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Integrating Reliability-Centered Maintenance with Cost Optimization & Application in Plant of Hard Chrome Plating

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Abstract

This paper describes the application of reliability-centered maintenance (RCM) methodology and cost optimization to the development of maintenance & cost management for the plant of Hard Chrome Plating. The main objective of reliability-centered maintenance and cost optimization is the effective maintenance & cost management of the plant components inherent reliability value. Consequently, this research aims to manage the costs necessary to extend the service life of a plant through the use of probabilistic methods and simulation techniques in order to better identify the importance of every components in a plant with respect to maintenance costs. As a result of this research, our costing model allows to develop a methodology to determine maintenance costs which must be applied to some subsets of the elements of a plant, grouped according to their criticality and to identify the gap of costs between the true solution and the optimal maintenance interval.

Key words: *RCM, Maintenance Planning, FMEA, Cost Optimization*

1. INTRODUCTION

Cost minimization has been always the traditional objective in maintenance planning; over the years, maintenance has been very often undervalued because of the strong business-oriented vision of firms managers who payed attention on production rather than on maintenance. Afterwards, the real advantages offered by the application of maintenance techniques have been understood giving them the right collocation inside the firm management. The present paper shows a costing model to manage maintenance costs and improves it introducing simulation techniques to diversify the importance of the components of a plant by classifying their criticality with respect to maintenance costs.

Reliability Centered Maintenance (RCM) is a corporate level maintenance strategy that is implemented to optimize the maintenance program of a company or facility. The final results of an RCM program are the maintenance strategies that should be implemented on each of the assets of the facility. The maintenance strategies are optimized so that the functionality of the plant is maintained using cost-effective maintenance techniques.

Equipment reliability and availability, achieved by minimizing the probability of system failure is the focus of Reliability Centered Maintenance (RCM). With this maintenance strategy, the function of the equipment is considered and possible failure modes and their consequences are identified. Maintenance techniques that are cost-effective in minimizing the possibility of failure are then determined. The most effective techniques are then adopted to improve the reliability of the facility as a whole.

2. LITERATURE REVIEWS

Cost minimization has been the traditional objective in maintenance planning. Deterministic models [16] on preventive maintenance optimization have established minima in costs based on operating cost parameters (repair, maintenance and acquisition). The use of deterministic methods, however, does not provide information about potential risk that results in nonoptimal maintenance planning for process plants [19]. Probabilistic models, on the other hand, use probability distributions to describe and represent natural variability and uncertainty in parameter, model and scenario [20]. Probabilistic models of scheduling preventive maintenance also minimize objective functions that reflect repair, replacement and preventive maintenance costs [22]. The preventive maintenance interval is optimized when the increasing rate of corrective maintenance costs (with respect to time) equals the decreasing rate of preventive maintenance costs.

In conducting this type of analysis, some important maintenance parameters must be considered: in general terms, it is possible to state that the main goal of a maintenance plan is to improve the availability of a production line. By defining up-time as the functioning time of the line and down-time as the off-duty time of the line due to a failure, the availability can be defined as the ratio between the up time and the sum of up-time and down-time. To improve this performance, one of the possible chance is to reduce the Mean Time Waiting for Spares (MTWS), i.e. the time necessary to wait for a spare when a substitution operation occurs.

The classical model dealing with the maintenance costs defines the management procedure by which the i-th component is substituted when it reaches a critical age; this time is defined, in the case of electromechanical components, by the number of utilization hours with respect to the service life, or life expectancy of its design. The substitution period, defined as tc, is considered with respect to the last intervention of preventive or corrective maintenance independently. By defining ETTC(t_c) the average expected life for a component in the period t_c as the equation (1).

$$ETTF(t_c) = \int_0^{t_c} R(x)\,dx \qquad (1)$$

Where R(x) is the reliability function of the component.

The total cost between two maintenance interventions can be so evaluated as the sum of the cost related to a planned and to an unplanned intervention because of a failure of the component; each of those is weighted with its probability represented by the reliability and unreliability functions respectively. So, the total provisioning cost per time unit is the equation (2).

$$E(C_i) = \frac{E(C_{pi}).R_i(t_c) + E(C_{ui}).[1 - R_i(t_c)]}{\int_0^{t_c} R(x)\,dx} \qquad (2)$$

where:

E(C_i) is the total expected cost of planned maintenance per time unit related to the i-th component;

E(C_{pi}) is the expected cost of a planned and preventive intervention for the i-th component;

E(C_{ui}) is the expected cost of an unplanned intervention due to a failure for the i-th component;

Ri(t) is the cumulative distribution function of the reliability of the i-th component.

By deriving the cost function with respect to t_c time and setting to zero its first derivative, it is possible to evaluate the minimum of this equation (3) obtaining the optimal maintenance time which minimize the total costs:

$$\frac{d[E(C_i)]}{dt_c} = 0 \qquad (3)$$

This work aims to generate a maintenance program that based on the RCM technique for the process-steam plant components. This technique should be able to minimize the downtime (DT) and improve the availability of the plant components. Also, it should benefits to decrease the spare parts consumption system components. RCM is a systematic approach to determine the maintenance requirements of plant and equipment in its operating [1]. It is used to optimize preventive maintenance (PM) strategies.

The developed PM programs minimize equipment failures and provide industrial plants with effective equipment [2]. RCM is one of the best known and most used devices to preserve the operational efficiency of the steam system. RCM operates by balancing the high corrective maintenance costs with the cost of programmed (preventive or predictive) polices, taking into account the potential shortening of “useful life” of the item considered. But it is difficult to select suitable maintenance strategy for each piece of equipment and each failure mode, for the great quantity of equipment and uncertain factors of maintenance strategy decision [3,4]. RCM philosophy employs preventive maintenance, predictive maintenance (PdM), real-time monitoring (RTM), run-to-failure (RTF) and proactive maintenance techniques is an integrated manner to increase the probability that a machine or component will function in the required manner over its design life cycle with a minimum of maintenance [5,6].

3. METHODOLOGY

3.1 **Our Case Study**

With more than 30 years of expertise, Rojekolakarn & Machinery Co.,Ltd. has been providing the plant of Hard Chrome Plating, Surface Hardening, Grinding, and also Turning to a broad range of customers’ needs including mold and die makers, hydraulic systems rebuilders, plastic injection machine owners, and all types of machinery manufacturers in Figure 1 and 2. All process is performed in-house which offers the ultimate in control. The services of the plant give them a competitive advantage in their business.

Figure 1. Sample products in the plant

Figure 2. Hard Chrome Plating Machine

3.2 **RCM Steps**

The RCM steps are presented. The steps describe the systematic approach used to implement the preserves the system function, identifies failure mode, priorities failure used to implement the preserves the system function, identifies failure mode, priorities failure modes and performs PM tasks. The RCM steps are as follows [8]:

Step1: system selection and data collection

Step2: system boundary definition

Step3: system description and functional block

Step4: system function functional failures

Step5 : failure mode effect analysis

Step6: logic tree diagram

Step7: task selection.

3.3 **Criticality Analysis**

Criticality analysis is a tool used to evaluate how equipment failures impact organizational performance in order to systematically rank plant assets for the purpose of work prioritization, material classification, PM/PdM development and reliability improvement initiatives [9]. In general, failure modes, effects and criticality analysis (FMEA/FMECA) required the identification of the following basic information in Table 1. Criticality of each machine (MC) was calculated based on the following four criteria:

1. Effect of the machine downtime on the production process (EM)
2. Utilization rate of the machine (Bottleneck or not) (UR)
3. Safety and environmental incidence of machine failure (SEI)
4. Technical complexity of the machine and need of external maintenance resources (MTC).

Each of the criteria was given a weight showing its importance relative to the criticality indices. The weight of each criterion ranges from zero (no effect) to three (very important effect). Machine criticality was then calculated in the equation (4) and criticality codes such as A (most critical machine): 20 to 27, B: 12 to 19, C: 0 to 11.

$$MC = 3*EM + 2*UR + 3*SEI + I*MTC \quad (4)$$

Table 1. Sample of some values of machine criticality

Part No.	Weight	3	3	2	1	MC	Criticality Code
	Machine Code	SEI	EM	UR	MCT		
1	Carrier Body	3	3	2	3	26	A
2	Motor 1	2	3	3	2	23	A
3	Spur Gear 1	1	1	2	1	11	C
4	Spur Gear 2	1	1	2	1	11	C
5	End Cap 1	1	1	2	1	11	C
6	Collar 1	1	1	2	1	11	C
7	Y-Bearing 1	1	2	2	1	14	B
8	Y-Bearing 2	1	2	2	1	14	B

3.4 **Failure Mode Effects Analysis (FMEA)**

Failure modes and effects analysis (FMEA) is a step-by-step approach for identifying all possible failures in a design, a manufacturing or assembly process, or a product or service.

This is the severity rating, or S. Severity is usually rated on a scale from 1 to 10, where 1 is insignificant and 10 is catastrophic. If a failure mode has more than one effect, write on the FMEA table only the highest severity rating for that failure mode.

For each cause, determine the occurrence rating, or O. This rating estimates the probability of failure occurring for that reason during the lifetime of your scope. Occurrence is usually rated on a scale from 1 to 10, where 1 is extremely unlikely and 10 is inevitable. On the FMEA table, list the occurrence rating for each cause.

For each control, determine the detection rating, or D. This rating estimates how well the controls can detect either the cause or its failure mode after they have happened but before the customer is affected. Detection is usually rated on a scale from 1 to 10, where 1 means the control is absolutely certain to detect the problem and 10 means the control is certain not to detect the problem (or no control exists). On the FMEA table, list the detection rating for each cause.

The risk priority number, or RPN was then calculated in the equation (5).

$$RPN = (S) \times (O) \times (D) \quad (5)$$

Risk Evaluation such as Small Risk: RPN < 60, Medium Risk: RPN < 80 and High Risk: RPN <100 and Crisis Risk: RPN > 100, then we should consider the RPN of components with the highest value first.

3.5 **Maintenance Assessment of Reliability Engineering**

We applied Maintenance Assessment of Reliability Engineering to calculate the probability on the parameters of reliability. First, we collected the data of Time To Fail: TTF to support calculating parameters in Table 2.

Table 2. Sample of the data of Time To Fail: TTF (unit: week)

No.	Machine Code	Time To Failure : TTF (unit: week)									
		1	2	3	4	5	6	7	8	9	10
1	Carrier Body	16	40	47	64	78	140	162			
2	Motor 1	8	26	62	74	77	86	90	132	150	
3	Motor 2	13	17	29	60	95	123	143			
4	Bracket	14	15	26	74	81	121	125	150		
5	Bracket Buffer	12	14	26	81	83	122	125	147		
6	Limit Switch 1	22	74	99	132	151					
7	Photo Electric Switch 1	24	50	78	105	115					
8	Photo Electric Switch 2	20	38	57	85	103	132				
9	Photo Electric Switch 3	22	46	58	95	115	124				
10	Limit Switch 2	24	75	102	137	153					
11	Proximity	7	27	60	76	87	95	103	123	131	152

After that, we adopted Reliability Engineering for the calculation by using graph probability (Probability

Plotting) with Statistical Software in Figure 3 to estimate the parameters.

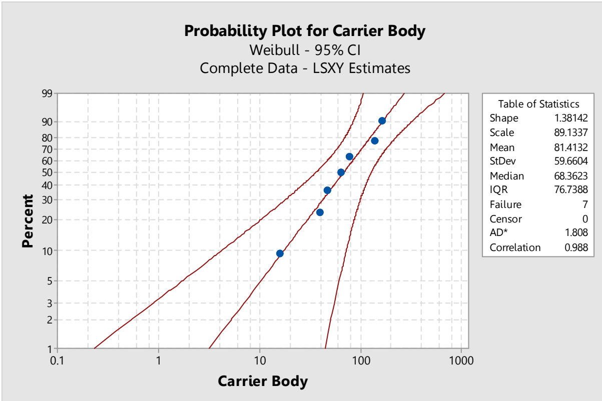


Figure 3. Sample of Probability Plotting with Statistical Software (Source: Minitab Inc., Minitab 17 trial version [Online], accessed 26 August 2014. Available from http://www.minitab.com)

In addition, we tested conditions about Goodness of Fit Test to confirm that a hypothesized distribution fits a data set by Kolmogorov-Smirnov Test for the small population using the equation (6)-(9). Then we created Excel Simulation to calculate the equation (6)-(9) in Figure 4 and the results on Goodness of Fit are summarized in Table 3.

Statistical Hypothesis:

H_0: TTF Data is Weibull distribution with β (Sharpe) and η (Scale)

H_1: TTF Data isn't Weibull distribution with β (Sharpe) and η (Scale)

Test Statistics by Kolmogorov-Smirnov Test :

$$d = \max\{|F(t_i) - \hat{F}(t_i)|, |F(t_i) - \hat{F}(t_{i-1})|\} \quad (6)$$

$$F(t_i) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (7)$$

$\hat{F}(t_i) =$ Opportunity of Breakdown (8)

d_α = Critical Values of Komogorov-Smirnov Tests (9)

Decision criteria on Significance level (α): Acceptd H_0 if $d < d_\alpha$

	A	B	C	D	E	F	G	H	I	J	K	L	M
2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	16	89.1337	0.1795	1.38142	0.0932	2.7182	1.09771	0.9110	0.0890	0.09428	0.0053		0.0053
4	40	89.1337	0.4488	1.38142	0.3306	2.7182	1.39178	0.7185	0.2815	0.22849	0.0530	0.1872	0.1872
5	47	89.1337	0.5273	1.38142	0.4131	2.7182	1.51146	0.6616	0.3384	0.36412	0.0257	0.1099	0.1099
6	64	89.1337	0.7180	1.38142	0.6328	2.7182	1.88285	0.5311	0.4689	0.50000	0.0311	0.1048	0.1048
7	78	89.1337	0.8751	1.38142	0.8317	2.7182	2.29710	0.4353	0.5647	0.63588	0.0712	0.0647	0.0712
8	140	89.1337	1.5707	1.38142	1.8659	2.7182	6.46116	0.1548	0.8452	0.77151	0.0737	0.2093	0.2093
9	162	89.1337	1.8175	1.38142	2.2827	2.7182	9.80220	0.1020	0.8980	0.95720	0.0592	0.1265	0.1265
10												max d =	0.2093

Figure 4. Excel Simulation to calculate the equation (6)-(9)

Table 3. Sample of the summarized results on Goodness of Fit

No.	Machine Code	Parameters		K-S Test (α = 0.05, n)			Hypothesis Test
		β	η	max d	d_α	n	
1	Carrier Body	1.38142	89.1337	0.2093	0.483	7	accepted H_0
2	Motor 1	1.27584	91.2374	0.2775	0.430	9	accepted H_0
3	Motor 2	1.14706	75.7195	0.2267	0.483	7	accepted H_0
4	Bracket	1.18000	83.7602	0.2580	0.454	8	accepted H_0
5	Bracket Buffer	1.12505	84.2839	0.2951	0.454	8	accepted H_0
6	Limit Switch 1	1.40548	112.993	00.2945	0.563	5	accepted H_0
7	Photo Electric Switch 1	1.64347	87.1670	0.2515	0.563	5	accepted H_0
8	Photo Electric Switch 2	1.51913	84.4034	0.2146	0.519	6	accepted H_0
9	Photo Electric Switch 3	1.62635	89.2101	0.2483	0.519	6	accepted H_0
10	Limit Switch 2	1.44917	115.923	0.2427	0.563	5	accepted H_0
11	Proxinity	1.27173	100.947	0.2433	0.409	10	accepted H_0

3.6 **Maintenance Period Analysis**

3.6.1 *If β ~ 1 : Constant Failure Mode regarded as Exponential Distribution.*

We applied the technique of Failure Finding by calculating the inspection interval in the equation (10) [13]. Also, we created Excel Simulation to calculate the equation (10) in Figure 5.

$$A = 1 - \frac{FFI}{2M} \quad (10)$$

A = Availability of the protective device
FFI = The inspection interval (t_i)
M = MTTF

	A	B	C	D	E
1			1. A of Carrier Body		
2	t_i	η	2M = 2η ; (if β~1)	t_i / 2M	A = 1 - (t_i / 2M)
3	1	89.1337	178.2674	0.005610	0.994390
4	2	89.1337	178.2674	0.011219	0.988781
5	3	89.1337	178.2674	0.016829	0.983171
6	4	89.1337	178.2674	0.022438	0.977562
7	5	89.1337	178.2674	0.028048	0.971952
8	6	89.1337	178.2674	0.033657	0.966343
9	7	89.1337	178.2674	0.039267	0.960733
10	8	89.1337	178.2674	0.044876	0.955124
11	9	89.1337	178.2674	0.050486	0.949514
12	10	89.1337	178.2674	0.056096	0.943904
13	11	89.1337	178.2674	0.061705	0.938295
14	12	89.1337	178.2674	0.067315	0.932685
15	13	89.1337	178.2674	0.072924	0.927076
16	14	89.1337	178.2674	0.078534	0.921466
17	15	89.1337	178.2674	0.084143	0.915857
18	16	89.1337	178.2674	0.089753	0.910247
19	17	89.1337	178.2674	0.095362	0.904638
20	18	89.1337	178.2674	0.100972	0.899028
21	19	89.1337	178.2674	0.106581	0.893419
22	20	89.1337	178.2674	0.112191	0.887809

Figure 5. Excel Simulation to calculate the equation (10)

3.6.2 *If β > 1 considered Increase Failure Mode.*

We applied the technique of Determination of Optimal Preventive Replacement Interval to determine the optimal replacement interval (t_p) between preventive replacements to minimize total downtime per unit time by calculating in the equation (11) and (12) [13]. So, we created Excel Simulation to calculate the equation (11) and (12) in Figure 6.

$$D(t_p) = \frac{H(t_p)\,T_f + T_p}{t_p + T_p} \quad (11)$$

$$H(t) = \frac{\beta}{\eta} \times \left[\frac{t}{\eta}\right]^{\beta - 1} \quad (12)$$

$D(t_p)$ = The total Downtime per unit time

$H(t_p)$ = The number of failures in interval (0, t_p)

T_p = The mean downtime required to make a failure replacement

T_f = The mean downtime required to make a preventive replacement

t_p = Preventive replacement at time

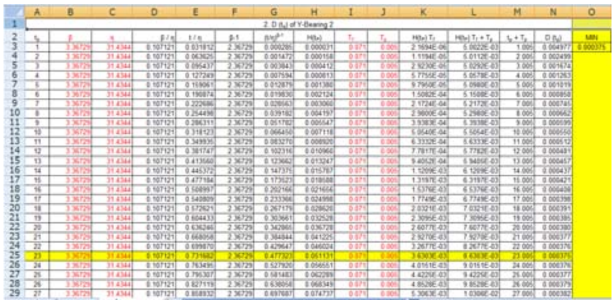


Figure 6. Excel Simulation to calculate the equation (11) and (12)

and the results on Assessment Guidelines for the maintenance of Reliability Engineering are summarized in Table 4.

Table 4. Sample of Assessment Guidelines in Maintenance & Reliability Engineering

No.	Machine Code	Parameters		Type of maintenance	Period of Maintenance (Week)
		β	η		
1	Y-Bearing 1	2.75330	30.2882	PdM	29
2	Y-Bearing 2	3.36729	31.4344	PdM	23
3	Set Collar 1	1.35107	99.0734	PM	39
4	Set Collar 2	1.55273	57.0060	PM	22
5	Hexagon Head Bolt 1	1.60266	63.0625	PM	25
6	Hexagon Head Bolt 2	1.46333	62.6294	PM	25
7	Hexagon Head Bolt 3	1.46505	63.4103	PM	25
8	Hexagon Head Bolt 4	1.62350	61.8738	PM	24
9	Hexagon Head Bolt 5	1.55235	62.7911	PM	25
10	Hexagon Head Bolt 6	1.57265	62.0271	PM	24

3.7 **Our Model for Cost Optimization**

The aim of the work is to develop a new equation representing the model to determine and optimize the maintenance costs which could be applied not only to the single component but to a set of components grouped in a particular way, i.e. to their criticality. At the same time, this new model allows to overcome some limits in the application of the classical one, when dealing with big dimensions plants. One of the problem is in fact due to the application of the classical model to a complex plant; the model forces to divided the plant by a very detailed tree-structure which is a very difficult task dealing with machines rich in components. Another problem is represented by the meaning of the integral in the denominator of the equation; it represents an estimate of the service life of a component over a fixed time interval which must be the same for every component. Its meaning is in fact the substitution period provided by the analysis of the data sheets of the component i.e. without considering the real use in the plant or for example without considering repairs whereas possible. So, the classical model does not take into account an historical study of all of the past conditions of the component to be analyzed, determining a loss of precision in the determination of the total maintenance costs and so providing a result in term of optimal maintenance interval which may be quite far from the true one.

As said, the proposed method tries to overcome these limits by a re-elaboration of the classical model; it introduces two important features represented by the possibility to apply the model to the whole machine and by the combination of the maintenance statistics of the firm and the probabilistic analysis about the components.

It is possible to manipulate the classical equation of maintenance costs to define a new model. As said, the classical equation (13) is as follows:

$$E(C_i) = \frac{E(C_{pi}).R_i(t_p) + E(C_{fi}).[1 - R_i(t_p)]}{\int_0^{t_p} R(x)\,dx} \tag{13}$$

The first step is to split this equation since it will be applied to a group of components rather than to a single one. Then, we need to define the equation (14) to (16).

$$E_A(C_A) = \sum_{i=1}^{N_A} E_{Ai}(C_{Ai}) \tag{14}$$

$$E_B(C_B) = \sum_{i=1}^{N_B} E_{Bi}(C_{Bi}) \tag{15}$$

$$E_C(C_C) = \sum_{i=1}^{N_C} E_{Ci}(C_{Ci}) \tag{16}$$

Where:

i is the single component belonging to a particular criticality class;

N_A, N_B and N_C are respectively the sum of all the components belonging to A,B and C criticality classes.

At the same way, Total E(C) must be redefined as the equation (17).

$$\text{Total } E(C) = E_A(C_A) + E_B(C_B) + E_C(C_C) \tag{17}$$

It is now possible to rewrite the equation as the equation (18).

$$\text{Total } E(C) = \sum_{i=1}^{N_A} E_{Ai}(C_{Ai}) + \sum_{i=1}^{N_B} E_{Bi}(C_{Bi}) + \sum_{i=1}^{N_C} E_{Ci}(C_{Ci}) \tag{18}$$

So it is necessary to find some reliability function R(t) which represents the average of the Ri(t) functions of every components on the equation (19) to (21).

$$R_{At}(t_{At}) = h_{At}(t_{At}) = e^{-\left(\frac{t_{At}}{\eta_{At}}\right)^{\beta_{At}}} \quad (19)$$

$$R_{Bt}(t_{Bt}) = h_{Bt}(t_{Bt}) = e^{-\left(\frac{t_{Bt}}{\eta_{Bt}}\right)^{\beta_{Bt}}} \quad (20)$$

$$R_{ct}(t_{ct}) = h_{ct}(t_{ct}) = e^{-\left(\frac{t_{ct}}{\eta_{ct}}\right)^{\beta_{ct}}} \quad (21)$$

Moreover, by substituting and putting in evidence, we are able to state $E_A(C_A)$, $E_B(C_B)$, and $E_C(C_C)$ on the equation (22) to (24).

$$E_A(C_A) = \sum_{i=1}^{N_A}\left\{\left[E(C_{pAt}).\left(e^{\left(\frac{t_{At}}{\eta_{At}}\right)^{\beta_{At}}}\right) + E(C_{uAt}).\left[1-\left(e^{\left(\frac{t_{At}}{\eta_{At}}\right)^{\beta_{At}}}\right)\right]\right].\left(\int_0^{t_{wAt}}\left(e^{\left(\frac{t_{At}}{\eta_{At}}\right)^{\beta_{At}}}\right)dt\right)\right\} \quad (22)$$

$$E_B(C_B) = \sum_{i=1}^{N_B}\left\{\left[E(C_{pBt}).\left(e^{-\left(\frac{t_{Bt}}{\eta_{Bt}}\right)^{\beta_{Bt}}}\right) + E(C_{uBt}).\left[1-\left(e^{-\left(\frac{t_{Bt}}{\eta_{Bt}}\right)^{\beta_{Bt}}}\right)\right]\right].\left(\int_0^{t_{wBt}}\left(e^{-\left(\frac{t_{Bt}}{\eta_{Bt}}\right)^{\beta_{Bt}}}\right)dt\right)\right\} \quad (23)$$

$$E_C(C_C) = \sum_{i=1}^{N_C}\left\{\left[E(C_{pCt}).\left(e^{-\left(\frac{t_{Ct}}{\eta_{Ct}}\right)^{\beta_{Ct}}}\right) + E(C_{uCt}).\left[1-\left(e^{-\left(\frac{t_{Ct}}{\eta_{Ct}}\right)^{\beta_{Ct}}}\right)\right]\right].\left(\int_0^{t_{wCt}}\left(e^{-\left(\frac{t_{Ct}}{\eta_{Ct}}\right)^{\beta_{Ct}}}\right)dt\right)\right\} \quad (24)$$

3.8 **Solving Techniques on Our Mathematical Problems**

We tried to solve mathematical problems of style in the eqution (25).

$$E(C_1) = \frac{E(C_{p1}).e^{-\left(\frac{t_a}{\eta}\right)^{\beta}} + E(C_{u1}).\left[1-e^{-\left(\frac{t_a}{\eta}\right)^{\beta}}\right]}{\int_0^{t_a}\left[e^{-\left(\frac{x}{\eta}\right)^{\beta}}\right]dx} \quad \textbf{(25)}$$

After that, we applied Numerical Methods for solving

$$\int_0^{t_a}\left[e^{-\left(\frac{x}{\eta}\right)^{\beta}}\right]dx.$$

Let $u = \left(\frac{x}{\eta}\right)^{\beta}$ and $x = \eta u^{\frac{1}{\beta}}$

$$dx = \frac{\eta}{\beta}u^{\left(\frac{1}{\beta}-1\right)}du$$

$$\int_0^{t_a} R(x)dx = \int_0^{t_a}\left[e^{-\left(\frac{x}{\eta}\right)^{\beta}}\right]dx = \int_0^{u_a}\left[(e^{-u})\left(\frac{\eta}{\beta}u^{\left(\frac{1}{\beta}-1\right)}\right)\right]du$$

$$= \left[\frac{\eta}{\beta}\right].\int_0^{u_a}\left[(e^{-u})\left(u^{\left(\frac{1}{\beta}-1\right)}\right)\right]du \quad ; \quad u_a = \left(\frac{t_a}{\eta}\right)^{\beta}$$

Accordingly, we used Gauss Integration (Gaussian quadratures) for solving $\int_0^{u_a}\left[(e^{-u})\left(u^{\left(\frac{1}{\beta}-1\right)}\right)\right]du$ in the following steps.

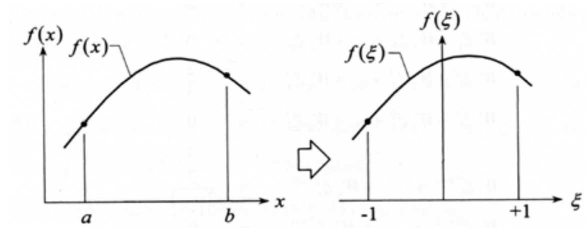


Figure 7. Converting coordinates from x to ξ

1. Converting coordinates from x to ξ before the integration by using Gauss Legendre formulas in Figure 7.
2. The Gaussian quadratures provide the flexibility of choosing not only the weighting coefficients (weight factors) but also the locations (abscissas) where the functions are evaluated. When the function is known and smooth, the Gaussian quadratures usually have decisive advantages in efficiency.
3. All Gaussian quadratures share the following the eqution (26).

$$\int_a^b f(x)dx = \sum_{k=1}^{n} w(x_k)\,f(x_k) + R_n(x) \quad (26)$$

Where:

x_k, associated with zeros of orthogonal polynomials, are the integration points.

$w(x)$ is the weighting function related to the orthogonal polynomials.

4. Gauss-Legendre Formula: The Gauss-Legendre integration formula is the most commonly used form of Gaussian quadratures in the eqution (27).

$$\int_a^b f(x)dx = \int_{-1}^{1} f\left(\frac{b-a}{2}\xi + \frac{b+a}{2}\right)\left[\frac{b-a}{2}d\xi\right]$$

$$= \frac{b-a}{2}\int_{-1}^{1} g(\xi)d\xi = \frac{b-a}{2}\sum_{k=1}^{n} w(\xi_k)g(\xi_k) + R_n(\xi)$$

$$= \frac{b-a}{2}\sum_{k=1}^{n} w(\xi_k)\,f\left(\frac{b-a}{2}\xi_k + \frac{b+a}{2}\right) + R_n(\xi) \quad (27)$$

Where:

$$\xi = \frac{2x-b-a}{b-a}, \text{ i.e., } \quad x = \frac{b-a}{2}\xi + \frac{b+a}{2}, -1 \le \xi \le 1,$$

ξ_k is the k^{th} zero of $P_n(\xi)$,

$$w(\xi_k) = \frac{2}{(1-\xi_k^{\,2})[P_n'(\xi_k)]^2},$$

$$g(\xi) = f\left(\frac{b-a}{2}\xi_k + \frac{b+a}{2}\right),$$

$$R_n(\xi) = \frac{2^{2n+1}(n!)^4}{(2n+1)\,[(2n)!]^3}\, g^{(2n)}(\xi),$$

5. Thus, we applied MATLAB & Excel about Gauss Integration for solving this model (E(C) in Figure 8 and The total expected cost of planned maintenance per time:Total E(C) in Figure 9.

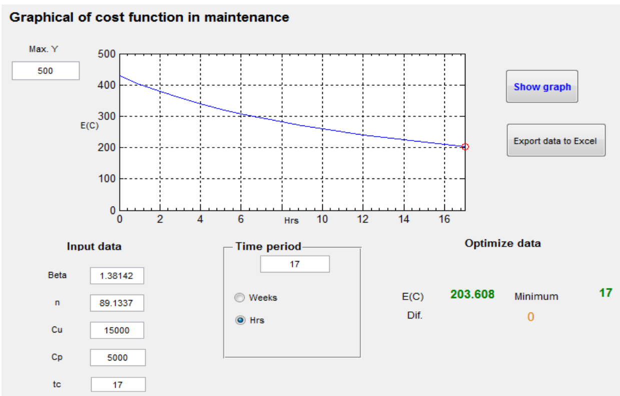
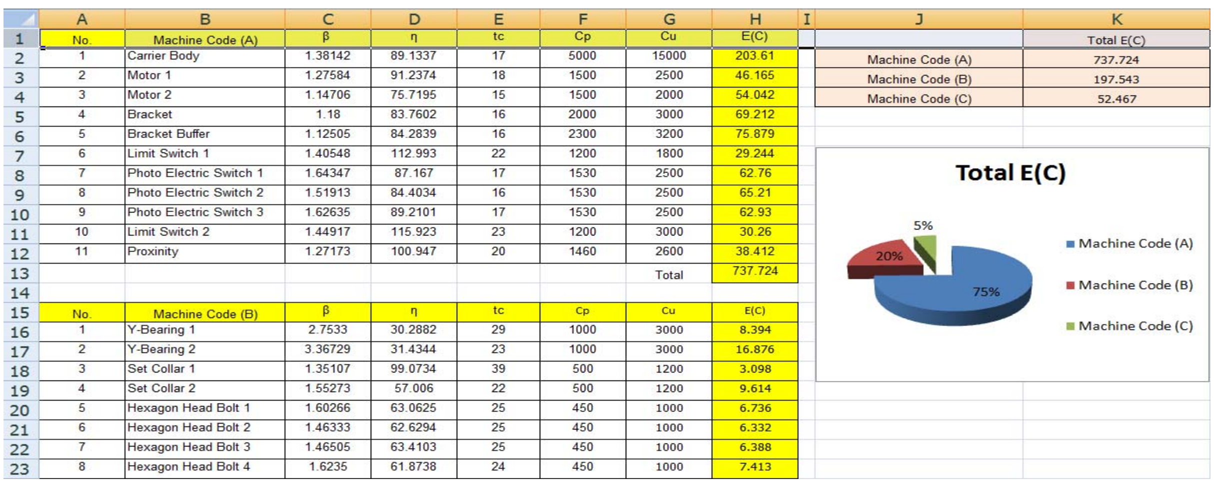


Figure 8. E(C) on Machine Code (A): Carrier Body

4. CASE STUDY RESULT

The model has been applied to the previous case study by the use of MATLAB & Excel software to generate simulation results. The analysis has been focused on the determination of the maintenance costs over a time period of 36 months. After the data history analysis of the treated components of the plant, it is possible to show that Total E(C) consisted of 75% of $E_A(C_A)$, 20% of $E_B(C_B)$, and 5% of $E_C(C_C)$ in the trend of the reliability function for each criticality class. It can be said that, in spite of their main criticality, the elements belonging to A class have higher mantenance costs; therefore, the elements belonging to C class have low mantenance costs on analyzing costs which together contribute to generate the total maintenance costs from planned and unplanned maintenance costs.



No.	Machine Code (A)	β	η	tc	Cp	Cu	E(C)
1	Carrier Body	1.38142	89.1337	17	5000	15000	203.61
2	Motor 1	1.27584	91.2374	18	1500	2500	46.165
3	Motor 2	1.14706	75.7195	15	1500	2000	54.042
4	Bracket	1.18	83.7602	16	2000	3000	69.212
5	Bracket Buffer	1.12505	84.2839	16	2300	3200	75.879
6	Limit Switch 1	1.40548	112.993	22	1200	1800	29.244
7	Photo Electric Switch 1	1.64347	87.167	17	1530	2500	62.76
8	Photo Electric Switch 2	1.51913	84.4034	16	1530	2500	65.21
9	Photo Electric Switch 3	1.62635	89.2101	17	1530	2500	62.93
10	Limit Switch 2	1.44917	115.923	23	1200	3000	30.26
11	Proximity	1.27173	100.947	20	1460	2600	38.412
						Total	737.724

No.	Machine Code (B)	β	η	tc	Cp	Cu	E(C)
1	Y-Bearing 1	2.7533	30.2882	29	1000	3000	8.394
2	Y-Bearing 2	3.36729	31.4344	23	1000	3000	16.876
3	Set Collar 1	1.35107	99.0734	39	500	1200	3.098
4	Set Collar 2	1.55273	57.006	22	500	1200	9.614
5	Hexagon Head Bolt 1	1.60266	63.0625	25	450	1000	6.736
6	Hexagon Head Bolt 2	1.46333	62.6294	25	450	1000	6.332
7	Hexagon Head Bolt 3	1.46505	63.4103	25	450	1000	6.388
8	Hexagon Head Bolt 4	1.6235	61.8738	24	450	1000	7.413

	Total E(C)
Machine Code (A)	737.724
Machine Code (B)	197.543
Machine Code (C)	52.467

Figure 9. Sample of Excel simulation to calculate Total E(C)

5. CONCLUSIONS

5.1 We can make a comprehensive analysis of maintenance strategy and reliability requirements throughout the lifecycle of maintenance. The model has been applied to the previous case study by the use of integrated Reliability Theory on Hazard Rate for optimal cost of maintenance with the number of components in a semi automatic machine of coating to generate suitable results. The analysis has been focused on the determination of the costs throughout the lifecycle of maintenance.

5.2 The present work focused on the definition of a model to manage the costs necessary to extend the service life of a plant through the use of probabilistic methods and Reliability Theory on Hazard Rate in order to better identify the importance of every components in a plant with respect to maintenance costs.

5.3 The new model is able to develop a methodology to determine maintenance costs which must be applied to some subsets of the elements of a plant, grouped according to their criticality.

5.4 The model allows also to overcome some limits of the classical model, providing a more precise determination of the costs. In fact, the previous data history of the components and the previous maintenance plans together with a probabilistic study are considered in the model to enhance the model to be more accurate.

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Integrisanje održavanja baziranog na pouzdanosti sa optimizacijom troškova i primenom u postrojenju za hromirane ploče

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Apstrakt

Ovaj rad opisuje primenu metodologije održavanja baziranog na pouzdanosti (RCM) i optimizacije troškova za razvijanje menadžmenta održavanja i troškova za postrojenje za hromirane ploče. Osnovni cilj optimizacije održavanja baziranog na pouzdanosti i optimizacije troškova je efikasan menadžment održavanja i troškova sopstvenih vrednosti pouzdanosti komponenti postrojenja. Kao posledica toga, ovo istraživanje teži da upravlja troškovima koji su neophodni za produženje životnog veka postrojenja putem upotrebe metoda verovatnoće i tehnika simulacije kako bi se bolje identifikovao značaj svake komponente u postrojenju, vodeći računa o troškovima održavanja. Kao rezultat ovog istraživanja, naš model troškova omogućava razvoj metodologije za određivanje troškova održavanja koji moraju da se primene na neke podskupove elemenata u postrojenju, grupisanih prema njihovoj kritičnosti, kao i da se identifikuje jaz troškova između pravog rešenja i optimalnog intervala održavanja.

Ključne reči: *RCM, planiranje održavanja, FMEA, optimizacija troškova*