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Optimal preventive maintenance interval model with time value of money consideration

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Abstract

The search for a plant maintenance strategy to mitigate the impact of random factory machine failures has never been more challenging. Apart from the harsh global competition, manufacturing facilities have become more sophisticated and expensive; frequent and prolonged breakdowns may ruin a firm's business. Consequently, many have turned to the Preventive Maintenance (PM) strategy for a solution. However, the efficacy of PM has been shown to depend on finding a maintenance time interval decision model capable of incorporating most of the relevant maintenance cost components. While past studies have considered maintenance system set-up, execution, and breakdown cost components, the literature is sparse on decision models incorporating the cost of borrowing money. Exploring the feasibility of developing such a model is the aim of this study. Accordingly, a maintenance-investment cost function was formulated in terms of PM time interval and plant reliability; a PM decision problem was then defined and solved as that of PM investment cost minimization. Using three cases from the literature, the optimal maintenance time intervals (238.11, 14695.28, and 2076.54), failure probabilities (0.71, 0.35, and 0.61), and costs for preventive maintenance (PM) (840950.87, 149352.55, and 33979.57) were found to be reasonable.

Keywords: Preventive Maintenance; Time Value of Money; Reliability; Maintenance Time Interval

1. Introduction

Rapid technological advances fueled by global competition have triggered a fresh desire for more effective maintenance strategies; production and service facilities have to be maintained for profitable operations. Over the years, reactive, predictive, reliability-centered, optimization, and preventive maintenance have been the strategies for maintenance planning and execution. Cost-benefit considerations have been the basis for strategy selection and improvement [1].

However, in situations where maintenance execution costs far outweigh the benefits of judicious planning, reactive (breakdown) maintenance tends to be more attractive [2-4]. In predictive and reliability-centred strategies, the cost of plant condition monitoring instruments is factored into the decision analysis process [5-7]. If any of these strategies is found to be favourable, maintenance planning may be carried out when major plant components are found to be deteriorating; execution follows appropriately [5, 6]. The optimization strategy was popular for plant replacement studies [8–10]. Preventive maintenance strategies adopt a similar approach for determining the most beneficial maintenance time interval (Bottazzi *et al.* 1992; Chareonsuk *et al.* 1997; Bevilaoqua and Braglia, 2000; Dhillon, 2002; Afey 2012) [11–15].

It may be noted that, apart from modelling challenges, the effectiveness of strategy application depends largely on the ability to identify all appropriate cost components as well as accurately estimate cost values. Inaccuracies due to exclusions and/or estimations may adversely impact on maintenance decisions. While the costs of most resources and

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activities have been found in many of the reported strategies, the literature is sparse on cases that include the cost of borrowing money for preventive maintenance. An exception is in equipment replacement decisions, which depend mostly on engineering economics principles. In preventive maintenance planning, where heavy periodic cash outlays, high interest rates, and an asset's entire life span consideration are inevitable, exclusion of the future worth of money in a decision may result in erroneous plans.

The main thrust of this paper is to address the preventive maintenance time interval problem, which includes the cost of borrowing money, among others. In particular, a preventive maintenance system function consisting of set-up, execution, breakdown, and money borrowing cost components will be formulated in terms of maintenance duration, interest rate, and system life span as parameters and reliability and time interval as variables. A preventive maintenance cost minimization problem of determining the inter-maintenance time interval and system reliability will be defined and solved.

2. Literature Review

The concept of preventive maintenance was first mentioned by [16] while suggesting means of reducing factory machine failure and downtime. Jardine (1973) [17] proposed a preventive maintenance cost function consisting of three components: preparation, execution, and breakdown costs. It was, however, [11] who scientifically carried out extensive empirical studies by systematically identifying and collecting actual failure times on preventive and corrective maintenance activities of 900 buses over a period of five years. The impact of different maintenance policies on total maintenance cost and machine availability was examined using Monte Carlo simulation.

Several studies have discussed different mathematical strategies for scheduling preventive maintenance (PM) of complex systems [18–23]. Finding the optimal preventive maintenance interval that maximizes machine reliability, minimizes maintenance cost, or optimizes both criteria was the main focus. [24] I reviewed some of these works and concluded that some of the approaches have been applied successfully in the industry while others are unable to cope with some commonly-occurring situations whose failure patterns vary with time. He observed that the inappropriate assumption of minimal repairs in corrective work in some industries was responsible. [24] Carried out similar studies using Monte Carlo simulation. A Weibull probability distribution was adopted for estimating equipment life span and maintenance execution cost. [26] Proposed a sequential preventive maintenance scheduling approach. At different points in time [27–29], they introduced the genetic algorithm as the preferred formulation and solution approach to the PM interval optimization problem.

The derived maintenance policies at the time considered such breakdown-preventive and corrective activities as inspections, lubrication, adjustments, replacements, overhauls, and repairs. Some of these activities were mandatory, while others were discretionary [30]. The mathematical modeling was premised on renewal, reliability, and other stochastic theories.

The research community has put significant effort into modeling and application of the preventive maintenance function. The following are some of the environments in which such models have been applied:

In a paper production factory [31], developed and applied an optimization model to determine an optimal preventive maintenance interval for various machines, combining total cost and system reliability as decision support functions. In preventively maintaining and replacing various machine parts in paper sack manufacturing, [32] presented an optimal preventive maintenance interval model which considered either an age-related or a diagnostic-related renewal strategy. It was applied to rubber strips of a cylindrical feeder beater machine; it indicated the relationship between PM intervals, survival probability, and mean lifetime characteristics. [33] Proposed a multiple-objective maintenance planning optimization model for a cellular manufacturing environment where cost-based, reliability-based, and combined approaches were implemented as deemed necessary.

[34] Developed a model to determine the optimal interval for the PM of semiconductor equipment in foundries, combining failure mode and effect analysis and Monte Carlo simulation. By judiciously analyzing cumulative film-thickness in semiconductor factories, time-points for executing PM in the equipment were predicted to enable the preparation of necessary support and the required resources to minimize disruptions in production runs.

[35] Proposed and successfully implemented a bi-criteria optimization model in an agro-products processing firm, reducing the total cost of machine maintenance, breakdown, and loss earning while increasing reliability. A similar report reported by [36] included the cost of opportunity and spare parts inventory management.

In an oil and gas firm, the optimal preventive maintenance interval of a good barrier component corresponding to a minimum total maintenance cost was determined by [37] using company historical data. Considering multiple equipment maintenance preemptive scheduling environments, [38] defined and solved a constrained PM interval problem to minimize long-run cost rates.

[39] Used a net present worth cost function and fuzzy logic to determine the optimal period in a machine replacement period selection problem involving capital cost, scrap value, maintenance cost, and interest rate. In a recent attempt to develop a production program model, [40] considered production, inventory, maintenance, and quality control policy parameters in an integrated cost function using the net present worth modeling framework. It may be noted that in these last two time-value-of-money based models, the modelers aimed exclusively at deciding the replacement period and production plan, respectively; there was no desire to determine the PM time interval. It thus appears safe to state that, concerning the PMI interval problem, the literature is sparse on models that include the cost of borrowing money for maintenance preparation, correction, and execution. In the following, an attempt is made to develop such a model.

3. Model Development

The cost model of Jardine (1973) including the notations and assumptions (some reproduced here) provide the framework of this study.

3.1. Problem Definition

Given all necessary parameters to establish a time interval of preventive maintenance with consideration to time value of money; that's the interest on money spent in carrying out the preventive maintenance at the determined intervals.

3.1.1. Model Notations

- t_{pm} : Interval of preventive maintenance
- TC : Total maintenance system cost within its economic life
- C_o : Maintenance preparation cost
- C_{pm} : Preventive maintenance execution costs
- C_f : Cost of breakdown maintenance during the interval t_{pm}
- H (t_{pm}): Average number of machine failures during maintenance interval, t_{pm}
- α, β: Scale and shape parameters of the Weibull distribution machine failure times.
- σ : Interest rate per period of borrowed money
- N : Economic life of machine in number of running hours

3.1.2. Model Assumptions

- Machine failure rate exhibits the Weibull distribution (failure rate increases with age)
- Unit preventive maintenance execution cost remains the same per interval
- Preparation cost of preventive maintenance is deterministic
- Cost of performing breakdown repairs is stochastic
- The number of machine failure between intervals is deterministic
- Operation of machines is in accordance with the designer's specification
- Maximum acceptable failure probability of machine is specified
- Duration to complete set of preventive maintenance activities is known and remains the same per period.
- Preventive maintenance time interval remains the same throughout its lifespan.

The following assumptions are unique to this study.

- Interest rate for each period is fixed and deterministic
- Money for maintenance is borrowed
- Economic life (N) of machine is known
- Basic maintenance system cost (without the borrowing component) remains the same at each PM point.

3.1.3. Formulation

The Jardine considered PM cost components are:

- Maintenance preparation, C_o
- Preventive maintenance execution, C_{pm}
- Breakdown maintenance during interval, C_f :

Hence, from assumption 11, the amount of money borrowed at maintenance instance i, A_i, is

$$A_i = C_0 + C_{pm} + C_f \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$\frac{TC(tpm)}{tpm} = \frac{\left(C_o + C_{pm} + C_f\left(\frac{tpm}{\alpha}\right)^{\beta}\right)}{tpm} \ldots\ldots\ldots\ldots\ldots\ldots(4.1)$$

The reliability model has also been established by (Das *et al.*, 2007). The failure probability $F(t_{pm})$ for equipment whose failure rate is Weibull distributed is expressed as

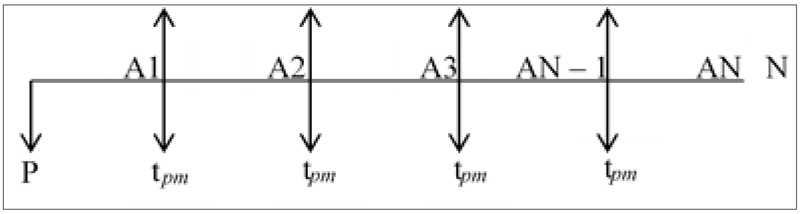
$$F(t_{pm}) = 1 - e^{-\left(\frac{tpm}{\alpha}\right)^{\beta}} \ldots\ldots\ldots\ldots\ldots\ldots (4.2)$$

where $t_{pm}, \alpha, \beta > 0$

Making t_{pm} the subject of formula

$$t_{pm} \leq \alpha\left[\ln\left[\frac{1}{1 - F(t_{pm})}\right]\right]^{\frac{1}{\beta}} \ldots\ldots\ldots\ldots\ldots\ldots (4.3)$$

Applying the principles of engineering economics the time value of money (Present Worth) function was determined



Where

- A – Is the total maintenance cost spent at every interval of preventive maintenance, an annuity
- P – Principal amount deposited at start zero when equipment life begins which is zero

t_{pm} – interval of preventive maintenance ranging from the first to last before equipment salvage or end of planning horizon

1, 2, 3……N, N periods of compounding/discounting in lifetime of equipment (e.g. years, hours etc.)

- F – Future amount of money to be spent on maintenance at intervals
- Pr – Present amount of money spent on maintenance at each interval (Present Worth)

Since maintenance costs are periodic then;

At the end of period 1 which is the first interval of PM

$$\text{F1} = \text{A1}(1 + \text{i})^{N-1}$$

At the end of period 2

$$\text{F2} = \text{A2} \quad (1 + \text{i})^{N-2}$$

$$F3 = A3 \quad (1+\mathrm{i})^{N-3}$$

$$FN = AN \quad (1+\mathrm{i})^{0}$$

Where $F = F1 + F2 + F3 + \cdots + F_{N-2} + F_{N-1} + FN$

Then $F = A1 \quad (1+\mathrm{i})^{N-1} + A2 \quad (1+\mathrm{i})^{N-2} + A3 \quad (1+\mathrm{i})^{N-3} + AN\,(1+\mathrm{i})^{0}$

Since it is an annuity A = A1 = A2 = A3 = A4

Since the term in parenthesis are in a geometric progression

$$F = A\left[\frac{(1+i^{N-1})(1+i^{-1})}{1-(1+i)^{-1}}\right] \text{.................} (4.4)$$

$$F = A\ \left[\frac{(1+i)^{N}-1}{i}\right] \text{.................} (4.5)$$

Where $\frac{(1+i)^{N}-1}{i}$ is the uniform series compound interest factor.

The future value $F = Pr(1+i)^{N}$

Therefore,

$$Pr(1+i)^{N} = A\ \left[\frac{(1+i)^{N}-1}{i}\right]$$

$$Pr = A\left[\frac{(1+i)^{N}-1}{i(1+i)^{N}}\right] \ldots\ldots\ldots\ldots\ldots\ldots (4.6)$$

Hence developing the total maintenance cost function considering time value of money for a planning horizon where total maintenance cost is the summation of all costs involved in the maintenance activity is stated as

Total maintenance cost = [Preparation cost for PM + Cost of executing PM + Cost of expected breakdown + time value of money cost]

Now a cost minimization problem is then defined using the cost function to determine the optimal values of the preventive maintenance optimization problem as shown below

Mathematically,

$$\text{Min TC(T)} = n\left(C_o + C_{pm} + C_f\left(\frac{t_{pm}}{\alpha}\right)^{\beta}\right) + A\left[\frac{(1+i)^{N}-1}{i(1+i)^{N}}\right]$$

$$\text{Min TC(T)} = n\left(C_o + C_{pm} + C_f\left(\frac{t_{pm}}{\alpha}\right)^{\beta}\right) + \left[\frac{(1+i)^{N}-1}{i(1+i)^{N}}\right](C_o + C_{pm}) \text{.................} (4.7)$$

Subject to

$$t_{pm} \le \alpha\left[\ln\left[\frac{1}{1-F(t_{pm})}\right]\right]^{\frac{1}{\beta}} \text{.................} (4.3)$$

$$F(t_{pm}) \le upper\ bound \quad \text{.................} (4.8)$$

Where n = $\frac{T}{t_{pm}}$ is an integer, N is known

Where $A = C_o + C_{pm}$ the total cost spent at each PM interval (annuity) in the planning horizon.

For given value of the maximum bound for failure probability of the selected machine and specified α, β values, equation 4.3 is used to obtain the value of t_{pm} and then substituted into equation 4.7 to obtain the minimum total cost. This procedure is carried out for several upper bound of failure probability values and PM intervals as well as total cost of maintenance are derived where interest rate applies.

3.2. Solution Procedure for the preventive maintenance interval with time value of money consideration

- Step 1: Define all the necessary parameters values: C_o, C_{pm},C_f, upper bound, α, β, i, N
- Step 2: Apply the reliability function of the developed model in equation 4.3 to find the optimum t_{pm}
- Step 3: Substitute the obtained t_{pm} in the cost function of equation 4.7 to compute the total cost in the model at a maximum failure probability set and the PM interval t_{pm} computed. Step 4: Repeat for several values of failure probability within the limit to select the optimum.

4. Numerical Example

Using three sets of data collected from different production companies in the South and West of Nigeria, the model was tested using the above listed steps.

Table 1 Maintenance Data for 3 Cases

Item	Parameter Identity	Parameter Values For		
		Case 1:(Adebimpe *et al.,* 2015)	Case 2: (Okwuchi 2017)	Case 3: (Ayeni 2017)
1	MTBF	187	20790	2022.5
2	α	199.61	23389.56	2177.64
3	β	1.21	1.812	1.26
4	Co (Naira)	1400	8700	1150
5	Cpm (Naira)	2560	11320	2050
6	Cf (Naira)	15190	32900	12900
7	Pt (Naira)	1650	9850	5000
8	Dm (hours)	8	85.33	2
9	T (1 quarter in Hours)	8760	30304	4400(11 months)
10	F(tpm)	0.25	0.15	

Result for Case 1 Applying data listed in table 4.1

Table 2 Result of PM Interval with Consideration to Time Value of Money and Without Time Value of Money (Case 1)

Upper Bound of Machine Failure Probability	Proposed Model at interest rate of 13.5%		Existing Model	
	t_{pm} (Hrs)	Cost(Naira)	t_{pm}(Hrs)	TC(T) (Naira)
0.25	71.29	1027091.13	71.29	1023602.14
0.27	76.78	1000729.65	76.78	997240.66
0.29	82.34	978288.55	82.34	974799.56
0.31	87.97	959067.23	87.97	955578.25
0.33	93.7	942439.47	93.7	938950.48
0.35	99.52	928031.59	99.52	924542.60
0.37	105.45	915473.09	105.45	911984.11

0.39	111.5	904493.75	111.5	901004.76
0.41	117.68	894875.76	117.68	891386.77
0.43	124	886441.78	124	882952.79
0.45	130.48	879035.45	130.48	875546.47
0.47	137.12	872549.57	137.12	869060.59
0.49	143.96	866859.51	143.96	863370.53
0.51	150.99	861903.30	150.99	858414.32
0.53	158.24	857599.30	158.24	854110.32
0.55	165.74	853883.32	165.74	850394.33
0.57	173.5	850712.03	173.5	847223.05
0.59	181.55	848040.94	181.55	844551.95
0.61	189.93	845832.31	189.93	842343.33
0.63	198.66	844061.33	198.66	840572.34
0.65	207.79	842702.52	207.79	839213.53
0.67	217.37	841738.30	217.37	838249.31
0.69	227.46	841156.55	227.46	837667.56
0.71	238.11**	840950.87	238.11**	837461.88
0.73	249.41	841118.74	249.41	837629.76
0.75	261.47	841665.10	261.47	838176.11
0.77	274.4	842600.95	274.4	839111.96
0.79	288.36	843946.39	288.36	840457.41
0.81	303.56	845733.53	303.56	842244.54
0.83	320.27	848009.22	320.27	844520.23
0.85	338.85	850840.51	338.85	847351.52

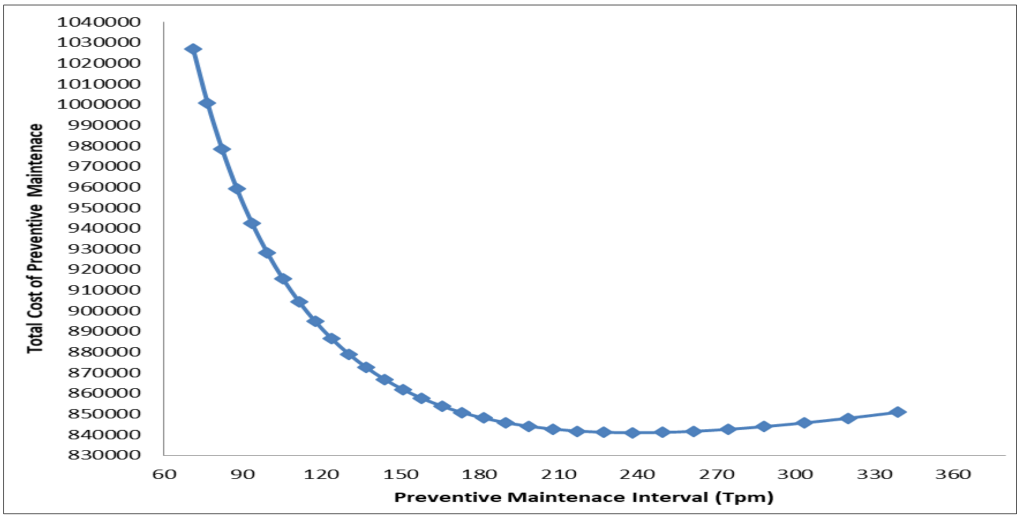


Figure 1 Graph of Total Maintenance Cost of Firm against the Preventive Maintenance Interval with Consideration to Time Value of Money (Case 1)

Table 3 Result of PM Interval with Consideration to Time Value of Money and Without Time Value of Money (Case 2)

Upper Bound of Machine Failure F(tpm)	Proposed Model at interest rate of 13.5%		Existing Model without time value of money	
	t_{pm} (Hours)	Cost(Naira)	t_{pm} (Hours)	Cost (Naira)
0.05	4540.83	205919.44	4540.83	144869.03
0.15	8581.01	157712.64	8581.01	89583.58
0.25	11760.04	149677.04	11760.04	75978.11
0.35	14695.28**	149352.55	14695.28	70510.89
0.45	17608.54	152249.70	17608.54	68303.82
0.55	20658.19	157194.33	20658.19**	67905.26
0.65	24025.66	164005.54	24025.66	68816.44
0.75	28009.72	173174.21	28009.72	71004.78
0.85	33303.97	186454.91	33303.97	75009.61
0.95	42854.14	212030.52	42854.14	83852.71

Table 4 Result of PM Interval with Consideration to Time Value of Money and Without Time Value of Money (Case 3)

Upper Bound of Machine Failure	Proposed Model at interest rate of 13.5%		Existing Model Without time value of money	
	t_{pm} (hours)	Cost(Naira)	t_{pm} (Hours)	Cost (Naira)
0.11	398.46	53788.11	398.46	52096.27
0.13	458.89	49718.88	458.89	48069.71
0.15	518.27	46714.88	518.27	45113.18
0.17	577.37	44415.82	577.37	42843.31
0.19	636.33	42607.51	636.33	41056.31
0.21	695.26	41155.38	695.26	39621.80
0.23	754.5	39970.24	754.5	38447.97
0.25	813.86	38990.37	813.86	37480.35
0.27	873.62	38171.71	873.62	36672.15
0.29	934.05	37482.39	934.05	35990.02
0.31	995.14	36898.28	995.14	35412.02
0.33	1056.92	36401.05	1056.92	34920.59
0.35	1119.6	35976.47	1119.6	34500.75
0.37	1183.19	35613.28	1183.19	34142.05
0.39	1248.07	35302.60	1248.07	33834.30
0.41	1314.03	35037.23	1314.03	33572.03
0.43	1381.46	34811.32	1381.46	33348.35
0.45	1450.32	34620.08	1450.32	33159.16
0.47	1520.98	34459.51	1520.98	32999.99
0.49	1593.2	34326.38	1593.2	32868.47
0.51	1667.52	34217.95	1667.52	32761.15
0.53	1744.07	34131.98	1744.07	32675.98

0.55	1822.99	34066.55	1822.99	32611.22
0.57	1904.57	34020.14	1904.57	32565.29
0.59	1988.93	33991.49	1988.93	32536.99
0.61	2076.54**	33979.57	2076.54**	32525.24
0.63	2167.83	33983.60	2167.83	32529.31
0.65	2262.87	34003.01	2262.87	32548.58
0.67	2362.59	34037.44	2362.59	32582.80
0.69	2467.2	34086.75	2467.2	32631.71
0.71	2577.55	34150.99	2577.55	32695.44
0.73	2694.31	34230.47	2694.31	32774.22
0.75	2818.73	34325.79	2818.73	32868.81
0.77	2951.87	34437.87	2951.87	32979.99
0.79	3095.18	34568.07	3095.18	33109.01

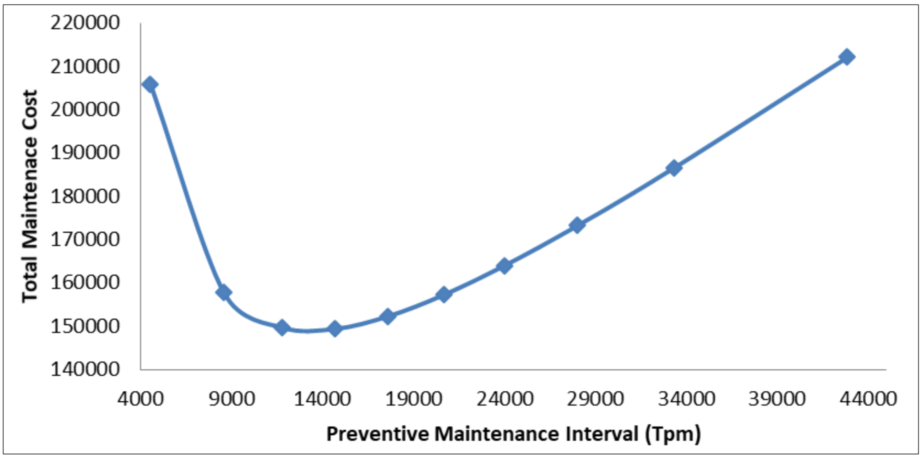


Figure 2 Graph of Total Maintenance Cost of Firm against the Preventive Maintenance Interval with Consideration to Time Value of Money (Case 2)

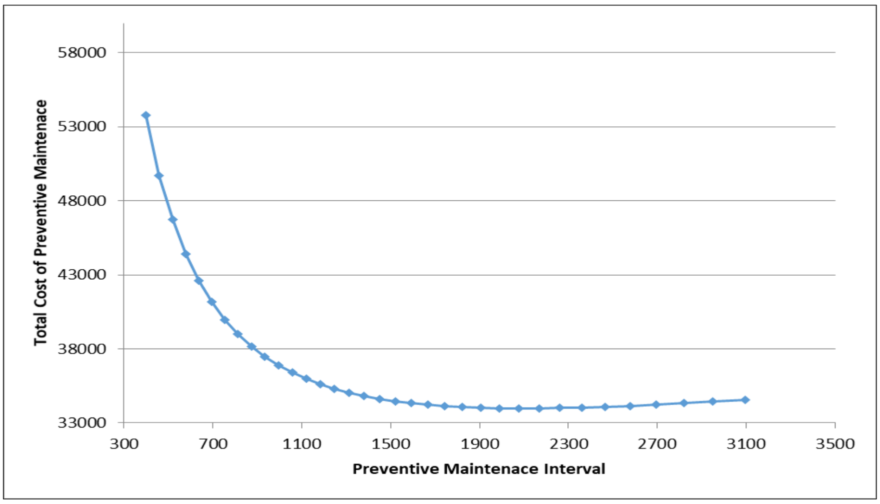


Figure 3 Graph of Total Maintenance Cost of Firm against the Preventive Maintenance Interval with Consideration to Time Value of Money (Case 3)

5. Results and Discussion

This infers that they share a directly proportional relationship with the upper bound of failure probability as the independent variable and preventive maintenance interval as the dependent. Also, as the total cost of PM activities increases the PM interval reduces which is in line with already established total maintenance cost behaviour. However, from the above cases solved in the numerical solution the t_{pm} remained same for Case 1 and 3 despite changes in total maintenace cost but for Case 2 the tpm changed. This is because the time value of money changes reflect better or is more significant in cases where the period was for a longer time (in this case 3.5years).

The proposed model which considered the time value of money cost addition to the existing (Das *et al.,* 2007) with a known interest rate applied resulted in an increase in the total cost of maintenance for one of the cases. Tables 4.2 shows the result of the first case using data collected from an agricultural firm. The addition of time value of money cost into the Das *et al.,* (2007) model showed same optimum solution for the interval of preventive maintenance. The increase in cost of proposed model was followed by a higher reliability when compared to the past model. More so, when discounting is over different periods in the lifetime of equipment the Tpm will not be the same. The result is sensitive to the duration or time over which discounting occurs thus be applied for situations where machine will be used over a longer period.

Table 5 Summary of Results for Optimum PM Interval of the Various Data Collected Before and After Considering the Time Value of Money (TVM)

Case	Tpm with TVM addition (Hrs)	Total Maintenance Cost (Naira)	F(tpm)	R(t)	Tpm without TVM addition (Hrs)	Total Maintenance Cost (Naira)	F(tpm)	R(t)
1	238.11	840950.87	0.71	0.29	261.47	837461.88	0.71	0.25
2	14695.28	149352.55	0.35	0.65	20658.19	67905.26	0.55	0.45
3	2076.54	33979.57	0.61	0.39	2076.54	32525.24	0.61	0.39

As the Upper Bound of Machine Failure Probability increases the Interval of Preventive Maintenance also increases. Conclusion and Recommendation

The PM preparation, PM execution, and expected breakdown costs, the interest rate, and the economic life of equipment were identified as the time value of money interval prediction parameters and the PM interval as the variable. A nonlinear mathematical cost function relating the time value of money to PM interval parameters and variables was established. A model for determining the optimal PM interval in a production environment with time value of money consideration has been established. The secondary data that was used to test this model did not give enough information for the salvage value to be added to the model. Because of this, it is recommended that more research be done on this cost factor.

Compliance with ethical standards

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Disclosure of conflict of interest

All the authors have seen and approved the article in the form presented for publication and declare there are no potential conflicts of interests with respect to the research, authorship and publication of this article.

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