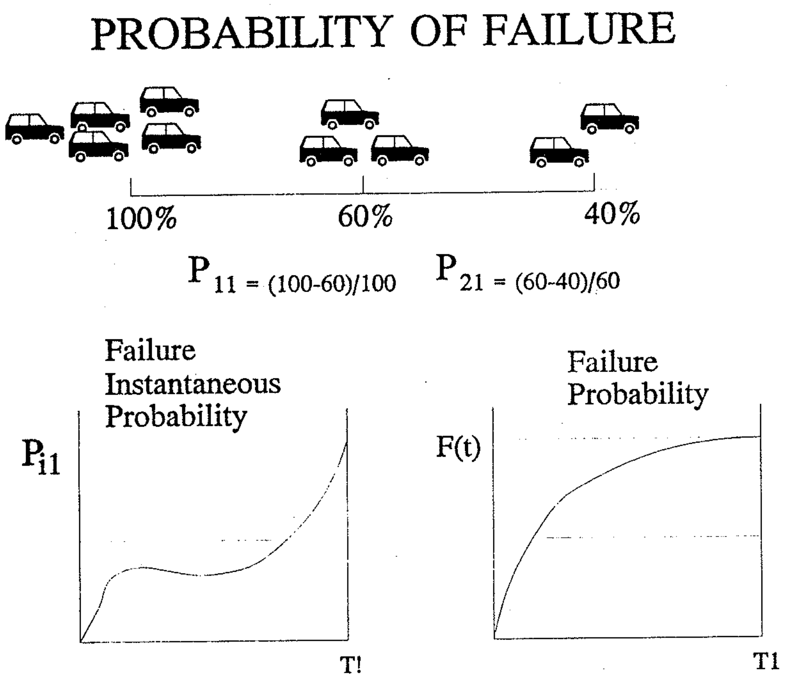


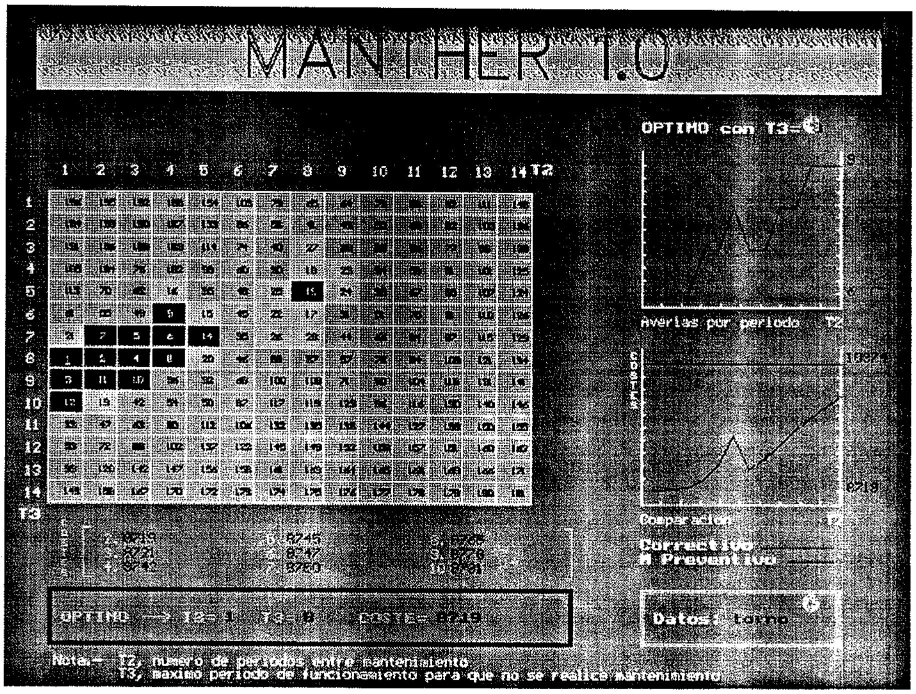
Figure 4

The final design adopted for the software development has been a "top-down" design (Fairley, 87) which has ensured the capability to experiment with different prototypes while the system has been developed, and also has allowed a gradual subsystems integration that made very easy this software to grew up. The problem of closing the loop backwards was easily solved with a small code writing.

An important contribution is the fact that the data introduction phase has a direct link to the information maintenance system. The software extracts from the history records the information of the mode of failure mode, processes this information and elaborates the inputs to the quantitative models module. Besides all this, the software has to give the possibility to store the information for a particular simulation in order to restore those results later.

ANALYSIS AND DESIGN OF POLICIES

Once all input data for the models is obtained from the information system. A simulation of all manintenance methods can be easily carried out. An example of the computer program results is shown in Figure 5. In that figure, the bigest part of the screen is occupied by a tridimensional representation. Each small square represents a possible preventive maintenance policy, this policies depend on the cycle selected (presented only cycles for $T2 <= T1$) and on the TSLF (T3) choosen for the quipment to maintain. The numbers appearing in each little square represent the order in cost of the associated policy, compared to the other ones represented in this graph. Optimum is for $T2=1$, $T3=8$, i.e. to maintain each period of time those equipments with more than 8 periods of TSLF. In the same screen is presented the evolution of number of repairs along the time (from 0 to T2). Also in the same screen, a comparison appears between the preventive policy and the



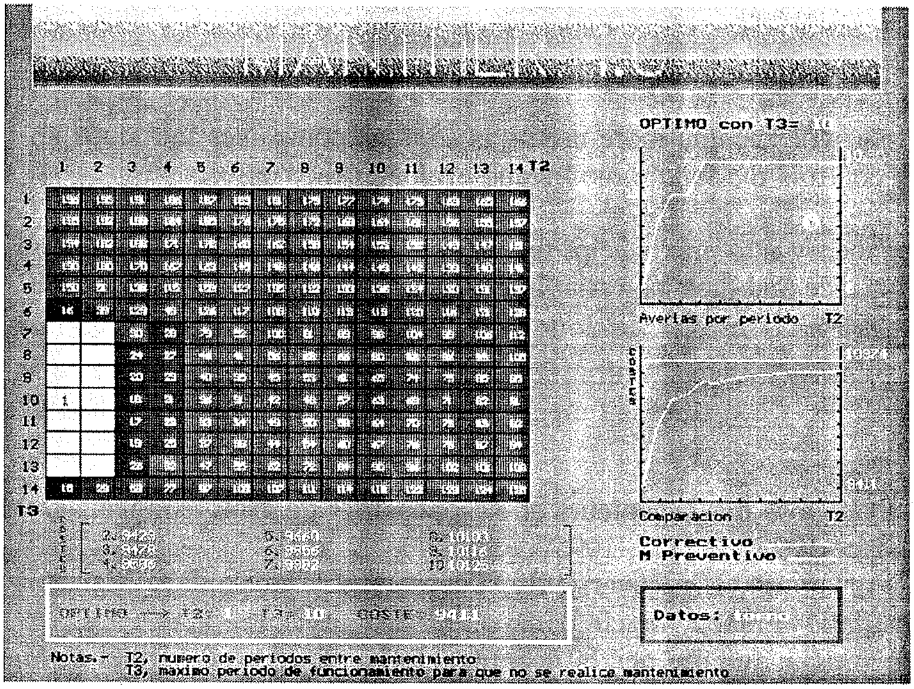
2. 8719
3. 8721
4. 8742
5. 8745
6. 8747
7. 8750
8. 8765
9. 8778
10. 8781

OPTIMO ---> T2= 1 T3= 8 COSTE= 8719

Datos: torno

Nota.- T2, numero de periodos entre mantenimiento
T3, maximo periodo de funcionamiento para que no se realice mantenimiento

Figure 5



OPTIMO ---> T2= 1 T3= 10 COSTE= 9411

Datos: torno

Notas.- T2, numero de periodos entre mantenimiento
T3, maximo periodo de funcionamiento para que no se realice mantenimiento

Figure 6

possible corrective one. In that comparison, can be observed the fact that the destinantion of less resources to solve a particular maintenance problem, can lead to better results for the cost of our maintenance. This will very valuable in case of resources constraints.

In Figure 6, we have the same information but now considering also inspection possibilities.

THE LOCATION OF THE MAINTENANCE POLICIES

Many times, a strategy which is different from the optimal policy has to be chosen due to several technical factors limiting the access to the best one. In the screen offereing the simulation results, the user has the opportunity to select the optimal policy from those possible ones.

OPTIMAL ROUTING TOWARDS THE OPTIMAL POLICY

To go from one strategy to a better one (optimal if possible) could require somtimes several steps. For one or more steps is clear that the routing can be an important matter. The time taken for the system to reach the new stability and the system behaviour during that time can condition this process. This software analyzes this problem and show the optimal routing from all possibilities.

CONCLUSIONS

This paper is an explanation of how, using quantitative models and information recorded in the history files of the maintenance information system, a direct feedback to the system can be produced.

This tool will become more useful as soon as companies introduce an information system which controls the failure modes and evaluates their effects.

Putting theory into praxis helps the maintenance managers to know more about their present performance and their potential improvement following a strategy for a given mode of failure.

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