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Duarte, José Caldeira
Instituto Politécnico de Setúbal, Setúbal, Portugal

A unified approach to maintenance management supported by statistical techniques

Keywords

maintenance, reliability, availability, forecasting

Abstract

Maintenance activities represent an increasingly high cost in any manufacturing system or in different types of structures. Its achievement or not has a major impact on availability of equipment or structures. Nowadays cost reduction, minimizing downtime and ensuring reliability levels are central objectives in any sector of industrial activity and maintenance is observed as an important service. To achieve these goals, decision support systems should be available, optimizing the exploration and maintenance plans and ensuring companies meeting their goals. In this paper a global model for maintenance management based on the reliability theory and other statistical techniques, is presented. This model is being applied to several industrial sectors and some prototypes have been developed. The need for a maintenance database is also highlighted.

1. Introduction

The economic drivers behind modern human activities raise pressures in all industries to be efficient and competitive. On the other hand, safety of the people and protection of the environment are the critical values underpinning sustainable development and progress. Recent developments show an increasing need to consider social and cultural aspects, as well. This leads to the challenge of providing safe and cost-effective solutions to products, systems, facilities and structures across different industries.

To meet the challenge, the safety, reliability and availability requirements, which are critical to efficiency and cost, need to be ensured not only in the design and manufacturing phases but also during the operational and ageing phases of the products and facilities. This requires an integrated treatment of the technical and organizational aspects involved in design, production and operation, in the face of dynamically changing work organisations and including the extended use of information technologies [22].

The globalization and the fluctuation of the markets challenge all industries to be effective in designing their products, efficient in theirs manufacturing process, reliable in delivering their products and to pursue customer satisfaction during their products usage lifecycle phase. It is also recognized that the product lifecycle is becoming shorter and original equipment manufacturers (OEM) need to look continuously for innovation and improvements in the performance of their products if they want to keep their competitiveness [13].

OEM innovation has been occurring in their overall business model with companies to enhance their abilities to design and supply high customized products, equipment or system solutions following the customer needs throughout product life-cycle. In this context maintenance services has been increasing its relevance in sustain a long term relationship between OEM and end users or customers.

To assure a desired maintenance service level and satisfying the customer needs OEM has also been looking for partnerships with suppliers and other partners in which can be included maintenance services providers, dependently from customers location. Hence, the OEMs have to design and adapt their business models according each customer requirements with the aim to increase dependability and to assure an acceptable cost throughout product lifecycle.

Based on a survey on enabling technologies to improve the performance of Flexible Manufacturing Systems (FMS), conducted by a CIRP Working

Group on "Flexible Automation-Assessment and Future" in collaboration with the ERC for reconfigurable manufacturing systems, mentioned by Ni et al [19], it is revealed that industry considers the cost of maintenance as the second more important critical factor for the success of large FMS. This shows a very low level of industry satisfaction due to the high cost of maintenance of FMS and their disappointment with the low level of availability of the systems, when compared with the expectation when those systems were installed.

Maintenance activities represent an increasingly high cost in any industry or structure. The decision making for effective maintenance is increasing in complexity with the increase in size of the systems and distant locations of customers and also due to the several independent sources of information [19]. Due to need to keep their competitive position customers are demanding improved system availability, safety, sustainability, cost-effectiveness and operational flexibility. Also there is a need for tailored support 24 hours a day, seven days a week to keep the expectation established during the customers' decision of investment [19].

To fulfil the needs mentioned above the product design requires changes to integrate technology that through a new organizational structure can provide safe and cost-effective solutions or services to products, systems, facilities and structures across different industries. Maintenance activities can be offer as solutions or as a service which has a major impact on availability of equipment or structures and its operational cost.

Cost reduction, minimizing downtime and ensuring reliability levels, nowadays are central objectives in any sector of industrial activity. To achieve these goals, due to the complexity of the systems and the strong dependency between critical activities, e.g. production, maintenance and quality, decision support systems should be available to propose effective plans and achieve the desired results. However, for an effective use of such systems it is necessary to have collections of reliable and consistent data about product performance that should support those systems running. The analysis and treatment of collected data will allow calculating values of reliability, to validate FMECA and re-plan production and maintenance operations or actions.

The relevance of maintenance requires a global understanding of maintenance functions as part of a manufacturing facility for a required effective product use, without constraining the operational performance (i.e. production capability, cost, time, quality and safety). To make the best use of a product it is of interest not only to know the initial behaviour of the product, based on data from its predecessors, but also the development of that behaviour throughout its life cycle. Thus we have to manage all activities related to the product maintenance in an effective way, with ability to manage relevant data to the product life cycle.

When an industrial company is purchasing a product or an equipment the maintenance requirements to be evaluated are related to product performance, in terms of its maintainability, availability, reliability and safety. Those aspects are mainly established at the design stage. In fact reliability can be considered as being a characteristic of design which results in durability of the product or system while performing its intended use over a predetermined time interval [20]. Reliability can also be considered a discipline that has been developed to provide methods to guarantee that any product or service will function efficiently when its user needs it. Related to reliability theory it incorporates techniques to determine what can go wrong, what should be done in order to prevent that something goes wrong, and, if something goes wrong, what should be done so that there is a quick recovery and consequences are minimal. Considering the reliability of whole system it depends mainly in the quality and reliability of its components and in the implementation and accomplishment of a suitable preventive maintenance and inspection program.

Reliability, availability, maintainability and safety as product characteristics, can only partially change in usage phase, however they can have a huge influence on manufacturing system performance. This highlights the need of maintenance to be a proactive function, interacting with production and planning facilities. Thus at each decision level within a company a right appropriate perspective about the impact of a good service and the definition of best practices and methodologies is required. Also there is a clear need for cooperation between the product design and its maintenance that can be shown through in an attempt to reduce the product life cycle cost. It depends on product production and assembly options, as well as of its final use and maintenance requirements.

Although a lot of effort is devoted to enhancing reliability and maintainability in the product design phase, occurrences of malfunctions in its usage are almost inevitable. Thus, according to [23], it is important to learn from such experiences and to make use of them for improving design of new products as well as for the operations and maintenance planning of current products. This statement establishes the link of maintenance with the designers/manufacturers work within the product life cycle.

2. Theoretical background

In this section we present the main probabilistic concepts that govern models and decisions related with maintenance planning.
A brief bibliographic review [3], [15], [17], [18], is enough to conclude that the discipline known as reliability was developed to provide methods that can guarantee that any product or service will function efficiently when its user needs it. From this point of view, reliability theory incorporates techniques to determine what can go wrong, what should be done in order to prevent that something goes wrong, and, if something goes wrong, what should be done so that there is a quick recovery and consequences are minimal.
So, reliability has several meanings. However it is usually associated to the ability of a system to perform successfully a certain function. To measure quantitatively the reliability of a system it is used a probabilistic metric, which we state next.

- Reliability of a component or system at time t is the probability that the component survives up to time t.

According to Elsayed [15], reliability of a system depends mainly in the quality and reliability of its components and in the implementation and accomplishment of a suitable preventive maintenance and inspection program in the case of deteriorating components. If failures, degradation and aging are characteristics of any system, however, it is possible to prolong its useful lifetime and, consequently, to delay the wear-out period carrying out maintenance and monitoring programs.
This type of programs leads necessarily to expenses and so we are taken to a maintenance optimisation problem.
The main function of planned maintenance is to restore equipment to the “as good as new” condition; periodical inspections must control equipment condition and both actions will ensure equipment availability. In order to do so it is necessary to determine:

- frequency of the maintenance, substitutions and inspections
- rules of the components replacements
- effect of the technological changes on the replacement decisions
- the size of the maintenance staff
- the optimum inventory levels of spare parts

Another measure of the performance of a system is its availability that reflects the proportion of time that we expect it to be operational.

- Availability of a component or system at time t is the probability that the component or system is operating at time t.

Availability is a function of the operating time (reliability) and the downtime (maintainability). Availability is a decreasing function of failure rate and that is an increasing function of repair rate (*Figure 1*).
Availability is also a function of the preventive maintenance program and shows the possible effects on system availability of such a program.

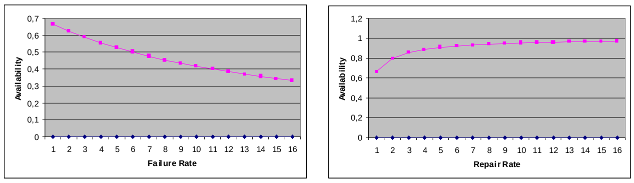


Figure 1. Availability versus Failure Rate and Repair Rate

- Maintainability of a component or system within a given period of time is the probability that the component or system will be restored to specified conditions within the given period of time when maintenance action is performed in accordance with prescribed procedures and resources.

Maintainability, like reliability, is an inherent characteristic of system or product design. It concerns to the ease, accuracy, safety, and economy in the performance of maintenance actions. Maintainability is the ability of a system to be maintained.
Next we present the classical concept of availability, while describing how to calculate it on a particular situation.
Pointwise availability of a system at time t, A(t), is the probability of the system being in a working state (operating properly) at time *t*. The unavailability of the system, $Q(t)$, is $Q(t) = 1 - A(t)$.
The pointwise availability of a system that has constant failure rate λ and constant repair rate μ is

$$A(t) = \frac{\mu}{\mu + \lambda} + \frac{\lambda}{\mu + \lambda} \exp[-(\mu + \lambda)t]. \qquad (1)$$

and the limiting availability is

$$A = \lim_{t \to +\infty} A(t) = \frac{\mu}{\mu + \lambda}. \qquad (2)$$

The second parcel in formula (1) decreases rapidly to zero as time *t* increases; so, we can state

$$A(t) \approx \frac{\mu}{\mu + \lambda}$$

and this means that the availability of such a system is almost constant.

Example
A system is found to exhibit a constant failure rate of 0,000816 failures per hour and a constant repair rate of 0,02 repairs per hour.
Using formula (1), the availability of such a system (see *Figure 2*) is obtained as

$$A(t) = 0.9608 + 3.9201\times10^{-2}\exp(-2.0816\times10^{-2}\,t)$$

and the limiting availability is

$$\lim_{t\to\infty} A(t) = 0.9608.$$

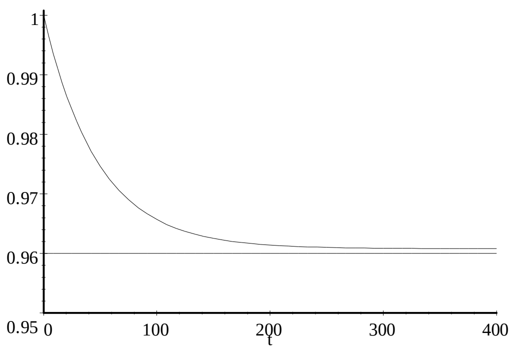


Figure 2. The availability function

It should be noticed that, in this in case, we do not have almost any variation in the value of component's availability for $t > 200$. ■

We can therefore conclude that, to guarantee a value of availability A, known the constant repair rate, μ, the value of the constant failure rate of the system it will have to satisfy the relationship

$$A \approx \frac{\mu}{\mu+\lambda} \Leftrightarrow \lambda \approx \frac{\mu(1-A)}{A} \tag{3}$$

3. Model and assumptions

In this section we present the main result that supports the global approach to maintenance management.
Suppose a system is found to exhibit an increasing hazard rate,

$$h(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1}, \theta > 0, \beta > 0, t \ge 0,$$

and a constant repair rate, μ.
Our goal is to determine the interval time between preventive maintenance tasks (we assume that the system is restored to the "as good as new" condition after each maintenance operation) in such a way that the availability of the system is no lesser than A.
The key for the solution of this problem consists on determining the time interval during which the increasing hazard rate can be substituted by a constant failure rate in order to guarantee the pre-determinate availability level.
Applying the mean value theorem of integral calculus to the function

$$h(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1}, \theta > 0, \beta > 0, t \ge 0,$$

we obtain

$$\int_0^x \frac{\beta}{\theta^\beta} t^{\beta-1} dt = \lambda x \Rightarrow \left[\frac{t^\beta}{\theta^\beta}\right]_0^x = \lambda x \Rightarrow$$
$$\Rightarrow \frac{x^\beta}{\theta^\beta} = \lambda x \Rightarrow$$
$$\Rightarrow x = 0 \vee x = \sqrt[\beta-1]{\lambda\theta^\beta}. \tag{4}$$

Substituting λ in equation (4) by its approximate value given in formula (3), we have

$$x = \sqrt[\beta-1]{\frac{\mu(1-A)}{A}\theta^\beta}.$$

We can therefore conclude that in the time interval

$$\left[0, \sqrt[\beta-1]{\frac{\mu(1-A)}{A}\theta^\beta}\right],$$

the hazard functions,

$$h(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1}, \theta > 0, \beta > 0, t \ge 0,$$

and

$$h(t) = \frac{\mu(1-A)}{A}$$

guarantee approximately the same value of availability. What we have just demonstrated [12] can formally be stated on the following form:

Proposition: Let S be a system exhibiting an increasing hazard rate,

$$h(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1}, \theta > 0, \beta > 0, t \geq 0$$

and a constant repair rate μ. To guarantee an availability for the system equal or greater than A the interval of time between two consecutive preventive maintenance tasks must be equal or lesser than

$$\sqrt[\beta-1]{\frac{\mu(1-A)}{A}\theta^{\beta}}.$$

Example

A system is found to exhibit an increasing hazard rate, $h(t) = 5\times10^{-8} \times t^{1.25}$, and a constant repair rate $m(t) = 4\times10^{-2}$.

What should be the greatest time interval between preventive maintenance tasks (we assume that the system is restored to the "as good as new" condition after each maintenance operation) in such a way that the availability of the system is at least *98%*?

If the system had a constant failure rate, to guarantee such availability it should be

$$\lambda = \frac{4\times10^{-2}(1-0.98)}{0.98} = 0.0008163.$$

We want to calculate the instant x in order to satisfy the following condition

$$\int_0^x 5\times10^{-8} \times t^{1.25} dt = 0.0008163x \Rightarrow$$

$$\Rightarrow \frac{5\times10^{-8} \times x^{2.25}}{2,25} = 0.0008163x \Rightarrow$$

$$\Rightarrow x = 0 \vee x = 4488.$$

We can therefore conclude that the system must be restored to the "as good as new" condition after each maintenance task every 4488 hours in order to achieve the availability target of 98%.

Figure 3 illustrates this example. ■

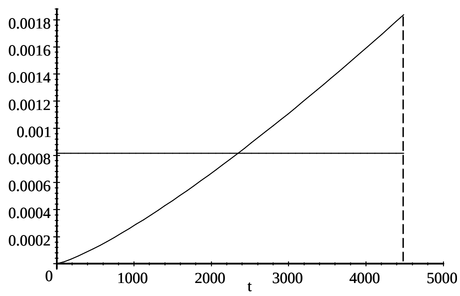


Figure 3. Hazard functions $h(t)$=5×10$^{-8}t^{1.25}$ and $h(t)$=0.0008163 over the interval [0, 4488].

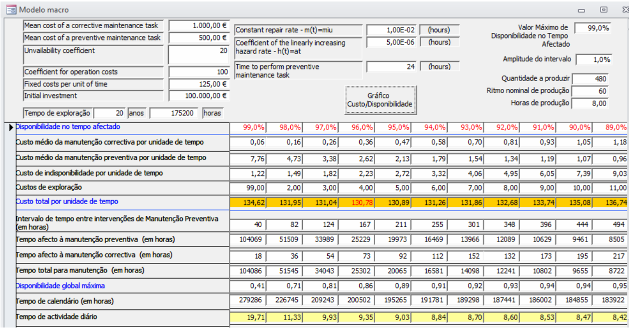
3. Macro model

This model makes the assessment of maintenance costs as a function of the goals defined for availability. It's based on the previous algorithm and its purpose is to determine the level of availability that satisfy plant requirement at the minimum cost.

The objective function of costs is defined taking into account the following costs:

1. Average cost of a preventive maintenance task – *pmc*.
2. Average cost of a corrective maintenance task – *cmc*.
3. Constant repair rate - *m* (*t*) = *m*.
4. Coefficient of linear increasing hazard function – *a* (*h* (*t*) = *at*).
5. Time to perform preventive maintenance – *TTR*.
6. Coefficient cost of downtime per unit time.
7. Coefficient operating costs.
8. Fixed costs – facilities initial Investment.
9. Production time (in years).
10. Maximum value of availability in Time Affected.
11. Quantity to produce.
12. Nominal production rate.

Figures 4 and *Figure 5* show the output generated by the prototype we have developed to implement this model.



Disponibilidade no tempo afectado	99,0%	98,0%	97,0%	96,0%	95,0%	94,0%	93,0%	92,0%	91,0%	90,0%	89,0%
Custo médio da manutenção correctiva por unidade de tempo	0,06	0,16	0,26	0,36	0,47	0,58	0,70	0,81	0,93	1,05	1,18
Custo médio da manutenção preventiva por unidade de tempo	7,76	4,73	3,38	2,62	2,13	1,79	1,54	1,34	1,19	1,07	0,96
Custo de indisponibilidade por unidade de tempo	1,22	1,49	1,82	2,23	2,72	3,32	4,06	4,95	6,05	7,39	9,03
Custos de exploração	99,00	2,00	3,00	4,00	5,00	6,00	7,00	8,00	9,00	10,00	11,00
Custo total por unidade de tempo	134,62	131,95	131,04	130,78	130,89	131,26	131,86	132,68	133,74	135,08	136,74
Intervalo de tempo entre intervenções de Manutenção Preventiva (em horas)	40	82	124	167	211	255	301	348	396	444	494
Tempo afecto à manutenção preventiva (em horas)	104069	51509	33989	25229	19973	16469	13966	12089	10629	9461	8505
Tempo afecto à manutenção correctiva (em horas)	18	36	54	73	92	112	152	132	173	195	217
Tempo total para manutenção (em horas)	104086	51545	34043	25302	20065	16581	14098	12241	10802	9655	8722
Disponibilidade global máxima	0,41	0,71	0,81	0,86	0,89	0,91	0,92	0,93	0,94	0,94	0,95
Tempo de calendário (em horas)	279286	226745	209243	200502	195265	191781	189298	187441	186002	184855	183922
Tempo de actividade diário	19,71	11,33	9,93	9,35	9,03	8,84	8,70	8,60	8,53	8,47	8,42

Figure 4. The output generated by the prototype of macro model

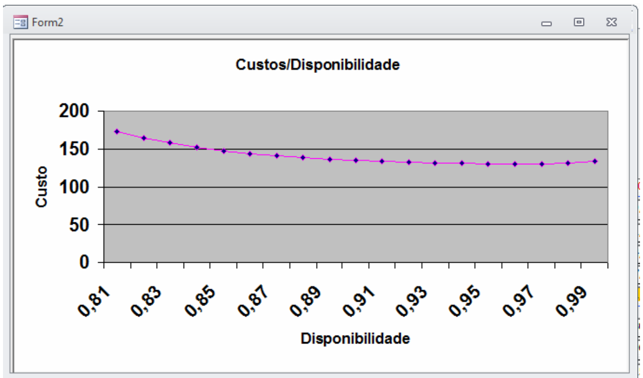


Figure 5. Availability versus costs in macro model

4. Optimization of the preventive maintenance plan of a series components system

In this section we will present a model for the preventive maintenance management of a series system.
The system is composed by a set of n components in series as *Figure 6* shows.

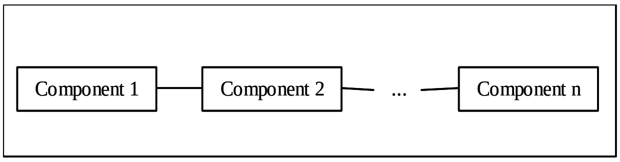


Figure 6. A series system of *n* components.

Let $\tau_1, \tau_2, \ldots, \tau_n$ be the time units between preventive maintenance tasks on components 1, 2, …, *n*, respectively (*Figure 7*); assuming that these actions will restore periodically the components to the "as good as new" condition, they will have, therefore, consequences at the reliability and availability levels of the system.

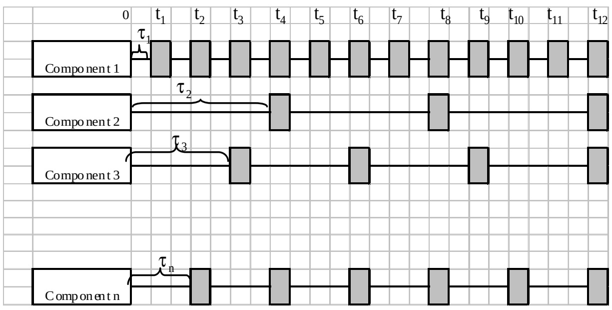


Figure 7. A preventive maintenance plan

Our goal is to calculate the vector

$$[\tau_1 \quad \tau_2 \quad \tau_3 \quad \cdots \quad \tau_n]^T$$

in such a way that the total down time in a certain period of time does not exceed a predetermined value, that is to say, that it guarantees the specified service level and simultaneously minimizes the maintenance costs.
We assume that each component has a Weibull hazard function,

$$h_i(t) = \frac{\beta_i}{\theta_i}\left(\frac{t}{\theta_i}\right)^{\beta_i - 1}, \theta_i > 0, \beta_i > 0, t \geq 0$$

and a constant repair rate

$$m_i(t) = \mu_i .$$

The cost of each preventive maintenance task is cmp_i and the cost of each corrective maintenance task is cmc_i.
Since the availability of the system consisting of *n* components in series requires that all units must be available (assuming that components' failures are independent), system availability *A* is

$$A = \prod_{i=1}^{n} A_i$$

where A_i is the availability of component *i*.
Applying proposition presented in section 3 we can write that the availability of each component *i* is A_i over the interval

$$\left[0, \sqrt[\beta_i - 1]{\frac{\mu_i(1 - A_i)}{A_i}\theta_i^{\beta_i}}\right],$$

and its hazard function can be approximated by the constant function

$$h_i(t) = \frac{\mu_i(1 - A_i)}{A_i}$$

Then, the expected number of failures in that time interval is

$$\sqrt[\beta_i - 1]{\frac{\mu_i(1 - A_i)}{A_i}\theta_i^{\beta_i}} \times \frac{\mu_i(1 - A_i)}{A_i}$$

The objective function (defined as a cost function per unit time) is

$$c(A_1, A_2, \ldots, A_n) = \sum_{i=1}^{n}\left[\frac{cmp_i}{\sqrt[\beta_i - 1]{\frac{\mu_i(1 - A_i)}{A_i}\theta_i^{\beta_i}}} + \frac{cmc_i}{\frac{\mu(1 - A_i)}{A_i}}\right]$$

subject to

$$\begin{cases} \prod_{i=1}^{n} A_i \geq A, \\ 0 < A_i < 1, i = 1,2,\ldots,n. \end{cases}$$

This model has been already generalized to parallel-series systems.

5. Numerical example

The model described on section 4 was implemented to a three components series system.

We assume that each component has a Weibull hazard function and a constant repair rate. Components are maintained preventively at periodic times.

Data is presented in *Table 1*.

First we present the nomenclature.

θ_i , β_i – parameters of hazard function.

TTR – Mean Time to Repair (corrective maintenance).

TTP – Time of one preventive maintenance action.

PMC – Preventive maintenance cost.

CMC – Corrective maintenance cost.

τ - time between two consecutive preventive maintenance tasks.

Table 1. Initial conditions

Compo-nents	θ_i	β_i	TTR	TTP	PM Cost	CM Cost	τ_i
1	4472.136	2	100	10	2000	4000	2000
2	1873.1716	2	50	40	2500	5000	1500
3	500.94	2	80	10	1000	2000	250

With this preventive maintenance plan the availability achieved is about 90.30% and the life cycle cost is 122055.79.

The target for availability is 90%.

The objective function was slightly modified in order to include the cost of down time.

MATLAB was used to optimize the objective function. *Table 2* shows the results. With this new preventive maintenance policy we have a reduction of 5.5% in Life Cycle Cost (LCC) and simultaneously the availability *A* achieved (92,70%) is greater than the existing one (90,30%).

Table 2. Results of MatLab optimization

MatLab Optimization	τ_1	1600.2
	τ_2	1246.8
	τ_3	170.7535
	A - %	92.70
	LCC	115345.22
	Δ LCC - %	-5.5

With these results as initial conditions we have applied the tool "SOLVER" of Excel and we got a better solution (*Table 3*).

Table 3. Results of MatLab + Excel optimization.

MatLab + Excel Optimization	τ_1	1606.498
	τ_2	1255.498
	τ_3	175.4996
	A - %	93.02
	LCC	113809.75
	Δ LCC - %	-6.8

6. Routines inspections and reliability

The main purpose of routine inspections [14], as well as condition monitoring [24], is to obtain useful information about equipment operational status and to identify degradation rates of components. There are two possible results when equipment is inspected:

- a failure or degradation is detected and equipment is repaired or adjusted and is returned to its original condition;
- nothing is detected.

In the first case the equipment is returned to a good state through maintenance and, equipment reliability is restored accordingly to simple reliability definition. If no failure or degradation is detected it is important to revaluate equipment reliability taking into account such information.

Duarte and Craveiro [10] have addressed the problem of the influence of routine inspections on evaluation of equipment reliability. Two simple algorithms have been developed to determine a new schedule for preventive maintenance actions when routine inspections detect equipment in a good state.

It is assumed that between two successive preventive maintenance actions there are *n* routine inspections. When an inspection with positive results is performed it's proposed the following formula to compute equipment reliability:

$$R_{j+1}(t) = \beta^j \times \left[1 - R_j\left(\frac{j\tau}{n+1}\right)\right] + R_j(t),\ j = 1,\ldots,n.$$

β is a parameter that allows an increase of equipment reliability if equipment operational status is better (when routine inspection is performed) than it was foreseen; stated another way, β is a parameter that incorporates the reliability of routine inspection itself.

This idea is described in *Figure 8*. Assuming that the time between two consecutive routine inspections is 1000 time units, it is reasonable to accept a small increase of the value of equipment reliability depending on the results of inspections and on inspector's knowledge about equipment.

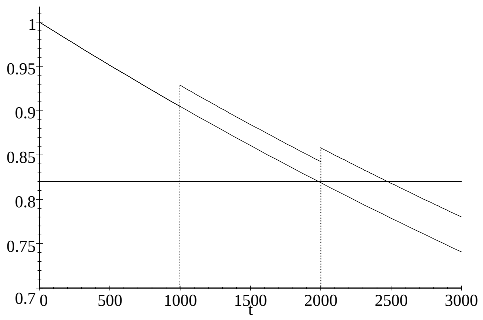


Figure 8. The effects of routine inspections on reliability

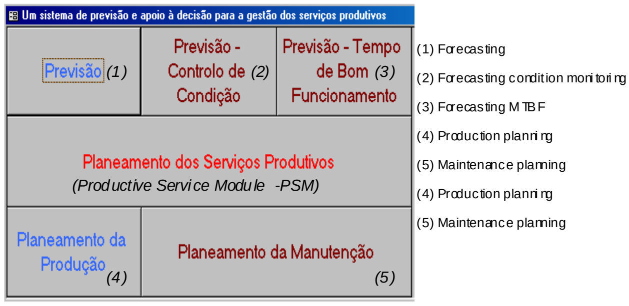
Integrating both perspectives, we can conclude that the value of equipment reliability is a function of maintenance actions and equipment evaluation made at each routine inspection.

7. Developed experience in integrating production planning and maintenance tasks

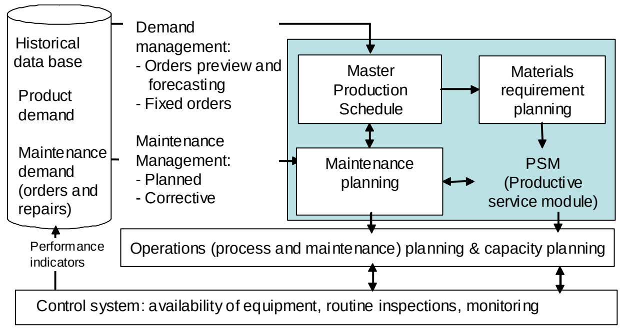
The absence of a unified production-maintenance planning model results in limited understanding of the relationships between production and maintenance parameters and the trade-offs between alternative maintenance and production policies. The integration of production and maintenance planning tasks has been mentioned in the literature basically according to two different perspectives. Some authors have developed this topic by determining the optimal maintenance policy in the production system. Others take maintenance as a constrain to the production schedule. A complete review of this subject can be found in the book edited by M. A. Rahim and Mohamed Ben-Daya [21].

Although the undeniable importance of all these models we consider that they still represent a partial perspective of the problem related with the integration of maintenance and production.

Thus, taking into account the needs of both production planning and maintenance demand for the production equipment, we have developed prototypes [7] for a planning and control model called Productive Service Module (PSM), *Figure 9*. It manages the maintenance and production functions while also accommodating the product reliability forecasting as a demand input. The PSM integrates therefore the history of product failures.



a) Integration of production and maintenance planning using PSM.



b) PSM user interface.

Figure 9. Proposed Productive Services Module (PSM).

Through the PSM we are proposing the maintenance planning as an input for production planning. These two tasks can be concurrent in terms of development and execution, with the opportunity to refine and to work with plans in a more far-reaching perspective. The possibility to have in real time the knowledge about the operational status of equipment as well as its availability, allows to maximize the utilization rate of equipment, its efficiency, the product quality and the effectiveness of maintenance tasks. Another consequence of this approach it is the ability to obtain a more realistic evaluation of existing productive capacity, helping to satisfy the promise due dates.

According to the study presented by Cunha [8] certain aspects with negative impact in the performance of production planning task are identified and its integration with other productive tasks is discussed. Also, studies carried out by Duarte [11] provide a basis to conclude, albeit empirically, that the information related to equipment working times and halt times recorded by independent production and maintenance planning systems may be substantially different. Only a system that records these data in a unified and coherent way will allow the calculation of appropriate estimations of the most important reliability parameters, such as the distribution of failure rate, mean time between failures (MTBF) and mean time to repair (MTTR).

From another point of view, the integration of all this information will allow that priorities and therefore ranking of different productive services - production operations and maintenance services - may be defined in an integrated overall way. In practice, this means that as long as the reliability of a piece of equipment is decreasing, the degree of priority of the maintenance action required to restore it to its functional state, increases. This leads to a situation where maintenance operations acquire a priority status against production. The importance of such a policy is undeniable because only in this way is it possible to ensure realistic availability of equipment. In this way we close one of the information loops of this system.

Through the productive service module (PSM) it is also possible to use data from routine inspection and condition monitoring to predict production equipment failures or breakdowns and support of decision making. The main purpose of routine inspections as well as condition monitoring is to obtain useful information about the equipment operational status and to identify degradation rates of a critical component. If a failure or degradation is detected, it will be repaired or adjusted and the production unit is returned to its original condition. In this case, due to the maintenance intervention the equipment reliability is restored, accordingly to simple reliability definition. Simple reliability is a new definition of reliability introduced in [9]. To some kind of systems, particularly those ones whose components repair process pass for its integral replacement (either it is by new components or by repaired components) it seems that the classical definition of reliability can be complemented with a new one: Simple Reliability or non-cumulative reliability. Simple reliability of a system at time t is the probability that the system works continuously over [0, t], assuming that the beginning of its operation (t = 0) is the instant of the last preventive maintenance action that restored the system to the "as good as new" condition.

Forecasting techniques are also an essential tool to infer the possibility of any damage or equipment failure, thus allowing an intervention a priori that prevents it. Equipment condition monitoring allows collecting data of the values of essential parameters. All these types of information help to create a picture of what may happen in the future. The higher the volume of data and its quality, the lower will be the error. If recorded data highlight a trend in the observed values it may be forecasted when the parameter will overcome the limits of alert or alarm of the signature. Some of the forecast techniques we have embedded in PSM are shown in *Figure 10*.

However, it is quite important to emphasize the applicability conditions of these methods:

- There is sufficient quantitative information about the past;
- The historical pattern will continue into the future – stability hypothesis.

It should be noticed that there are more sophisticated quantitative methods but, empirical studies within the field of forecasting and outside, concluded [16] that the post-sample accuracy of simple methods is, on average, at least as good as that of complex or statistically sophisticated ones. Furthermore the averaging of the forecasts of more than one method results in more accurate predictions than the individual methods themselves.

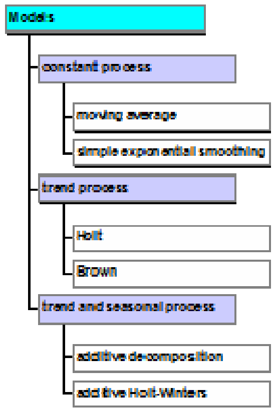


Figure 10. Forecasting models

Figure 11 displays the form that presents the predictions of the mean time between failures of equipment based on these forecasting techniques.

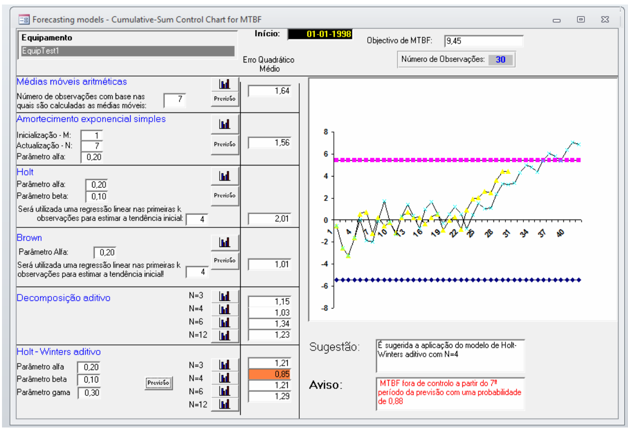


Figure 11. Forecasts of MTBF

A prototype for the optimization of the preventive maintenance plan of a series components system was also developed.

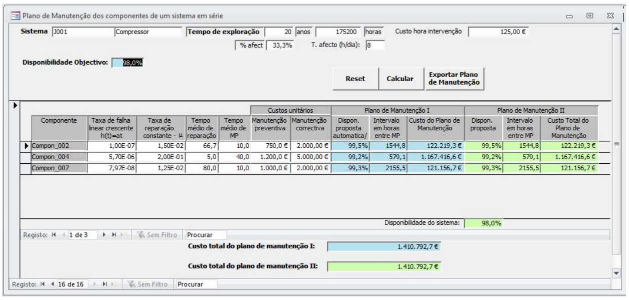


Figure 12. Optimization of the preventive maintenance plan of a series components system

8. The need for a maintenance database

Despite of OEM recommend maintenance schedule they may be not optimal because operational conditions may be quite different from those considered at the design phase. So, the necessity exists to obtain complete and exact data concerning equipment functioning, accidents and their consequences, maintenance operations and their costs. The best case would be if such information were collected from the same equipment (specific failure data) or from analogous equipment in similar conditions. These information must also be used on equipment to be planned for implementation combined with expert judgments on new equipment reliability parameters or using standard values or standard reliability models (e.g. MIL-217 or Bellcore). So, there is a need for reliability data collection in relation to all types of components from the field records of installations and operations, in order to allow us to analyse, compare, or predict the reliability levels of complex systems [1].

According to Cooke [5], there are, at least, three categories of users of reliability databases and all of them need different types of data:

- Risk and reliability analysts for analyzing and predicting a reliability of complex systems;
- Maintenance engineers for measuring and optimizing the maintenance performance;
- Component designers for analyzing and optimizing the component performance.

The systematic collection of reliability-data dates from the Titan Missile program [6]. Since the 1980s there have been many attempts to provide systems for collecting and organizing raw data, and to standardize the information presented in the data banks. But these efforts have been partial and focused on some particular industrial areas. Besides, there is a lack of accurate data, leading to suboptimal parameter estimates and inaccurate decisions about replacement intervals and preventive maintenance activities [2].

According to the study presented by Cunha [8] certain aspects with negative impact in the performance of production planning task are identified and its integration with other productive tasks is discussed. Also, studies carried out by Duarte [11] provide a basis to conclude, albeit empirically, that the information related to equipment busy and idle times recorded by independent production and maintenance planning systems may be substantially different. Only a system that records these data in a unified and coherent way will allow the calculation of appropriate estimations of the most important reliability parameters, such as the distribution of failure rate, mean time between failures (MTBF) and mean time to repair (MTTR). From another point of view, the integration of all this information will allow that priorities and therefore ranking of different productive services – production operations and maintenance services - may be defined in an integrated overall way. In practice, this means that as long as the reliability of a piece of equipment is decreasing, the degree of priority of the maintenance action required to restore it to its functional state, increases. This leads to a situation where maintenance operations acquire a priority status against production. The importance of such a policy is undeniable because only in this way is it possible to ensure realistic availability of equipment. In this way it is closed one of the information loops of this system.

In our perspective, the construction of a reliability and maintenance database demands a collaborative effort from the OEM, the customers, e.g. the equipment owners, and the independent maintenance providers. These three agents are the vertices of a collaborative triangle that must be built to increase efficiency of production systems, and in particular through a dynamic planning of maintenance operations. *Figure 13* ilustrastes this perspective.

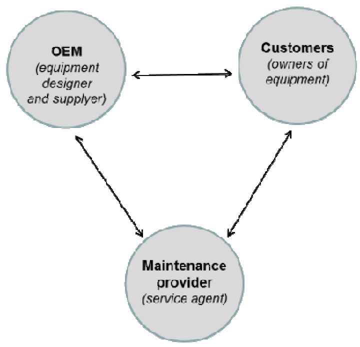


Figure 13: The collaborative triangle for maintenance efficiency

The appearance of e-technologies allows the integration and the process of data generate, by several sources, contributing in this way for the construction of such a database. Once filled with data the database must be complemented by a set of tools that can compute or estimates the reliability and maintenance parameters. These tools should also be able to make diagnosis, prognosis and schedules for maintenance activities. Therefore they should be considered an important element in a support decision management system. *Figure 14* is a schematic diagram of what we have just said.

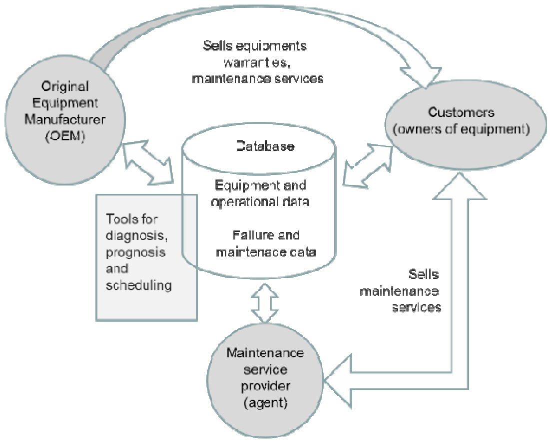


Figure 14. Maintenance Database collects specific information and is a supplier of processed information.

9. Conclusions and future research directions

This paper proposes a global model for maintenance management based on the reliability theory and other statistical techniques. Simple models were developed to support maintenance management. First of all it should be compute the target for availability that satisfy plant requirement at the minimum cost. Then, optimization of the maintenance plan for the components of system should be done.

A simple algorithm has been presented to determine a new schedule for preventive maintenance actions when routine inspections detect equipment in a good state. With this methodology it is possible to increase the length of the interval between two consecutive preventive maintenance actions. This leads to more cost-effective maintenance by reducing unnecessary repairs, overhauls, and replacements.

Forecasting techniques were used to predict values of MTBF and of condition monitoring parameters.

Prototypes are being developed and applied to industrial cases.

Lots of work must be done and several challenging problems in various maintenance areas require further attention and research including:

- Condition monitoring and condition-based maintenance.
- Inventory and maintenance models.
- Integrated models.
- Maintenance scheduling.
- Maintenance database.
- Bridging the gap between theory and practice through intelligent maintenance optimization systems.

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