Control of maintenance policies by means of a simulation model. A case study in a hospital

Mª CARMEN CARNERO
Department of Business Administration
University of Castilla-La Mancha
ETS Ingenieros Industriales, Avda. Camilo José Cela s/n, 13071 Ciudad Real
SPAIN
carmen.carnero@uclm.es http://www.uclm.es

Abstract: - This paper describes a simulation model formed by means of Matlab software that enables the visualization of trends in maintenance policies (Corrective, Preventive and Condition Monitoring), taking into account specific initial conditions and different levels of efficiency in the set-up of a Condition Monitoring Programme. Once a maintenance policy has been set up, different factors must be controlled to enable deficiencies to be detected early. The detection and diagnosis of these irregularities is the reason for the development of the simulation model of trends in maintenance policies. The model has been applied to a Hospital where maintenance efficiency has an influence not only on machines but also on people, by directly influencing the quality of the patients´ welfare service. Considering the characteristics of the Condition Monitoring Programme set up in the Hospital, maintenance trends are simulated to forecast future behaviour in relation with different alternatives, from the worst to the best possible states.

Key-Words: - Preventive Maintenance, Condition Monitoring, Corrective Maintenance, Simulation, Control, Hospital.

1 Introduction

The maintenance system, traditionally considered a source of expenses, has acquired a strategic dimension [18], due to its implications in matters of availability, quality, safety and costs.

The maintenance policies are defined as follows; in Corrective maintenance the maintenance activities are limited to repairing the equipment when a failure appears. In Preventive maintenance, the maintenance activities are developed with the intention of reducing the probability of failure of facilities or the degradation of a service. Maintenance activities are scheduled before the failure takes place [13]. In order to determine the interval between inspections the maintenance history of the equipment has to be taken into account [19]. In Condition Monitoring (CM), selected physical parameters associated with an operating machine are sensed, measured and recorded intermittently or continuously for the purpose of reducing, analysing, comparing and displaying the data and information obtained for support decisions related to the operation and maintenance of the machine [15]. See [7], [8] and [20] for examples of Condition Monitoring applications.

Numerous contributions in relation to the calculation of Maintenance performance by means of fundamentally descriptive indicators can be found in literature (see [2], [16], [1], [3], [10], [12], [11], [5], [21]).

Multiple models have been developed for the optimisation of maintenance policies, (see [14], [6], [22] and [17]); however, whilst an effort has been made to construct mathematical models for optimising Preventive maintenance policy, attention should be drawn to the lack of tools for optimising and checking Corrective, Preventive and Condition Monitoring maintenance policies simultaneously. The aim of this paper is to contribute to research by developing a model which will enable the simulation of different trends in the setting up of maintenance policies, an aspect that has not been analysed until now.

Once a maintenance policy has been set-up, different factors must be controlled so that the appearance and development of deficiencies in the new maintenance policy can be detected during set-up, maintenance and extension of the programme. The detection and diagnosis of these irregularities is the reason behind the development of the simulation model of trends of maintenance policies.

The model described is applied to a service company where the number of contributions in maintenance is almost non-existent [24]. This lack of contributions is even more evident in hospitals, where maintenance efficiency has an influence not only on machines but also on people, by directly influencing the quality of the patients´ welfare service.

Due to the specific characteristics of the hospital facilities, such as the coexistence of conventional facilities (of a low or medium technological level) with equipment and facilities of a high technological level, it is essential to have a system control to maintenance policies. Besides, the setup of a CM programme is a strategic decision. Therefore, it may be advisable to simulate maintenance policies and, in relation with their trends, make decisions regarding the organization of different maintenance policies as a whole, taking into consideration the needs and particularities of this organization.

This paper continues in section 2 with the creation of the simulation model. Section 3 describes the functioning of the simulation model. In section 4, the examples resulting from the simulation model are given. Section 5 shows the results of the application of the model to a Hospital. Section 6 gives the conclusions and finally the references.

2 Simulation model of trends of Maintenance Policies

A Condition Monitoring programme set-up is composed of the following phases [4]:

- Design and planning phase. This is the interval of time from the first suggestions of modifying maintenance policies by introducing a Predictive policy until the human and technical resources are available to begin the set-up.
- Adaptation phase. The aim is to obtain reliable diagnoses regarding of the state of the machinery. This period can be between 8 months and 14 months.
- Extension or globalisation phase. When the return on the investment is reached, the number of machines under control is increased. This phase is usually reached after a period of three years from the start of set-up.
- Integration phase. Integration with the other maintenance systems such as computerised maintenance management system and enterprise resource planning.

The previous phases will be considered in the simulation model, as in each of them different characteristics regarding the trend in maintenance policies could be defined.

In order to construct the model the following variables must be defined: CMA is the time integrally assigned per month to Corrective maintenance activities, PM is the time assigned per month to Preventive maintenance activities and CM is the time assigned per month to Condition Monitoring activities. These variables can be expressed as is shown in equation (1).

$$CMA = \sum_{i=1}^{N} T_i \quad i = 1, 2, ..., N; \qquad PM = \sum_{j=1}^{M} T_j \quad j = 1, 2, ..., M; \qquad CM = \sum_{k=1}^{L} T_k \quad k = 1, 2, ..., L \tag{1}$$

Where N, M and L represent Corrective, Preventive and CM maintenance activities respectively; T_i, T_j and T_k are the time assigned to each Corrective, Preventive and CM activity. The characteristics of the simulation model are described in the next section; it should be taken into account that the Preventive and Corrective maintenance policies are set up before the Condition Monitoring one.

When a CM policy is set up the Preventive maintenance activities should be progressively removed, as shown in equation (2). This is due to the fact that when a CM programme is set up accurate information regarding the state of each machine is already available and it is therefore not necessary to schedule preventive maintenance periodically, (such as changing the bearings every 5 years, independent of the state of the bearings); now that the state of the machine is known, if there is a component of the machine with an incipient failure, corrective maintenance can be applied. However, this trend is only achieved after the three maintenance policies have been applied simultaneously for a long time, as the CM programme does not provide reliable diagnoses in the initial phases of set up.

$$PM \to 0, \quad t \to \infty. \tag{2}$$

Once the stage of adjustment has been reached and reliable diagnoses are obtained, the time destined for the CM activities tends to stabilize, since procedures for acquisition, analysis and diagnosis of data have been established. This characteristic is shown in equation (3).

$$CM = a, \quad a = \text{constant}, \ t \to \infty \tag{3}$$

The corrective activities are limited to a minimum value [13]. This value is called residual Corrective maintenance and is generally considered to be 5% of the total maintenance activities. This characteristic in the model is illustrated in the equations (4) and (5).

$$CMA = b, \ b = \text{constant}, \ t \to \infty \tag{4}$$

$$b \approx \frac{5(MT)}{100}, \quad t \to \infty; \quad MT = \sum_{i=1}^{N} T_i + \sum_{j=1}^{M} T_j + \sum_{k=1}^{L} T_k \tag{5}$$

The number of CM activities must be superior to corrective activities. If this condition is not verified, the CM programme will not provide the reliable diagnoses expected, maybe as a result of the alarm limits established by the CM programme being too high and therefore leading to machines in good conditions to be diagnosed as being in a state of failure. This means that the number of corrective activities increases considerably. Therefore, $a > b$.

In the globalization phase the results of the CM programme must stabilize, and therefore, the time destined to CM activities must experience a reduction similar to the curves of experience of the production activities. In equation (6) this characteristic is shown.

$$CM = CM_3 e^{\frac{\log\varphi}{\log 2}} \text{, previous to } t \to \infty, \qquad (6)$$

With CM_3 the value corresponding to the CM activities in the globalisation phase; φ is the percentage associated with the experience in data acquisition and diagnosis in the CM programme.

The model that simulates the possible trends of Corrective, Preventive and CM maintenance is developed in Matlab.

3 Functioning of the simulation model

The software enables the user to choose between two temporary formats to represent the trends: days and hours.

The software is formed to fulfil the calculus in 5 phases. These 5 phases are included in the model instead of the 4 phases describes in section 2, due to the fact that a point of inflexion must exist in the adaptation phase. At a certain moment, the number of correct diagnoses must progress from an average level (which can be considered up to 75 %) to a high level (over 95 %). These percentages depend a lot on the available resources, typology of analysed machines, training of the personnel for the CM programme, etc. Therefore, the adaptation phase divides the software into two subphases.

The following information is requested from the user in the first phase of implantation of the CM programme:

- Duration of the phase in months.
- Total percentage of maintenance activities. If 100% is included, it means that the sum of the percentages of the corrective and preventive activities must reach this value.
- Maintenance policy with a percentage of activities known.
- The initial percentage of the maintenance policy known.

Later, the programme draws the trends for this phase. Due to the fact that the CM programme is still being designed, the percentage of activities relating to this policy is 0 %. Only when it is carrying out activities of data acquisition, transference of information to the software and diagnosis of machine condition is there considered to be a contribution of this policy.

In the second phase, the programme requests the following information:

- Duration of the phase in months.
- Percentage corresponding to the total sum of activities of the different maintenance policies evaluated. With this quantity, it is able to include reductions or extensions of the percentage of time intended for maintenance activities. This is included with the aim of allowing variations of resources between the different phases.
- Policies of maintenance with the final value known in this stage. The options to choose between Condition monitoring and Corrective maintenance are provided to the user. Since the total percentage (from the previous data) is known, it is not necessary to include the percentage corresponding to Preventive maintenance. Only Condition Monitoring and Corrective maintenance can be selected due to the fact that the corrective kind always exists in a company, whereas it is possible that the preventive kind does not exist; though the latter situation is unusual since companies generally have a preventive policy as well as computer resources (hardware and software) before the setting up of the CM programme. The existence of these characteristics in a company can guarantee the success of the setting up of a CM programme.
- To choose between exponential or linear adjustment for the trend.
- Final percentage in this phase of the maintenance policy selected previously.

The software calculates trends in relation with the type of adjustment selected. Preventive maintenance activities can be kept at the same value as the initial conditions due to the fact that in this phase the diagnosis provided is not completely reliable yet. The corrective and/or preventive maintenance activities can also increase, due to the fact that the diagnosis provided can detect anomalies in the machines with different levels of severity. In high severity corrective activities should be carried out, and with low severity planned activities can be applied.

Next, the software draws the trends for this phase.

In the third phase, the following information is requested:

- Duration of the phase in months.
- Percentage corresponding to the sum of the time applied in the three maintenance policies.
- The maintenance policies with final percentage of activities known. These options are provided: CM

and Corrective, CM and Preventive and Corrective and Preventive.

- The type of adjustment that will be used in the creation of the trend: linear or exponential.
- The final percentage corresponding to the maintenance policies selected previously.

In this phase it is supposed that the CM programme is obtaining a reliable diagnosis of the state of equipment. Therefore, the percentage of Preventive maintenance may decrease.

In the fourth phase, the same information as in the previous phase is requested.

In the fifth phase, the following information is requested:

- Duration of the phase in months.
- Experience percentage that is associated with the CM programme.
- The programme asks if the provision of optimum trends, or another situation, is wanted. In the latter case, the percentage of corrective and preventive maintenance activities is requested.

In this phase, the total percentage of activities is not requested due to the fact that it is established by means of the initial values and the experience percentage for the CM.

Finally, a graph is drawn up with the trends in maintenance policies in all the phases. A file is drawn up too and the data from the simulation is included in it. An example of the data stored in a file with each simulation is shown in table 1.

Phases	Phase 1		Phase 2		Phase 3		Phase 4		Phase 5	
	I	F	I	F	I	F	I	F	I	F
CM activities (%)	0	0	3.3	23.3	20	15	13.3	25	25	4.5
CMA activities (%)	55	55	58.3	35	31.7	50	48.3	40	40	5
PM activities (%)	45	45	48.3	48.3	45	35	33.3	30	30	15
Total maintenance activities (%)	100		110		100		95		95	
Duration (months)	3		4		5		6		7	
Experience percentage	-		-		-		-		0.8	
Time of calculus	59×10^{-3} s									
Number of operations developed	5,856									

Table 1. Data registered by the programme with each simulation.

4 Trials generated by the model

Some trials resulting form the simulation model are presented in this section; these examples are grouped in Fig. 1 and Fig. 2 that are suggested as patterns for a control system. The Director of the Maintenance Department can compare the results obtained through his maintenance activities in each stage with the proposed examples and can assess the state of the activities. Moreover, the model can simulate erroneous behaviour in the future evolution of the maintenance policies.

The examples have been created by dividing the percentage of activities for each maintenance policy into 3 categories. These categories are: minimum (0-20%), middle (20-60%), outstanding (60-100%).

In the rows (denoted by l) the output state of each company is explained. 1 indicates lower output conditions of the CM programme (nearly 90% corrective activities and the remaining 10% preventive activities); 2 specifies medium layout (50% corrective maintenance activities and the remaining 50% preventive activities) and 3 indicates an optimum initial situation for the CM set up, requiring a high percentage of preventive activities in the initial stage. In columns (denoted by m) the efficiency of the CM programme is described. Value 1 indicates a minimum level of CM activities to attain the optimum state of the CM programme. Value 3 indicates a high level of CM activities to attain the optimum condition of the CM programme.

In Fig. 1 the behaviour of each maintenance policy is shown when the resources are intensified in different proportions during the CM programme set-up. In this figure it is possible to appreciate in all the cases that an increase in Preventive activities is produced during the adjustment phase of the CM programme. These effects are considered to be normal since a high level of reliability has not been reached in the diagnosis of the machines. Efficiency during this set up phase of the CM programme may also be low due to a lack of training and experience of the personnel involved in the new activities. Nevertheless, when the adjustment phase finishes the number of preventive activities must diminish, showing that the CM programme has reached a stable phase with reliable predictive diagnosis.

In Fig. 2 some anomalous tendencies simulated by the model during the CM programme set up are suggested and as the optimum state is not attained an increased number of resources have been considered in the CM programme.

In Fig. 2, if l=1 and m=1. The CM activities instead of eliminating the preventive maintenance, act by increasing the preventive activities. This is due to the fact that the CM programme is not applied with the aim of improving the maintenance area, but as an additional policy, in so doing increasing the costs of the area as it is applied together with the preventive policy.

If l=1 and m=2. The CM activities do not detect failures in the machinery, which means that the same quantity of corrective activities are maintained. The efficiency of the CM activities is very low.

If l=1 and m=3. The setting up of the CM programme means that together with the habitual preventive and corrective activities, additional, and but unnecessary activities, are developed in both policies suggested by the CM programme.

If l=2 and m=1. The CM activities have no influence over the Preventive and Corrective maintenance applied.

If l=2 and m=2. The introduction of the new maintenance policy does not diminish the corrective activities and increases the preventive activities.

If l=2 and m=3. The corrective and preventive activities are increased by the same amount. Thus, there are additional maintenance activities from the CM programme and the traditional activities have not been modified with the inclusion of the new maintenance policy.

If l=3 and m=1. The CM policy must not increase the corrective activities, since the CM activities do not have sufficient time to discover the failures from the initial phases of development; therefore, the detected breakdowns could lead to the inability to return the machinery to a working condition in a short period of time. The preventive activities experienced a slight decrease.

If l=3 and m=2. The preventive policy is not affected by the CM one, but the corrective activities experience a relevant increase. Therefore, the anomalies in the machinery have influenced other components leading to multiple breakdowns.

If l=3 and m=3. The CM policy does not eliminate the activities based on time and does not reduce the corrective activities. This suggests that the increase in preventive activities is causing an increase in corrective activities.

5 Case study in a Hospital

Hospital facilities include certain features that involve their maintenance having to be considered in a special way. The following points summarize these characteristics:

- Maintenance of medical systems, which are becoming increasingly complex and need highly qualified personnel to carry out maintenance activities. The tendency is to outsource maintenance service once the guarantee period has finished.
- Buildings and piping characteristics of a large and complex installation, which are required to be increasingly safer and more reliable , resulting in a tendency towards the introduction of intelligent buildings.
- Electricity, water and gas supplies. This matter is normally dealt with by the maintenance service of the hospital, and its economic importance can be quantified at 5% of the annual budget for the installation.

The data required to apply the model to the Hospital has been obtained by means of a questionnaire answered by the Director of the Maintenance Department.

There are numerous Condition Monitoring techniques, as can be seen in [9]: lubricant analysis, vibration analysis, thermography, penetrating liquids, radiography, ultrasound, control of corrosion, etc. Each technique is applied to a specific type of industrial equipment.

The setup of the CM programme in the Hospital is in the design and planning phase at the moment. The Condition Monitoring techniques selected are:

- Thermography. This is the first predictive technique set up in the Hospital. Now, 74 devices are included in the CM programme to control generally the transformers, the low-tension control panel and systems of uninterrupted supply belonging to operating theatres.
- Vibration analysis. It can be considered as the most widely used technique due to its suitability for application to rotary and reciprocating machines and its high capacity for diagnosis. This technique makes it possible to detect mechanical faults and identify the type of fault that is occurring [23].

As regards the staff of the Maintenance Department, the aim is to keep the same number over the coming years, and only one worker has joined the staff since the beginning of the setup of the CM programme. This worker will be kept on for at least 3 years.

The percentage of corrective activities at the beginning of the setup of the CM programme is 50%. Thus, the percentage of preventive activities is at least the remaining 50%.

Due to the previous characteristics, the percentage of CM activities is limited, and therefore so is efficiency. Because of this, the Hospital is given l=2, m=1. The simulation model gives the trends to the optimum shown in Fig. 3.

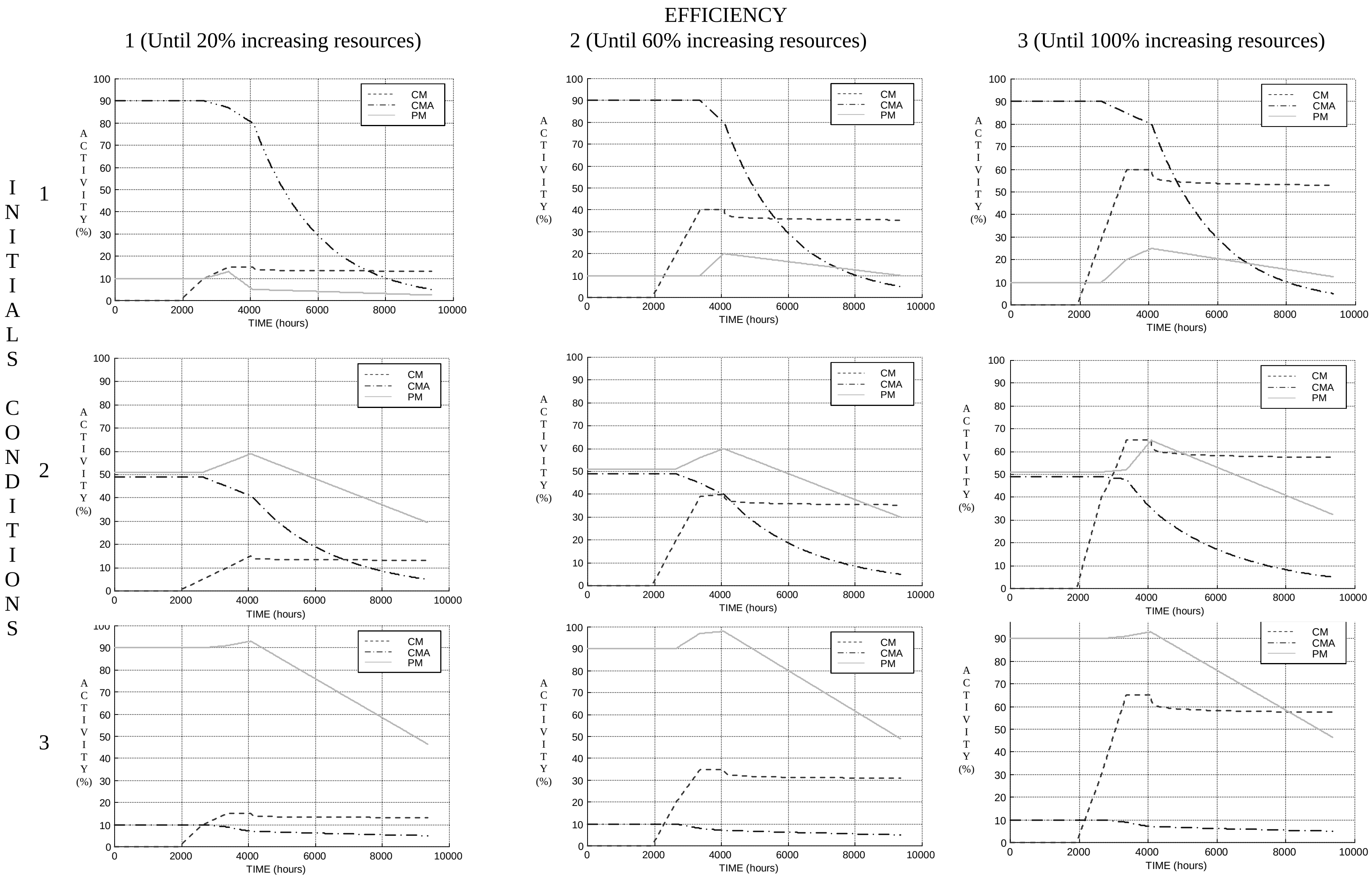

Fig. 1. Behaviour of each maintenance policy when the resources are intensified in different proportions during the CM set-up.

EFFICIENCY

1 (Until 20% increasing resources) 2 (Until 60% increasing resources) 3 (Until 100% increasing resources)

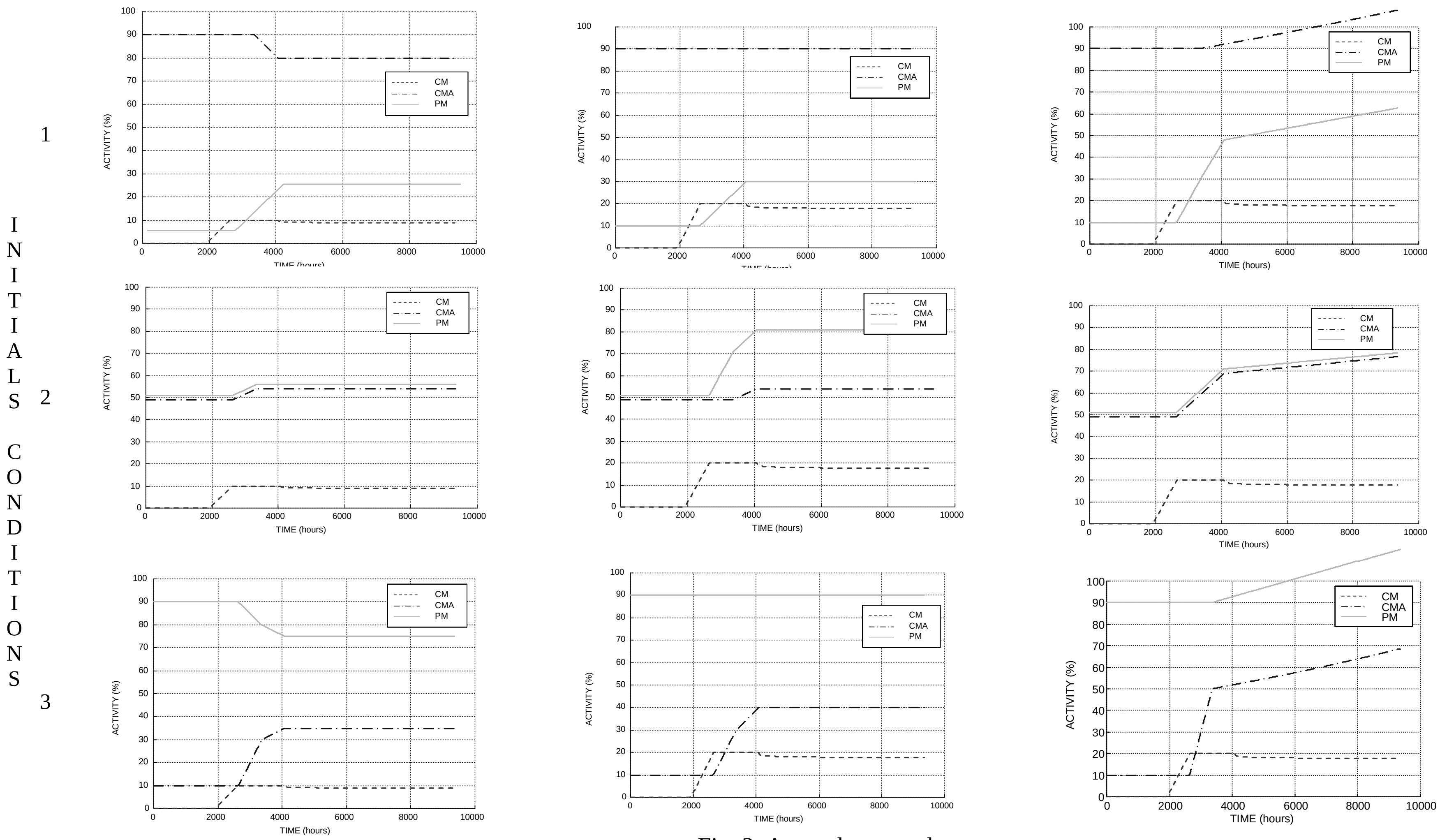

Fig. 2. Anomalous trends.

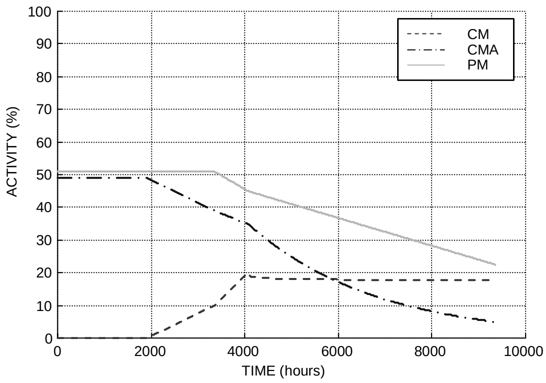

Fig. 3. Initial simulation of Maintenance trends in the Hospital.

As can be appreciated in Fig. 3, once the first phase has been completed (nearly 2,000 hours), Preventive maintenance (PM) is going to be carried on in the same state as previously. This is due to the fact that the reliability of the CM programme is not considered suitable yet. Therefore, no changes in this maintenance policy are going to be made. However, once the second phase began, it was appreciated that corrective and preventive maintenance activities underwent a slight increase that is not included in Fig. 3. Therefore, new trends were simulated by the software (see Fig. 4).

In this figure, the increase in resources is estimated at 20%. Only 10% of this increase is related to the CM programme; the remaining 10 % is brought about by increases in other maintenance policies, though the latter are caused by the diagnoses given by the predictive data. As can be appreciated in Fig. 4, all the figures begin with a very similar percentage of preventive and corrective maintenance activities, because this is the situation in the Hospital at the time the CM programme is set up.

The figures included in Fig. 4 are organized from worst to best behaviour in the Hospital. In the first column, it can be appreciated that Corrective maintenance has a final constant level higher than or similar to the initial conditions in every case. In the second column, preventive maintenance has a final constant level in every case and is always higher than the initial value. However, the trends in Corrective maintenance develop from the same level as the initial value in the case of l=1 m=2, to a slight decrease in Corrective maintenance in l=2 m=2 (although a substantial increase in preventive maintenance has been required). In the case of l=3 m=2, the quantity of Preventive maintenance required to obtain the decrease in Corrective maintenance (with regard to the initial conditions) is lower than in l=2 m=2 and is therefore considered more suitable than the previous case.

In the third column of Fig. 4, the trends are shown when both Preventive and Corrective maintenance have final downward trends which can be considered as a process of continuous improvement. In m=3, the final quantity of Corrective maintenance is lower than the Preventive one (this is always better than in the opposite case due to the fact that Corrective maintenance may mean that certain equipment or medical services are not available, and the preventive maintenance activities can be planned when these pieces of equipment or medical services are not required by any patient).

In the case of l=1 m=3, the final corrective maintenance level is slightly lower than the initial value, and the preventive one is higher than the initial conditions, but in both cases a slight decrease is expected in the future over these values.

In l=2 m=3, there is a slight decrease in Corrective and Preventive maintenance in the final values with regard to the initial values, and the quantity of preventive maintenance activities is higher than the corrective ones.

In l=3 m=3, the final value in both corrective and preventive maintenance activities is lower than in the previous case, especially in preventive maintenance, in which the downward trend is steeper, and then the quantity of preventive maintenance activities can be a low value in the future.

Therefore, the Director of the Maintenance Department in the Hospital can ensure that the trends in his maintenance policies will follow the behaviour from the last column of Fig. 4 and preferably the behaviour registered in l=3 and m=3.

6 Conclusion

This paper describes a simulation model developed in Matlab. This model can simulate the trends in Corrective, Preventive and Condition Monitoring Maintenance policies when a CM programme is set up. The model can describe not only the trends when suitable behaviour is developing, but also erroneous behaviour that may be caused. Different increases in resources during the CM programme setup can be considered. The trends in maintenance policies in a Hospital are given as an example of application. Considering the initial characteristics of the Maintenance area, the quantity of resources allocated to the new maintenance policy and estimated efficiency, some possible future states are forecast from the worst to the best situation.

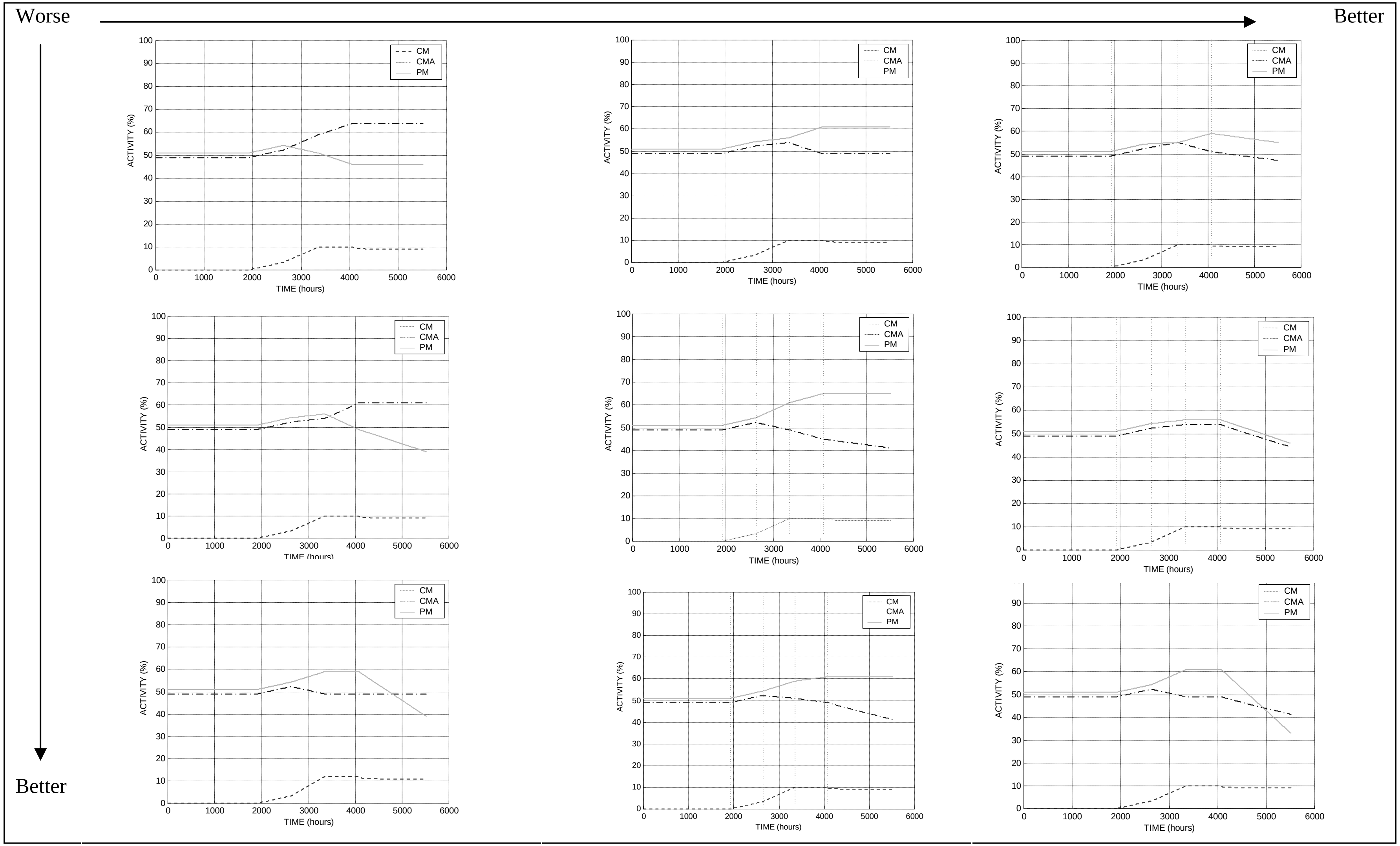

Fig. 4. Simulated trends related to possible future behaviour in the Hospital.

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