ISSN No:-2456-2165

A Delay Time Degradation Model for Optimal Preventive Maintenance Schedule Fora Gas Processing Plant

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Abstract:- The success of oil and gas operations relies significantly on efficient management and control of the operating expenses. It has been established that unplanned plant shutdown accounts for nearly half of the overall losses of an oil facility. These unplanned shutdowns usually result from unexpected equipment breakdown due to poor maintenance strategy or culture. Therefore, Equipment maintenance is essential in most industrial sector. In the case of oil and gas operation, unplanned shutdown or downtime immediately have significant impact on the commercial bottom-line due to the size of the operation. Equipment maintenance should be considered more in the oil sector because of the high cost of purchasing equipment. This study is aimed at developing maintenance model for effective equipment management for gas treatment plant. A delay time degradation model was proposed and considered aging of equipment, replacement and repair actions. The results showed that the proposed model was capable of planning preventive maintenance schedules for a gas processing plant.

Keywords:- *Maintenance Modeling, Gas Processing Plant, Delay Time Degradation Model.*

I. INTRODUCTION

Production maintenance has evolved to be one of the most important areas in the oil and gas business environment. The growth of global competition caused remarkable changes in the way manufacturing and oil gas companies operate. These changes have affected maintenance and made its role even more crucial in business success. Maintenance refers to all activities taken to ensure smooth and reliable operation of equipment, machinery or system. Further definitions are similar to this given here and could be found in Ahmad & Kamaruddin (2012), Tinga (2010) and Dhillon (2002). Failure of equipment will occur despite the quality of the design. High reliability of equipment is largely a function of good design, but in operation, the equipment undergoes deterioration coupled with the nature of the operating environment (Jardine et al., 2006). To ensure equipment is available for effective usage without random failure, maintenance is required. The purpose of maintenance is to ensure all equipment is available, reliable and carry on their designed functions optimally and continuously. Thus, maintenance plans are needed to ensure the availability and reliability of systems, improve system performance / economic viability and ensure the overall success of manufacturing systems (Shalaby, et al., 2019).

Implementing good and appropriate maintenance strategy is one of the significant changes in manufacturing and oil & gas production companies. Maintenance strategy refers to a planned way to carry out maintenance which involves several actions including carrying out repairs, carrying out researches concerning maintenance, carrying out replacements, and inspection of maintenance decisions (Gackowiec, 2019). A maintenance strategy provides the direction maintenance program will follow. A maintenance program specifies the type of maintenance to be carried out together with the resources involved. In most cases, maintenance strategy is loosely used in place of maintenance type and the two terms are used interchangeably. There are different types of maintenance models and their classification can be based on several criteria. Arts (2017) classified maintenance models into three major groups- usage based models, degradation models and condition-based models. Maintenance modelling is not a recent subject and reviews as far back as 1965 have been reported. The maintenance models under each maintenance type depend on the policy adopted. He identified some of maintenance policies to include block replacement, periodic replacement with minimal repair when failure occurs, age replacement, planned corrective maintenance with the usage of cycle time, and planned maintenance with the usage of optimal number of failures.

The cost of maintenance may not be the major consideration in maintenance modelling even though cost is meant to be minimized. That is, maintenance intervals should be forced to be longer than necessary in optimizing maintenance interval with a view to saving maintenance cost. From research as well as experience, for equipment relating to oil & gas, prolonging maintenance intervals so as to minimize maintenance cost always leads to unexpected or unforeseen equipment failures which in turn lead to unplanned / emergency shutdowns (Ikwunze& Nwosu, 2016). The associated maintenance cost in such cases far exceeds the cost that goes with optimum maintenance intervals. Thus, there is the need to have in place a well-structured maintenance program that will guide in the carrying out maintenance of a plant or system.

Savsar (2013) carried out preventive maintenance scheduling for fuel dispensers in a number of gas stations in a chain- consisting of over 40 gas stations and over 570 dispensers. Analysis, modelling and preventive maintenance scheduling was carried out on the fuel dispensers. Laggoune et al. (2011) used both maintenance cost and availability measures to obtain a 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 imperfect maintenance which brings the system somewhere between the two extreme situations.Sooktip et al. (2011) presented a system reliability optimization approach with multiple k-out-of-n subsystems connected in series. The design objective is to select multiple components to maximize system reliability while satisfying system requirements constraints such as cost and weight.

Moghaddam (2013) presented a new multi-objective nonlinear mixed-integer optimization model to determine Pareto-optimal preventive maintenance and replacement schedules for a repairable multi-workstation manufacturing system with an increasing rate of occurrence of failure. The operational planning horizon is segmented into discrete and equally-sized periods and in each period three possible maintenance actions (repair, replacement, or do nothing) have been considered for each workstation.Yu Liu et al. (2013) proposed a generalized imperfect repair model to characterize the stochastic behaviour of multi-state elements (MSEs) after repair, and a replacement policy under which an MSE is replaced once it reaches the pre-determined number of failures is introduced. Carvalho et al. (2015) presented a project in a furniture manufacturing factory, carried out to improve the efficiency of preventive maintenance actions, decreasing the number of failures and downtime of equipment, and maintenance costs.

Zhang et al. (2016) focus on proposing an optimal inspection-based maintenance policy for three-state mechanical components subject to competing failure modes. A double-Wiener-process degradation model is established to describe the two operation states, which includes two Wiener-process models under the same law but with different parameters. Park et al. (2018) considered an optimal periodic preventive maintenance policy after the expiration of a two-dimensional warranty. During the two-dimensional warranty period, both renewal warranty and nonrenewal warranty are considered and a repair time threshold is pre-specified so that the failed system is either minimally repaired or is replaced depending on whether the length of repair time exceeds the repair time threshold or not. Sembiring et al (2020) utilized reliability engineering approach in designing a preventive maintenance system in a palm oil processing factory (known as PT. Y). Using a sterilizer machine critical components’ reliability, a maintenance problem was formulated which provides maintenance schedules.

Maintenance model can be developed for each component in a system. Components are not operated in isolation in a system; hence, a maintenance program is needed for a system. Taking a gas treatment plant which is the focus in this study, the system comprises a number of major components which are provided later in this work. The goal of this study is to formulate maintenance model and carry out maintenance interval optimization for a gas treatment plant.

II. METHODOLOGY

From the results of previous failure and criticality considerations from experience, some components were selected for maintenance analysis in the gas treatment plant and the selected components are shown in Table 1.

Table 1: Selected components for maintenance analysis

Serial Number	**Component**
1	High pressure separator (HPS) vessels
2	Low pressure separator (LPS) vessels
3	Medium pressure separator (MPS)
4	Test separator vessels
5	MP and LP compression units
6	Solar turbines compressors
7	Transfer pumps
8	Oil export pumps
9	Gas boot
10	Flare system
11	Fuel gas system
12	Utility gas system
13	Gas export analyzer
14	Power generation system
15	Firefighting system / pumps
16	Instrument air system
17	Chemical injection system

For delay time degradation maintenance modelling, the length of the inspection interval is the parameter to be optimized. If a component degrades based on the delay time model, the time to defect and the delay time are needed. Let the time to defect be denoted as X and the delay time be denoted as Y. The two parameters X and Y are random variables that have densities and distributions. Let the densities and the distributions be denoted as $f_X(x), f_Y(y)$ and $F_X(x), F_Y(y)$ respectively.

In this work, the distribution of the delay time is assumed to be exponential. Inspections are carried out at regular intervals of time. The inspection intervals are denoted as $\tau, 2\tau, 3\tau, \ldots$, the starting point being after replacement of component where the component at that point is taken as good as new (AGAN). Whenever defect is detected, the component will be replaced via corrective maintenance with corrective maintenance cost denoted as C_u. The component may fail before inspection, fail during inspection or will not fail during inspection. Each of these three scenarios will lead to different cost relations. Renewal reward theory can be applied to analyze the failure where a cycle ends under each of the three scenarios presented above. Each of the three cases are considered in the cost modelling.

The two random variables X and Y are independent. Let us represent their sum with another variable T which is the replacement time:

$$T = X + Y \tag{1}$$

The probability that the replacement time is equal to or less than some value t gives the distribution function given as,

$$p(T \leq t) = p(X + Y \leq t) = F_T(t) = \int_0^t \int_o^t f_{XY}(x, t - x)dxdt \tag{2}$$

Since the two random variables are independent, the convolution principle can be introduced at this point and Equation(22) comes in the form,

$$p(T \leq t) = F_T(t) = \int_0^t f_X(x)F_Y(t - x)dx \tag{3}$$

The PDF is thus given as,

$$f_T(t) = \frac{d}{dt}F_T(t) = \int_0^t f_Y(t - x)f_X(x)dx \tag{4}$$

- *Expected Cycle Length and Expected Cycle Cost*

The maintenance model gives the maintenance cost per unit time. It is expressed as the ratio of the expected cycle cost and the expected cycle length. We have to therefore look for these two parameters.

The expected cycle length is the minimum value of the replacement time, where the inspection time is taken into account given as the sum of the minimum values of the expectations of the PDF of distribution of the replacement variable and the that of the inspection time;

$$ECL = E[\min(T, \tau)] = E[\min(T)] + E[\min(\tau)] \tag{5}$$

$$E[\mathrm{T}] = \int_0^\tau t f_T(t)dt \tag{6}$$

Since $F_T(\tau)$ is the probability of the random variable T less than or equal to the value τ, the probability of the value of the random variable up to the value τ is $1 - F_T(\tau)$. The expectation of τ is thus,

$$E[(\tau)] = \tau[1 - F_T(\tau)] \tag{7}$$

The expected cycle length is thus given as,

$$ECL = \int_0^\tau t f_T(t)dt + \tau[1 - F_T(\tau)] \tag{8}$$

The distribution function $F_T(t)$ and the density function $f_T(t)$ depend on the nature of the two random variables X and Y. In this work, exponential degradation is assumed. Thus, X and Y are given respectively as,

$$X = \gamma_X e^{-\gamma_X x} = f_X(x) \tag{9}$$

$$Y = \gamma_Y e^{-\gamma_Y y} = f_Y(y) \tag{10}$$

ISSN No:-2456-2165

where γ_X is the constant failure rate for exponential degradation of the given component while γ_Y is the constant failure rate for delay time exponential degradation. The constant γ_X will be taken as the failure rate of the component or equipment while the constant γ_Y will be taken as a value greater than γ_X.

From Equation (24), substituting for $f_X(x)$ and $f_Y(t-x)$ in the expression for $f_T(t)$ and simplifying further, we obtain Equation (11).

$$f_T(t) = \frac{\gamma_X\gamma_Y(e^{-\gamma_X t} - e^{-\gamma_Y t})}{\gamma_Y - \gamma_X} \tag{11}$$

The distribution function $F_T(t)$ is obtained by integrating Equation (11);

$$F_T(t) = 1 - \frac{\gamma_Y e^{-\gamma_X t} - \gamma_X e^{-\gamma_Y t}}{\gamma_Y - \gamma_X} \tag{12}$$

The expected cycle length is obtained by substituting the relevant terms into Equation (28). We proceed as follows:

$$ECL = \int_0^\tau t f_T(t)dt + \tau[1 - F_T(\tau)] \tag{13}$$

From Equations (12) and (13)

$$\tau[1 - F_T(\tau)] = \tau\frac{\gamma_Y e^{-\gamma_X \tau} + \gamma_X e^{-\gamma_Y \tau}}{\gamma_Y - \gamma_X}$$

The expected cycle length is thus obtained as,

$$ECL = \frac{\gamma_X\gamma_Y}{\gamma_Y - \gamma_X}\left[\!\left[\frac{1 - e^{-\gamma_X\tau} - \gamma_X\tau e^{-\gamma_X\tau}}{(\gamma_X)^2} - \frac{1 - e^{-\gamma_Y\tau} - \gamma_Y\tau e^{-\gamma_Y\tau}}{(\gamma_Y)^2}\right]\!\right] + \tau\frac{\gamma_Y e^{-\gamma_X\tau} + \gamma_X e^{-\gamma_Y\tau}}{\gamma_Y - \gamma_X} \tag{14}$$

Or

$$ECL = \frac{\gamma_X\gamma_Y}{\gamma_Y - \gamma_X}\left[\!\left[\frac{1 - e^{-\gamma_X\tau} - \gamma_X\tau e^{-\gamma_X\tau}}{(\gamma_X)^2} - \frac{1 - e^{-\gamma_Y\tau} - \gamma_Y\tau e^{-\gamma_Y\tau}}{(\gamma_Y)^2} + \tau\frac{\gamma_Y e^{-\gamma_X\tau} + \gamma_X e^{-\gamma_Y\tau}}{\gamma_X\gamma_Y}\right]\!\right] \tag{14a}$$

The next task is to look for the expected cycle cost (ECC). The ECC evaluated by considering the three scenarios that complete the renewal cycle. Considering the first scenario where the component fails before the next inspection time, the component will be replaced and bears only corrective maintenance cost C_u. Here, the time of replacement is less than the inspection time. The probability of the occurrence of this is given as,

$$p(T < \tau) = F_T(\tau)$$

From Equation (12),

$$p(T < \tau) = F_T(\tau) = 1 - \frac{\gamma_Y e^{-\gamma_X\tau} - \gamma_X e^{-\gamma_Y\tau}}{\gamma_Y - \gamma_X} \tag{15}$$

The ECC for this case is,

$$ECC_1 = C_u F_T(\tau) = C_u\left(1 - \frac{\gamma_Y e^{-\gamma_X\tau} - \gamma_X e^{-\gamma_Y\tau}}{\gamma_Y - \gamma_X}\right) \tag{16}$$

In the second scenario, the component did not fail at the point of inspection, hence $X < \tau$. In this case, there will be a delay time such that $X + Y > \tau$. The probability of the occurrence of this scenario has two parts:

- $p(X < \tau)$: the probability that the time to defect is less than the inspection time and
- $p(X + Y > \tau)$: the probability that the sum of the time to defect and the delay time is greater than the inspection time.

The combined probability is represented as $p((X < \tau) \cap (X + Y > \tau))$. Taking them separately as they were,

$$p(X < \tau) = F_X(\tau) = \int_0^\tau f_X(x)dx \tag{17}$$

For the second part,

$$p(X + Y > \tau) = 1 - p(X + Y < \tau) \tag{18}$$

ISSN No:-2456-2165

But,

$$p(X+Y<\tau)=p(T\leq\tau)=F_T(\tau)=\int_0^\tau f_X(x)F_Y(\tau-x)dx \quad (19)$$

Hence,

$$p(X+Y>\tau)=1-\int_0^\tau f_X(x)F_Y(\tau-x)dx \quad (20)$$

Combining Equations (27 and (20) gives the required probability as,

$$p\big((X<\tau)\cap(X+Y>\tau)\big)=\int_0^\tau(1-F_Y(\tau-x))f_X(x)dx \quad (21)$$

We know that $f_X(x)=\gamma_X e^{-\gamma_X x}$ and $f_Y(y)=\gamma_Y e^{-\gamma_Y y}$. We have to evaluate $F_Y(t-x)$ first before getting the expression for the probability in Equation (21);

$$F_Y(\tau-x)=\gamma_Y\left[\!\left[\frac{1}{\gamma_Y}e^{-\gamma_Y(\tau-x)}\right]\!\right]_x^\tau=\left[\!\left[e^{-\gamma_Y(\tau-x)}\right]\!\right]_x^\tau=1-e^{-\gamma_Y(\tau-x)} \quad (22)$$

From Equations (21) and (22)

$$1-F_Y(\tau-x)=1-\left(1-e^{-\gamma_Y(\tau-x)}\right)=e^{-\gamma_Y(\tau-x)}$$

Substituting for the different parameters in Equation (21), we obtain,

$$p\big((X<\tau)\cap(X+Y>\tau)\big)=\gamma_X\left(\frac{e^{-\gamma_X\tau}-e^{-\tau\gamma_Y}}{\gamma_Y-\gamma_X}\right) \quad (23)$$

In this scenario, both inspection cost C_{insp} and preventive maintenance cost C_{pm} will be borne. The ECC for this case is thus given as,

$$ECC_2=\left(C_{insp}+C_{pm}\right)\times\gamma_X\left(\frac{e^{-\gamma_X\tau}-e^{-\tau\gamma_Y}}{\gamma_Y-\gamma_X}\right) \quad (24)$$

In the third scenario that completes the renewal cycle, the component functions properly at the time of inspection. The only cost incurred is the inspection cost. The probability of having the component working properly at the time of inspection is the probability that the time of defect is greater than the inspection time; that is, $p(X>\tau)$. Mathematically

$$p(X>\tau)=1-p(X<\tau) \quad (25)$$

It is known that$p(X<\tau)=F_X(\tau)=\int_0^\tau f_X(x)dx$, Substituting for $f_X(x)$ and simplifying further gives Equation (26).

$$p(X<\tau)=-(e^{-\gamma_X\tau}-1)=1-e^{-\gamma_X\tau} \quad (26)$$

Equations (25) and (26) gives Equation (27)

$$p(X>\tau)=e^{-\gamma_X\tau} \quad (27)$$

The ECC in this scenario is,

$$ECC_3=C_{insp}\times e^{-\gamma_X\tau} \quad (28)$$

The expected cycle cost is the sum of ECC_1, ECC_2 and ECC_3.

Thus,

$$ECC=ECC_1+ECC_2+ECC_3$$

$$ECC=C_u\left(1-\frac{\gamma_Y e^{-\gamma_X\tau}-\gamma_X e^{-\gamma_Y\tau}}{\gamma_Y-\gamma_X}\right)+\left(C_{insp}+C_{pm}\right)\times\gamma_X\left(\frac{e^{-\gamma_X\tau}-e^{-\tau\gamma_Y}}{\gamma_Y-\gamma_X}\right)+C_{insp}\times e^{-\gamma_X\tau} \quad (29)$$

- *The Delay Time Degradation Model*

The maintenance model sought here is an expression of the maintenance cost per unit time. The model $MC(t)$ incorporates maintenance cost and maintenance interval and presented as,

$$MC(t) = \frac{ECC}{ECL} \quad (30)$$

where the term ECC is the expected cycle cost and ECL is the expected cycle length. For each of the components identified in the previous section for maintenance analysis, the maintenance model presented in Equation (30) will be applied to it and the minimum cost per unit cycle length will be estimated for each component. To do this, a number of input data are required. The data required include preventive maintenance cost of the selected equipment, curative maintenance cost, inspection cost, the rates of the exponential distribution for both the time to defect and the delay time. While the various maintenance cost items were obtained from the industry based on the actual values expended in the past, the rates of the distribution were estimated from failure information. Table 2 provides the various maintenance costs used for the analysis.

Table 2: Different maintenance costs of various components

Component	**Inspection cost** (US $)	**PM cost** (US $)	**CM Cost** (US $)
High pressure separator (HPS) vessels	65	220	4900
Low pressure separator (LPS) vessels	50	200	4700
Medium pressure separator (MPS)	50	210	4800
Test separator vessels	40	140	1100
MP and LP compression units	90	550	8700
Solar turbines compressors	120	650	9450
Transfer pumps	110	600	8600
Oil export pumps	110	600	8600
Gas boot	55	220	4500
Flare system	50	200	4400
Fuel gas system	50	210	4500
Utility gas system	50	200	4400
Gas export analyzer	50	260	5400
Power generation system	140	750	12800
Instrument air system	50	200	4400
Chemical injection system	50	230	5600

The maintenance model in Equation (30) cannot be solved analytically to know the value of the inspection interval that will give the minimum maintenance cost. One way of solving this problem is via graphical representation and reading the minimum maintenance cost and the corresponding inspection interval from the graph. Although, the graphs of the maintenance cost against maintenance interval for the different components are resented in the next chapter, more accurate results can be obtained via numerical analysis with the aid of modern programming languages. In this work, C-sharp (C#) programming language was used to develop software where the optimum maintenance cost was estimated for each component. The algorithm for achieving this is presented below.

- For each component, estimate the constant failure rate (for exponential degradation) from previous failure information and express it as number of failures per year;
- Estimate the constant failure rate for delay time degradation. The rate here is expressed as between 10% and 20% greater than that in i. That is $\gamma_Y = 1.1\gamma_X$ or $\gamma_Y = 1.2\gamma_X$;
- Get the inspection cost, preventive maintenance cost and the corrective maintenance cost for each component;
- Generate a range of inspection interval (in years), say 0.01:1:0.01. That is from an interval 0.01 year to an interval of 1 year, and increase steps by 0.01;
- For each inspection interval, estimate the equivalent cycle length for each equipment using Equation (14);
- For each inspection interval, estimate the equivalent cycle cost for each equipment using Equation (29);
- For each inspection interval, estimate the maintenance cost for each equipment using Equation (30);
- For each equipment, find the minimum value of the maintenance cost incurred;
- For each equipment, find the maintenance interval that led to the minimum value of the maintenance cost;
- Collate the optimum maintenance interval for each component and make them available for equipment availability analysis.

III. RESULTS AND DISCUSSION

The delay time degradation analysis requires a number of input data that were collected from the field. Tables 6 and 4.8 show the data collected from the field for this analysis.

Table 3: Failure rate of different equipment in the system

Component	Years of system operation	Number of failures	Failure Rate
High pressure separator (HPS) vessels	7	1	0.1429
Low pressure separator (LPS) vessels	12	1	0.0833
Medium pressure separator (MPS)	9	1	0.1111
Test separator vessels	7	1	0.1429
MP and LP compression units	2	1	0.5000
Solar turbines compressors	0.5	1	2.0000
Transfer pumps	0.33	1	3.0000
Oil export pumps	0.33	1	3.0000
Gas boot	12	1	0.0833
Flare system	1	1	1.0000
Fuel gas system	3	1	0.3333
Utility gas system	3	1	0.3333
Gas export analyzer	1	1	1.0000
Power generation system	0.5	1	2.0000
Instrument air system	1.5	1	0.6667
Chemical injection system	0.5	1	2.0000

Table 4: Maintenance cost components of different equipment in US Dollars

Component	Inspection cost	PM cost	CM cost
High pressure separator (HPS) vessels	65	220	4900
Low pressure separator (LPS) vessels	50	200	4700
Medium pressure separator (MPS)	50	210	4800
Test separator vessels	40	140	1100
MP and LP compression units	90	550	8700
Solar turbine compressors	120	650	9450
Transfer pumps	110	600	8600
Oil export pumps	110	600	8600
Gas boot	55	220	4500
Flare system	50	200	4400
Fuel gas system	50	210	4500
Utility gas system	50	200	4400
Gas export analyzer	50	260	5400
Power generation system	140	750	12800
Instrument air system	50	200	4400
Chemical injection system	50	230	5600

Figures 1 to 6 show the variation of the maintenance cost with inspection interval of some of the equipment in the gas processing system- the equipment selected is based on failure rate (for the first three equipment) and maintenance cost (for the last three equipment).

Based on failure rate:

- Transfer pumps - High
- Fuel gas system -Medium
- Low pressure separator vessels – Low

- Based on maintenance cost:
- Test separator vessels – Low
- Chemical injection system- Medium
- Power generation system- High

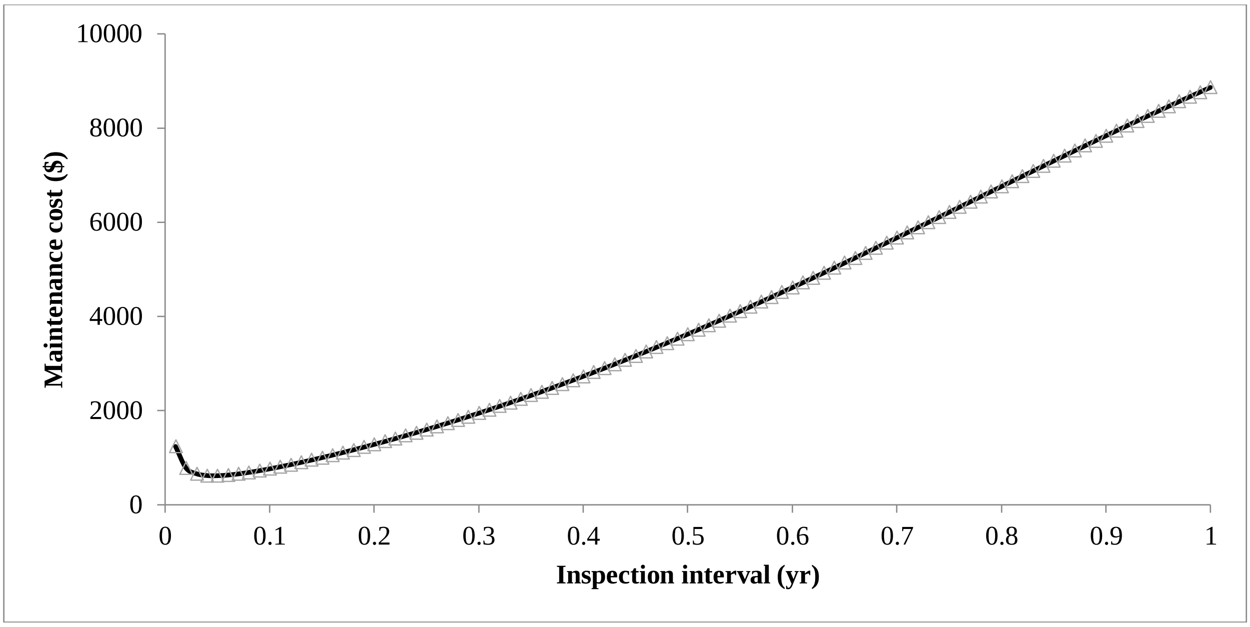

Fig. 1: Variation of Maintenance Cost with Inspection Interval for Transfer Pumps

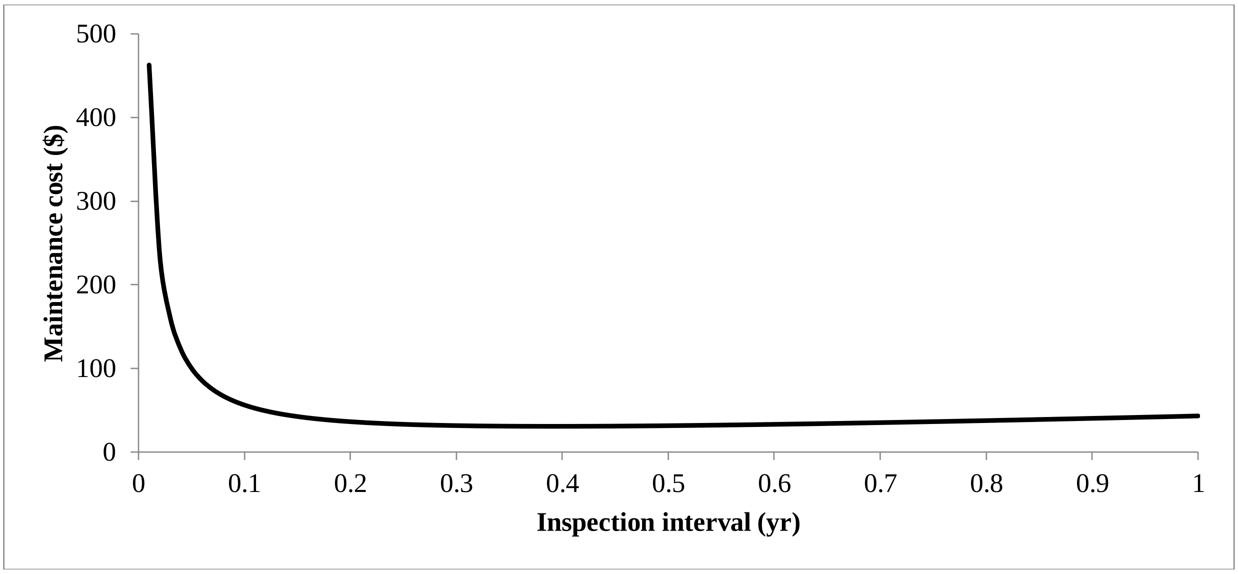

Fig. 2: Variation of maintenance cost with inspection interval for fuel gas system

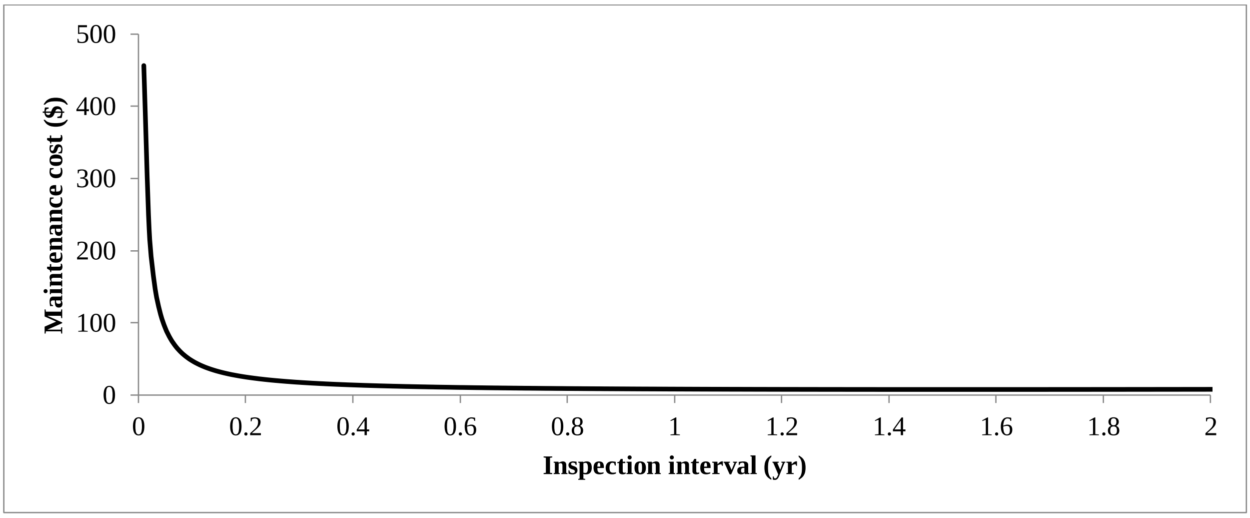

Fig. 3: Variation of maintenance cost with inspection interval for low pressure separator vessels

ISSN No:-2456-2165

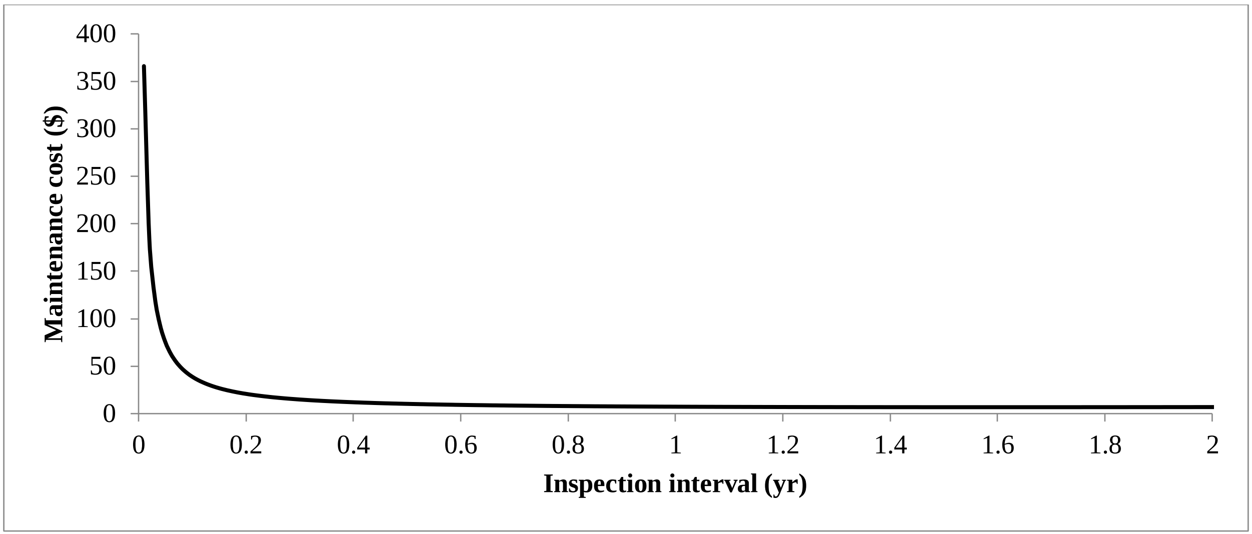

Fig. 4: Variation of maintenance cost with inspection interval for test separator vessels

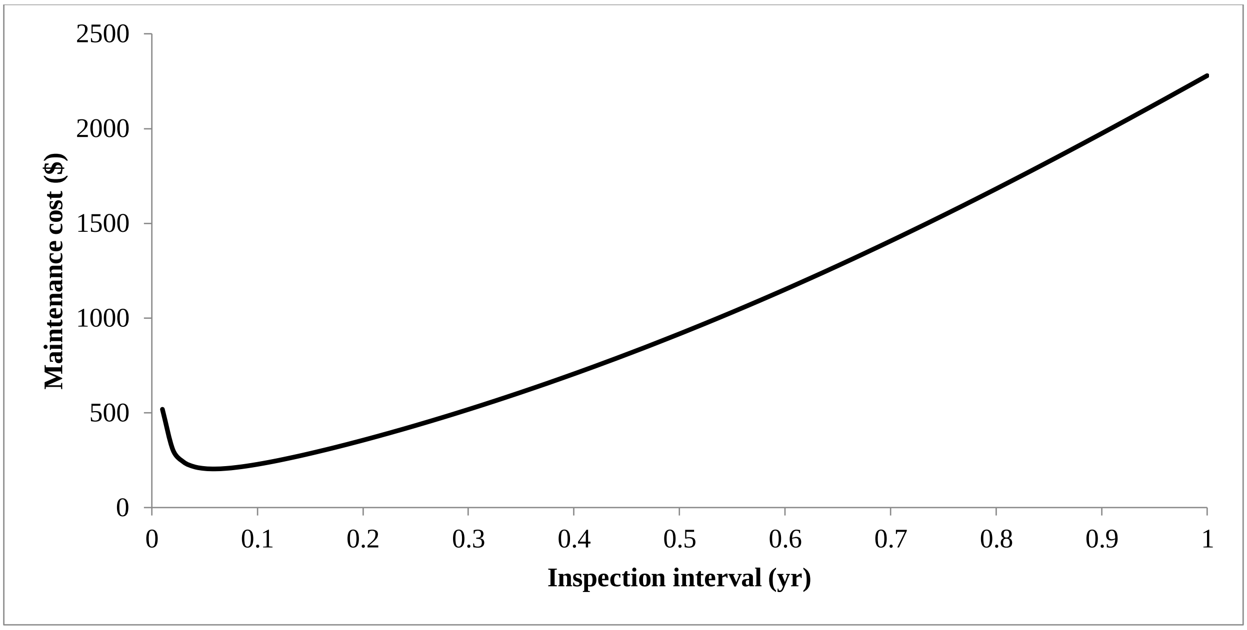

Fig. 5: Variation of maintenance cost with inspection interval for chemical injection system

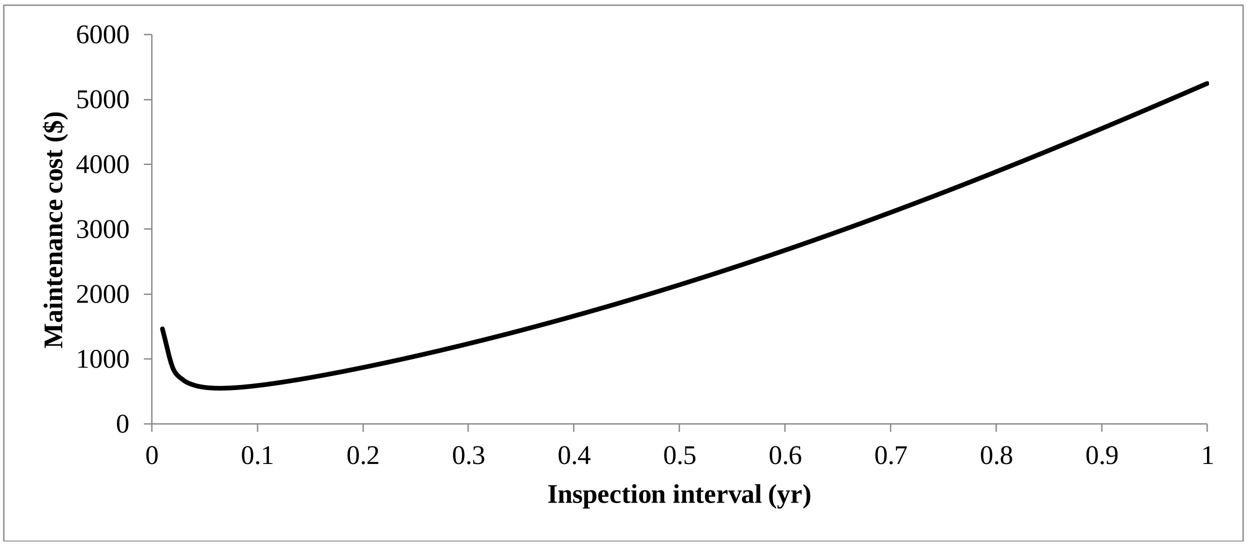

Fig. 6: Variation of maintenance cost with inspection interval for power generation system

The maintenance cost drops with increase in the inspection interval, reaches a minimum value, thereafter increases with further increase in the inspection interval. For components with high failure rate, the minimum value of the maintenance cost is reached within a short inspection interval. This is the case for the transfer pump shown in Figure 1. This is because the failure rate high and when inspection is delayed, failure will likely occur before the inspection and the maintenance cost will involve both the cost of inspection and curative maintenance. The maintenance cost for such equipment increases drastically beyond the optimum inspection interval. For components which failure rate is low, the minimum maintenance cost is achieved at much higher inspection interval, and beyond the optimum inspection interval, the maintenance cost increases gradually. There is a drastic drop in the maintenance cost as the inspection interval increases initially. This is the case for the low-pressure separator vessels with very low failure rate as in Figure 3. This occurrence is because the components do not fail often. Thus, frequent inspection leads to waste of cost in form of inspection cost. For components which failure rate is not very high (termed medium in this work), the optimum inspection is shorter than that for those with very low failure rate. This is the case in Figure 2 for the fuel gas system.

Figures 4, 5 and 6 shows respectively for components low maintenance cost, medium maintenance cost and high maintenance cost respectively. Figure 4 (for test separator vessel) is similar to Figure 3 (for low pressure separator vessels), both with very low failure rate, but the low-pressure separator vessels has much higher maintenance cost values. Figure 5 (for chemical injection system) is similar to Figure 1 (for transfer pumps), both with high failure rates. But, the maintenance cost values for transfer pumps are much higher than those for chemical injection system. Figure 6 is also similar to Figures 1 and 5, but the component involved (power generation system) has higher maintenance cost values compared to transfer pumps (Figure 1) and chemical injection system (Figure 5). The above occurrences indicate that the manner of the variation of the maintenance cost with inspection interval is affected by the failure rate and not by the maintenance cost values.

The optimum inspection interval (the inspection interval that gives the minimum maintenance cost) can be read from the Figures illustrating the variation of maintenance cost with inspection interval as shown in Figures 1 to 6. It will be difficult to read accurate values using this approach. Hence, software was developed to do this. Table 5 shows the optimum inspection interval of the various equipment in the gas processing system.

Table 5: Optimum inspection/maintenance interval of the different equipment

Component	Optimum inspection interval (yr)
High pressure separator (HPS) vessels	0.991
Low pressure separator (LPS) vessels	1.530
Medium pressure separator (MPS)	1.136
Test separator vessels	1.598
MP and LP compression units	0.252
Solar turbine compressors	0.069
Transfer pumps	0.046
Oil export pumps	0.046
Gas boot	1.635
Flare system	0.132
Fuel gas system	0.390
Utility gas system	0.395
Gas export analyzer	0.119
Power generation system	0.065
Instrument air system	0.197
Chemical injection system	0.059

The optimum inspection interval depends largely on the failure rate. Equipment with high failure rate need more frequent maintenance hence they go with low optimum inspection interval and vice-versa. From Tables 4 and 5, the failure rate of transfer pumps is very high while that of the low-pressure separator is very low, hence the optimum inspection interval of the transfer pumps is very low (0.043 yr) but that of the low-pressure separator is very high (1.53 yrs.).

IV. CONCLUSION

The delay time degradation model expresses the maintenance cost which comprises the inspection cost, preventive maintenance cost and the corrective maintenance cost as a function of the inspection interval. For all components, the maintenance cost decreases with increase in the inspection interval, gets to a minimum value and increases thereafter. The optimum inspection interval is where the maintenance cost is minimal. For components with high failure rate, the minimum maintenance cost is reached within a very short inspection interval. For components with very low failure rate, there is drastic drop of the maintenance cost with increase in inspection interval at very low values of inspection interval. This is followed by a very gradual drop in the maintenance cost as the inspection interval increases further. The minimum maintenance cost is obtained at a very high value of inspection interval, and the maintenance cost increases gradually with further increase in the inspection interval. Delay time degradation modelling can find more appropriate application in maintenance modelling for gas processing system.Further studies should consider Markovian degradation modelling if the relevant input data can be obtained.

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