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Preventive maintenance optimization based on both cost and availability measures. A case study

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Abstract

An optimal maintenance policy aims at improving the overall reliability, preventing system failures and reducing maintenance costs. The usual criteria on optimization policies are based on maintenance cost measures only; a small portion of maintenance models is based on reliability measures only. In this paper we use both maintenance cost and availability measures to obtain global optimal maintenance policy. On the other hand, the basic assumptions on maintenance efficiency are known as minimal repair (ABAO) and perfect maintenance (AGAN). The more realistic assumption is the imperfect maintenance which brings the system to somewhere between the two extreme situations. In this paper, we have used the quasi-renewal process to model the maintenance efficiency across the general assumption of imperfect maintenance.

This approach is considered to handle the maintenance management of a repairable system, which receives periodic overhauls, minimal repair at failure and a complete renewal after n overhauls. The optimization problem aims to obtain the preventive maintenance interval (T) which maximizes the system availability with respect to a budget constraint, and then the decision variables are n and s.

The approach is applied to optimize the preventive maintenance of an RTG (Rubber Tired Gantry) located at the container terminal of Bejaia harbor (BMT: Bejaia Mediterranean Terminal, Algeria). All the operations of loading and unloading are insured by the RTG, so it is vital for BMT. The RTG is constituted by four subsystems, an optimal maintenance plan is defined individually for each subsystem, and then we have introduced a rule for the rearrangement of maintenance instants to create occasions to joint maintenance actions. A maintenance plan for the whole system is obtained. The results showed that the availability can be improved by 6%.

Keywords – Imperfect maintenance, Quasi-renewal Process, Repairable system, Asymptotic availability, Cost rate.

1. Introduction

The growing trend of globalization and concentration of the economy determined major changes in the flow of raw materials and finished products in the world. Containerized merchandise continue to grow, so the main container terminals in the world are seeking to upgrade their technologies and management models to meet the demands and changes in the company of the future (Just-in-time, electronic data exchange, traceability, etc.). The performance of a container terminal is measured by stopover duration, the operations speed, the service quality and the cost of container transit. These factors are closely conditioned by a good performance of equipments; the performance of equipment depends on how fast it can resume operation after a system failure or breakdown. Companies can achieve this objective by using suitable and planned maintenance activities.

An effective maintenance management requires using optimization procedures, permitting to consider several criteria evolving contradictorily. Indeed an optimal maintenance policy aims at improving the overall reliability, preventing system failures and reducing maintenance costs. The usual criteria on optimization policies are based on maintenance cost measures only, such as the expected cost per unit time and total discounted costs [1], [2]. A small portion of maintenance models is based on reliability measures only, such as availability and average up time [3]. On the other hand, the basic assumptions on maintenance efficiency are known as minimal repair (ABAO) and perfect maintenance (AGAN). In the ABAO case, each repair leaves the system in the same state as it was before failure. In the AGAN case, each maintenance action restores the system to its new state. The more realistic assumption is the imperfect maintenance which brings the system to somewhere between the two extreme situations [4], [5], [6], [7].

In this paper, we have used the quasi-renewal process to model the maintenance efficiency across the general assumption of imperfect maintenance. On the other hand, we choose two criteria, namely availability and cost, to find the optimal overhaul interval s and number n. Both criteria are used simultaneously; in other words the model is used to determine the optimal couple (s^*, n^*) which maximizes the availability of the equipment with a cost (budget) constraint. The approach is applied to optimize the preventive maintenance of an RTG (Rubber Tired Gantry) located at the container terminal of Bejaia harbor (BMT: Bejaia Mediterranean Terminal, Algeria). The results showed that the availability can be improved by 6%.

2. Problem definition and hypothesis

A. Description of the maintenance policy

Let us consider the following maintenance policy; the system undergoes a PM (preventive maintenance) which is considered as an overhaul, it consists to replace certain components at the end of each time interval s. The failures are corrected by minimal repair to bring the system back to operating state without affecting its failure rate. After a certain number *n* of overhauls, the system receives a complete renewal which brings the system to the as good as new state; the cycle is repeated over an infinite time horizon. The proposed maintenance strategy is defined by the couple of decision variables *(s, n)*, our goal is to obtain the optimal couple (*s**, *n**) which maximizes the system availability with a budget constraint.

B. Maintenance model

B.1. Notations

$\lambda(t)$: Initial failure rate of the system (before any PM);

$\hat{\lambda}(t)$: Actual failure rate of the system after PM (partial renewals);

$H(t)=\int_0^t \lambda(x)dx$: Initial expected number of failures in the interval [0, *t*);

$\hat{H}(t)=\int_0^t \hat{\lambda}(x)dx$: Actual expected number of failures in the interval [0, *t*);

s: Overhaul (PM) interval;
n: Number of overhauls in a renewal cycle;
p: the improvement factor of the system ; $q=1-p$;
C_c, C_p, C_r : Cost of minimal repair, PM and renewal respectively;
T_c, T_p, T_r : Downtime of minimal repair, PM and renewal respectively;
$A(n,s)$: Availability function of the system;
$C(n,s)$: The expected unit-time cost when the system receives $n-1$ overhauls (Imperfect PM) with interval *s* in a renewal cycle;
B: Threshold value of unit-time cost of the system (Budget constraint).

B.2. Hypothesis

- An overhaul (PM) improves the system with a fixed degree *p*;
- Failure distribution is IFR (Increasing Failure Rate);
- All the renewal cycles have the same length *ns*;
- C_c, C_p, C_r, *p*, $\lambda(t)$ and $H(t)$ are known; $C_r \succ C_p \succ 0$ and $C_r \succ C_c \succ 0$; $p \prec 1$.

B.3. Problem formulation

Basing on Zhang & Jardine model [1] we used the steady availability as an objective function to be maximized with a budget constraint formulated as: the cost per unit of time must not exceed a predefined threshold, so the problem can be formulated as:

$$\begin{aligned} & Max\ A(n,s) \\ Subject\ to\ & \\ & C(n,s) \le B \end{aligned} \quad (1)$$

The system availability function is given by:

$$A(n,s) = 1 - \frac{Downtime}{Downtime + Uptime} \quad (2)$$

The downtime of the system is given by: $T_r + (n-1)T_p + \hat{H}(ns)T_c$
The uptime of the system is given by: ns
If we introduce this in equation (2) we obtain:

$$A(n,s) = 1 - \frac{T_r + (n-1)T_p + \hat{H}(ns)T_c}{ns + T_r + (n-1)T_p + \hat{H}(ns)T_c} = \frac{ns}{ns + T_r + (n-1)T_p + \hat{H}(ns)T_c} \quad (3)$$

The expected unit-time cost is given by:

$$C(n,s) = \frac{C_r + (n-1)C_p + \hat{H}(ns)C_c}{ns} \quad (4)$$

Where

$$\hat{H}(ns) = \sum_{i=0}^{n} \binom{n}{i} p^{n-1} q^{i-1} H(is) \quad (5)$$

For the Weibull case, the failure rate function is given by:

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \text{ with } \beta \succ 1 \quad (6)$$

By introducing this in equation (5), we obtain:

$$\hat{H}(ns) = \left(\frac{s}{\eta}\right)^{\beta} \sum_{i=0}^{n} \binom{n}{i} p^{n-1} q^{i-1} i^{\beta} \quad (7)$$

C. Solution procedure

The optimization can be achieved according to the following procedure; first, estimate a range in which the optimal time interval of overhauls (PM) is located, then find *s*, *n* that maximizes $A(n,s)$ for each fixed *s* within that range, and finally select *s* within that range and *s, n* such that $A(n,s)$ is maximized.

In this first step many couples (*n*, *s*) lead to same availability, thus, in a second step, a simple rule is introduced to select the optimum couple: The optimum couple is that which gives a minimum maintenance costs.

3. Application (the case study)

A. Studied case

The described approach is applied to a rubber tired gantry (RTG), located at the container terminal of Bejaia harbor. It is essentially constituted by: the hoist subsystem, the translation subsystem on wheels, the turning subsystem and the generator. The above model is used to obtain the optimum time interval and the number for overhauls for each subsystem, and then a simple rule is introduced to coordinate maintenance actions. Thus when the system is shutdown to receive preventive maintenance (overhauls), we include maximum actions for several subsystems, thus the system availability will be less penalized, and savings on the maintenance costs will be achieved, in particular the set-up cost.

B. Failure data collection and analysis

The data available at the Bejaia container terminal site are the failure dates of the RTG, the subsystem (or component) inducing failure, the preventive maintenance dates and the maintenance durations. The first analysis consists in extracting the times to failure for each subsystem in order to constitute the samples, the times to preventive replacement are considered as censored data; so the data sample includes failures and censored data. The samples are then fitted by two-parameter Weibull model (expression 6), this model was chosen because it adjusts well to mechanical components, and it allows describing alternately the three phases of the component life (early-life, mid-life, and wear-out). The Weibull parameter estimation is obtained by the "Statistica" software (Table 1), which uses the maximum likelihood method, and allows us to deal with censored samples.

Table 1: Weibull parameters of the subsystems

	β	η
Hoist subsystem	1.9	6848.2
Translation subsystem	1.4	6468.1
Turning subsystem	1.6	6471.1
Generator subsystem	3	7986.0

C. Cost data

The maintenance cost assessment is a very hard and complex task, as it depends on many parameters. Therefore, we have to use some simplifying assumptions and criteria to provide approximations close to the real costs, that is why the mean costs are often used. The subsystem preventive cost includes the spare part and labor costs; the corrective one includes the spare part, the labor, the production loss, and other fees. The time unit budget constraint (B) as recommended by BMT Company represents 60 % of a new subsystem cost divided by the number of operation hours before a complete renewal. Table (2) summarizes these costs.

Table 2: Cost data

Subsystem	**Corrective cost** C_c **[€]**	**Preventive cost** C_p **[€]**	**Renewal cost** C_r **[€]**	**Budget constraint** B **[€/*h*]**
Hoist subsystem	155.73	4612.74	200558.72	12.00
Translation subsystem	172.86	8221.62	100606.00	4.06
Turning subsystem	137.68	4830.35	80484.80	4.06
Generator subsystem	210.91	2100.34	31184.85	1.25

4. Optimization results

A. Individual (subsystems) optimization

As a first step, the policy based on separate subsystems is considered to obtain optimal numbers and time intervals for individual subsystems. The expected cost is computed for each subsystem, independently, and a one-by-one optimization is applied. Table 3 gives the optimal solutions for individual subsystems.

Table 3: optimization results for the hoist subsystem

n*	***s**** **(hour)**	***A*** **(%)**	***C*** **(€/hour)**
2	*28003.2*	*99.86*	*8.030*
4	14553.3	99.85	7.946
5	11820.0	99.85	8.030
7	*9178.10*	*99.86*	*7.530*
9	7054.30	99.85	7.867
10	3808.10	99.65	8.029
11	*5995.00*	*99.86*	*7.813*
14	5083.30	99.84	7.540

As we can see, several optimal couples (n^*, s^*) obtained, lead to the same maximum availability (99.86 %); thus we choose the couple which leads to the minimum time unit cost. For the hoist subsystem, the optimum solution is (n^*=7; s^*= 9178.10). Table 4 summarizes the final individual optimums for all subsystems.

Table 4: Individual subsystems optimization

Subsystem	n^*	s^* **(hour)**	***A*** **(%)**	***C*** **(€/hour)**
Hoist subsystem	7	9178.10	99.86	7.53
Translation subsystem	16	3386.00	99.78	1.88
Turning subsystem	18	3141.30	99.81	1.57
Generator subsystem	23	4376.70	99.80	0.78

If we consider a system constituted by n independent components ranged in series, its availability is given by: $A_s = \prod_{i=1}^{n} A_i$. In our case if the RTG subsystems are independent, the optimization solution lead to an availability of 99.25 %. Knowing that the current RTG availability is 93.59 %, we can see that the availability improvement is about 6 %.

B. System optimization

In a series system, the one-by-one overhaul of subsystems improves the global system reliability on the account of its availability, which would be largely penalized, because of frequent shutdowns for maintenance on different subsystems. For multi-component systems, an optimal maintenance policy must take into account the interactions between the various components of the system, especially the economic dependence. Thus we have introduced a simple rule permitting to coordinate the maintenance operations; it consists to rearrange the individual optimums in such a way that all subsystems overhaul instants become divisible by an even integer to allow for joint maintenance actions. In the other hand we have rearranged the subsystems renewal cycles to permit joint renewals and to create an occasion to renewal all subsystems simultaneously, which can be considered as an overall system renewal. Of course it may be more convenient to use multi-component optimization procedures to provide more efficient maintenance plan, more details in this topic can be found for example in [2], [8], [9].

Table 5 gives the coordination of subsystems renewal, then the couples (n^*, s^*) are readjusted with respect to the new renewal cycles and to coordinate also the overhauls, in such a way to permit many subsystems overhaul at the same occasion (table 6).

Table 5: Coordination of the subsystems renewal

Subsystem	n^*	s^* **(hour)**	$n^* s^*$ **(hour)**	$n^* s^*$ **(year)**	***Cycle length* (year)**
Hoist subsystem	7	9178.10	64246.7	10.75	12
Translation subsystem	16	3386.00	54176.0	9.07	8
Turning subsystem	18	3141.30	56543.4	9.46	8
Generator subsystem	23	4376.70	100664.1	16.84	16

Table 5 shows that the hoist subsystem undergoes a renewal every 12 years, the translation and the turning subsystems every 8 years, and finally the generator subsystem every 16 years. The least common multiple of these numbers is 48, so the overall system will be completely renewed after 48 years (288 000 hours) of operation, which corresponds to a lifetime of 63 years, knowing that the RTG is used for 6000 hours per year, this seems to be reasonable regarding our system (RTG).

Table 6 gives the new optimums couples (*n**, *s**) after readjustment to permit coordination of subsystems overhauls and their renewal. We can see that the overhaul interval is reduced, in reasonable proportion, for all subsystems, this may lead to an additional preventive maintenance cost but in the same time it leads to less corrective maintenance cost.

Table 6: Optimal solutions after coordination of overhauls and renewals

Subsystem	***n****	***s****	**Cycle length (hour)**	**Cycle length (year)**
Hoist subsystem	8	9000	72000	12
Translation subsystem	16	3000	48000	8
Turning subsystem	16	3000	48000	8
Generator subsystem	24	4000	96000	16

The rearrangement leads to a system availability of 99.73 %, the improvement is clearly proven.

5. Conclusion

As in series multi-component systems, the shutdown of any subsystem leads to the overall system, and the production losses are very high. Therefore, the maintenance optimization has the potential for substantially reducing the operating costs and for increasing corporate profit by increasing availability and production. When considering only the availability to maximize, the maintenance plan could be too expensive. To provide an effective maintenance plan, it is more convenient to consider both availability and cost measures. The proposed approach is based on the analysis of individual subsystems, according to the periodic overhauls (imperfect preventive maintenance) with minimal repair at failure policy. The model provided considers both availability and cost measures, the availability as an objective function and the time-unit cost as a constraint (Budget constraint). A simple rule has permitted us to rearrange the optimal individual overhaul intervals in such a way to allow for joint maintenance operations. The application to a real world system (RTG) shows the effectiveness of the approach in the performance improvement.

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