ASSET MANAGEMENT OF AGING DEVICES IN ENERGY SYSTEMS BASED ON PROBABILISTIC MODELLING: A CASE STUDY ON DIESEL ENGINES

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Dissertation submitted in partial fulfillment of the requirements for the Degree Master of Science in Electrical Installation

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April 2019

Declaration

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(N.P.D.S. Pathirana)

The above candidate has carried out research for the Masters Dissertation under my supervision.

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(Dr. Saranga K.Abeygunawardane)

Abstract

The purpose of maintenance is to lengthen the equipment lifetime. Too little maintenance may have costly consequences; whereas too frequent maintenance may not be economical. Hence the two costs, i.e. the cost of failures and the cost of maintenance must be balanced. In practice, the attempts to approximate this balance have often been based on trial and error.

Here, a probabilistic maintenance model is developed for inspection based preventive maintenance of diesel engines based on the practical model concepts discussed in the literature. Developed model is solved using real data obtained from inspection and maintenance histories of diesel engines and experts' views. Reliability indices and costs were calculated for the present maintenance policy of diesel engines. A sensitivity analysis is conducted to observe the effect of inspection based preventive maintenance on the life cycle cost of diesel engines.

Optimal rates are obtained for inspection based preventive maintenance of diesel engines using the developed model and a grid search algorithm. The reliability and cost measures of the present maintenance practice and the optimal maintenance practice are compared. It is found that the current maintenance practice maintains the reliability and the life cycle cost of diesel engines at an acceptable level. However, the optimal policy suggested by the model is capable of further reducing the lifecycle cost and increasing the reliability.

Further, a state prediction tool is developed to validate the model. The same can be used to predict the deterioration condition of the diesel engine. A software tool is also developed with GUI interface for calculating purposes and presenting results.

Index Terms-- Maintenance, Diesel engines, Markov models, asset management.

Acknowledgement

Foremost, I would like to express my sincere gratitude to my supervisor Dr. Saranga K. Abeygunawardane for her continuous support, patient guidance, enthusiastic encouragement and useful critiques of this research work and specially for enlightening me on the first glance of research. Her guidance helped me throughout the research and writing of this thesis. I could not have imagined having a better supervisor and mentor for my MSc study.

I am glad to extend my sincere gratitude to Prof. S.Kumarawadu, Head of the Department of Electrical Engineering, University of Moratuwa and all the lecturers and visiting lecturers of the Department of Electrical Engineering for the support extended during the study period.

I would like to thank Eng. P.W.Hendahewa, DGM (Thermal Complex) and Eng. R.G.P.K Gunasekera, CE (Sapugaskanda Power Station), of Ceylon Electricity Board who encouraged me and provided required facilities to carry out the study.

I also like to thank Eng. Mani Albert, Mechanical Engineer (Sapugaskanda Power Station) and Eng.Thilina Hettiarchchi, Mechanical Engineer (Sapugaskanda Powers Sation) for encouraging and sharing their knowledge to make this project successful.

It is a great pleasure to remember the kind cooperation extended by colleagues at the post graduate program and specially my colleagues at Sapugaskanda Power Station for their encouragement and continuous support during my MSc study and research period.

Last but not the least; I would like to thank my family for encouraging and supporting me to complete my research work successfully.

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LIST OF ABBREVIATIONS

CBM	- Condition Based Monitoring
CM	- Condition Monitoring
RUL	- Remaining Useful Lifetime
md	- Minor Deterioration
MD	- Major Deterioration
FPT	- Failure Passage Time
MTTF	- Mean Time to Failure
MTBF	- Mean Time between Failures
LCC	- Life Cycle Cost
U	- Unavailability

1 INTRODUCTION

1.1 The Background

The effectiveness and efficiency of the industrial environment is significantly influenced by the aspects such as time, financial constraints, technology, quality, reliability, and information management [1]. The enhancement of system maintainability and reliability are two necessary operational attributes for an organization to compete successfully. Therefore, a sufficient attention has to be paid for these aspects during the strategic planning stage of organization.

Accordingly, various definitions can be found for maintenance; briefing the concept that maintenance is a set of technical, managerial and administrative actions scoping to preserve the condition of an equipment as required [2]. The sole purpose of maintenance is to lengthen the lifetime of the equipment. While too little maintenance may have costly consequences; too frequent maintenance may not be financially and practically feasible. Thus; maintenance, repair and maintenance costs must be balanced.

Nowadays, maintenance can be used as a profit generating process. In this respect, a broad exploration of maintenance methodologies takes place, concerned with the most known methods and techniques scoping to motivate the development of an optimized, innovative and applicable maintenance strategy for diesel engines.

This section classifies maintenance between strategies, methodologies, well-known and applied monitoring technologies and tools by proving the importance of maintenance presenting guidelines from international safety agents.

1.1.1 Maintenance Strategies

An investigation on various sources indicates that maintenance strategies are classified differently from researchers. For instance, [3-5] combine maintenance strategies and techniques; conversely [6-7] separate those presenting maintenance strategies in a timeline form. In contrast, [8] approaches maintenance in the commonly cited types of corrective and preventive strategies. Investigating various applications and research methodologies, the core of strategies between corrective, preventive, predictive and proactive are identified as below.

1. Corrective Maintenance-A maintenance approach focused on components replacement after failure.

2. Preventive Maintenance-A maintenance approach scoping to reduce the possibility of failure due to equipment degradation.

3. Predictive Maintenance-A maintenance approach which determines the condition of the equipment and consequently consider the maintenance approach.

4. Proactive Maintenance- A maintenance approach which considers the pre-alert actions discovered from system's performance malfunctions that may lead to machinery deterioration. In further, it analyses the root causes of breakdown events and set operational limits.

1.1.2 Maintenance Methodologies

These are identified in [9] as maintenance policies and through research, it is discovered that the clustering of them is uniform compared to maintenance strategies which are described above.

1. Reliability Centered Maintenance- strives to pursue reduction of maintenance downtime, expenditures and enhancement of safety and equipment reliability.

2. Total Productive Maintenance- strives to achieve perfect production with no breakdowns, no accidents, no defects and no small stops or slow running.

3. Total Quality Management – strives to improve the quality in every aspect

4. Maintenance Risk based Methodologies- strives to minimize the occurrence of critical incidences

5. Asset Management– strives to achieve ultimate performance by reducing the running expenses and increasing the availability of the asset.

6. Computerized Maintenance Management Systems- an automated maintenance management system enhanced by computerized tools for asset management.

7. Condition Based Maintenance– monitors the actual condition of the asset to decide on which maintenance actions should be done.

1.1.3 Condition Monitoring Technologies

Condition Based Maintenance (CBM) is the latest maintenance methodology, which evaluates the equipment while in operation. Here, Condition Monitoring (CM) technology is exercised by evaluating measurable parameters using recording tools.

CM is the process of monitoring the condition of a parameter (vibration, temperature etc.) in a machinery, in order to recognize a substantial change in behavior which is indicative of a developing fault. The use of CM supports maintenance actions to be planned in order to prevent consequential damages. Another benefit of CM is the ability to address the conditions; that would curtail the lifespan of the machinery, before developing into a major failure.

Following are the most known CM technologies which expand the notion of CM into diagnostics and in further prognostics.

1. Vibration Monitoring-offers early warning of equipment faults involving parameters such as loading frequency, rotational speed and material state.

2. Thermography-offers identification of hot and cold spots which provides early warnings of the failures of equipment.

3. Oil Analysis Monitoring-offers laboratory concentration analysis for the composition of equipment wear particles. It also offers lubricant degradation analysis for chemical as well as physical characteristics.

4. Acoustic and Ultrasonic Monitoring-offers identification of leakages and other problems which produce a broad range of sounds.

5. Monitoring Diagnostics-process of diagnosing the failure of the machine.

6. Monitoring Prognostics-process of estimating the Remaining Useful Lifetime (RUL) of the machine.

1.1.4 Condition Monitoring Optimization Tool

Followings are the condition monitoring optimization tools which can be used to enhance the efficiency and precision of the already discussed condition monitoring technologies in chapter 1.1.3.

1. Artificial Intelligent Approaches-assist equipment degradation assessment, static failure analysis, prognostics and intelligent diagnosis for condition monitoring tasks and fault detection [10]. (i.e. Artificial Neural Network (ANNs), Expert Systems (ESs), Evolutionary Algorithms (EAs) and Fuzzy Logic Systems).

2. Signal Processing and Optimization Methods-assess the accuracy of the failure detection as it consists of signal de-noising processes, through which collected data are analyzed and unnecessary information is removed, rendering the signal filtering [11]. (i.e. Short Time Fourier Transforms (STFT), Continuous Wavelet Transforms (CWT) and Wigner-Ville Distributions (WVD)).

3. Probabilistic Methods- visualize the occurrences of failures as independent incidents for each concerned system component [12]. (i.e. Fault Tree Analysis (FTA), Dynamic Fault Tree Analysis (DFTA), Markov Analysis (MA), Failure Mode and Effect Analysis (FMEA)).

1.2 Literature Review

Electric power utilities recurrently carry out preventive maintenance programs in order to retain their assets in favorable condition. At present, the role of maintenance is predominantly significant as the procurement of new equipment is not very feasible due to financial constraints.

Thus, appropriate management of existing assets in electricity network is essential to ensure an uninterrupted power supply to the consumers. Network asset condition is assessed based on financial performance and reliability. Those are the two main aspects concerned when managing assets of existing electricity network and smart grids as well [13]. In the past, attempts to approximate the balance of those two aspects have often been based on trial and error. But later, probabilistic models were proposed for this purpose.

Probabilistic models could be used to evaluate the financial benefits and reliability of the maintenance aspects of electrical assets in power networks. Few such models are discussed in the literature [14-27]. The probabilistic models proposed in [14-23] are unable to represent the actual maintenance situation of electrical assets accurately. This has been revealed in [24]. In order to overcome this issue, a new probabilistic maintenance model is proposed in [25]; which could represent the actual inspection and maintenance situation of a degrading asset. That particular maintenance model is applied in [27] to select the optimal inspection rates of air circuit breakers.

Applications of these probabilistic models are limited owing to the fact that unavailability of real data of electrical assets. The same actual set of data specified in [15] is used for most of the cases discussed in the literature [15, 16, 17, 22, 23, and 27]. The aim of this research work; is to apply the concepts used in [25], for optimization of maintenance aspects of diesel engines using the opinions of experts and actual historic data.

1.3 The Objectives

As discussed in the literature review in chapter 1.2, applications of probabilistic maintenance models are limited due to the reluctance in providing actual data.

The main objective of this research is to apply a probabilistic maintenance model for optimization of maintenance actions of diesel engines.

The specific objectives of this research are as follows.

1. To develop a probabilistic maintenance model for diesel engines based on practical concepts discussed in the literature
2. To ascertain optimal maintenance policies for diesel engines and to assess the effectiveness of the present maintenance policy.

3. To forecast the condition of diesel engines for deciding when and how to carry out maintenance work.

1.4 Thesis Outline and Organization

The organization of this thesis is as follows.

- Chapter 2: In chapter 2, a maintenance model is developed for inspection and maintenance optimization of diesel engines; based on the concepts discussed in [25].
- Chapter 3: In Chapter 3, several performance measures are computed by solving the developed model in Chapter 2; using standard Markov methods. Further, a sensitivity analysis is conducted; to perceive the behavior of reliability indices and costs.
- Chapter 4: In Chapter 4, Optimal inspection based maintenance policy is found out using a grid search algorithm implemented in MATLAB.
- Chapter 5: In Chapter 5, State Prediction Tool is developed in order to validate the model.
- Chapter 6: In Chapter 6, Conclusion and future work are presented.

2 A PROBABILISTIC MAINTENANCE MODEL FOR DIESEL ENGINES

2.1 The Probabilistic Maintenance Model proposed for Diesel Engines

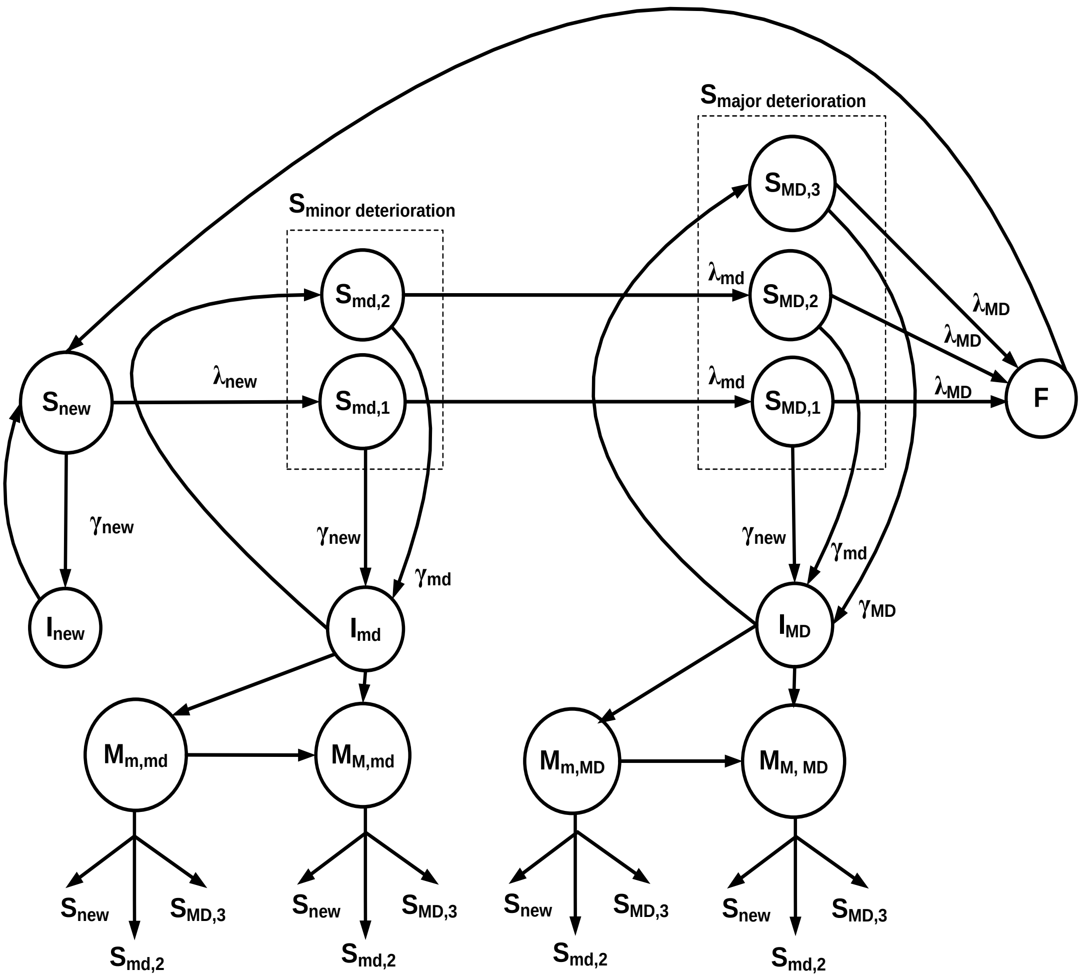

Figure 2.1 The State diagram of the maintenance model of diesel engines

Based on the practical concepts discussed in [25]; the state diagram of the maintenance model illustrated in Fig.2.1, is established for diesel engines. This state diagram is considered as the basis of the inspection and maintenance model proposed for diesel engines.

In this state diagram, the deterioration process of a diesel engine is modeled using new, minor deterioration and major deterioration states. These states are denoted by S_{new}, $S_{minor\ deterioration}$ and $S_{major\ deterioration}$ respectively. The states

$S_{minor\ deterioration}$ and $S_{major\ deterioration}$ have sub deterioration states. $S_{minor\ deterioration}$ has two sub deterioration states, i.e. $S_{md,1}$ and $S_{md,2}$. $S_{major\ deterioration}$ has three sub deterioration states, i.e. $S_{MD,1}$, $S_{MD,2}$ and $S_{MD,3}$.

Throughout the operational life time of diesel engines; inspections are carried out on regular basis. The inspection states corresponding to S_{new}, $S_{minor\ deterioration}$ and $S_{major\ deterioration}$ states are illustrated in fig.2.1 using I_{new}, I_{md}, and I_{MD}, respectively.

If required, maintenance actions are performed after inspections. Activities performed in minor and major maintenance schedules of diesel engines are shown in Table 2.1.

Table 2.1 Maintenance Activities

Minor maintenance activities	**Major maintenance activities**
• Replacing all baffle screws of fuel pumps • Servicing and pressurizing of fuel injector nozzles • Checking and adjusting of tappet clearances • Cleaning of duplex filters	• Replacing all baffle screws of fuel pumps • Servicing and pressurizing of fuel injector nozzles • Checking and adjusting of tappet clearances • Cleaning of duplex filters • Servicing of fuel injector pumps • Servicing and inspection of all engine heads • Cylinder liner measuring and horning • Servicing of the turbo-charger

Performance of minor and major maintenance activities on diesel engines at $S_{minor\ deterioration}$ and $S_{major\ deterioration}$ states are modeled using maintenance states $M_{m,md}$, $M_{M,md}$, $M_{m,MD}$, and $M_{M,MD}$, respectively.

Operational staff of the power station examines the engines on regular basis. As per the knowledge of the operational staff; if the diesel engine is in “New” condition (i.e. if the diesel engine is in S_{new} or $S_{md,1}$ or $S_{MD,1}$); inspections should be carried out at an inspection rate of γ_{new}. If the operational staff identifies that the diesel engine has minor deteriorations (i.e. if the diesel engine is in $S_{md,2}$ or $S_{MD,2}$), inspections should be carried out at a rate of γ_{md}. If it is identified that the diesel engine has major deteriorations (i.e. if the diesel engine is in $S_{MD,3}$), inspections should be carried out at a rate of γ_{MD}.

The state of condition of the diesel engine might get improved, worsened or remained as it was; after the performance of minor and major maintenance activities. If no any inspection and maintenance activities are being conducted, the diesel engine would start deteriorating gradually and reach the failure state of the diesel engine which is denoted as state F. Once the diesel engine get failed, it should be restored back to its original condition. Deterioration rates from S_{new} to $S_{minor\ deterioration}$ and $S_{minor\ deterioration}$ to $S_{major\ deterioration}$ are λ_{new} and λ_{md}, respectively. λ_{MD} is the failure rate of the diesel engine.

2.2 Data for Developed Maintenance Model

The data required for the proposed maintenance model are obtained through inspection, maintenance and failure records of a diesel engine which is presently under operation.Opinions of experts were also used for this purpose. Accordingly calculated deterioration rates and inspection rates are tabulated in Table 2.2.

Table 2.2 Deterioration Rates and Inspection Rates

Rate	**Value (1/years)**
λ_{new}	1.47
λ_{md}	0.5
λ_{MD}	0.72
γ_{new}	3
γ_{md}	6
γ_{MD}	6

Probabilities of choosing maintenance actions and outcome probabilities after inspection and maintenance activities are shown in Table 2.3. The choice probabilities associated with the various possible outcomes are based on user input and can often be estimated from historical records.

Table 2.3 Choice and Outcome Probabilities

State transition		**Probability**
From	***To***	
I_{md}	$M_{m,md}$	1
	$M_{M,md}$	0
I_{MD}	$M_{m, MD}$	0.1
	$M_{M,MD}$	0.9
$M_{m,md}$	$M_{M,md}$	0.05
$M_{m,md}$	S_{new}	0.5
	$S_{md,2}$	0.44
	$S_{MD,3}$	0.01
$M_{M,md}$	S_{new}	0.9
	$S_{md,2}$	0.1
	$S_{MD,3}$	0
$M_{m, MD}$	$M_{M,MD}$	0.8
$M_{m, MD}$	S_{new}	0
	$S_{md,2}$	0.1
	$S_{MD,3}$	0.1
$M_{M,MD}$	S_{new}	0.9
	$S_{md,2}$	0.1
	$S_{MD,3}$	0

Table 2.4 gives the mean duration obtained from [28].

Table 2.4 Mean Durations

State	**Value**
I_{new}	1 day
I_{MD}	1 day
I_{MD}	1 day
F	8 weeks
$M_{m,md}$	1 weeks
$M_{M,md}$	6 weeks
$M_{m, MD}$	1 weeks
$M_{M,MD}$	6 weeks

Costs of performing an inspection, a minor maintenance, a major maintenance and a repair are obtained from [29] and given in Table 2.5.

Table 2.5 Average cost per activity

Activity	**Average Cost per Activity (LKR)**
Inspection	0.1 million
Minor maintenance	4 million
Major maintenance	15 million
Repair	80 million

2.3 Discussion

A probabilistic maintenance model is established for inspection and maintenance activities of diesel engines based on the concepts discussed in [25]. The model parameters are calculated using actual data obtained from inspection and maintenance record history of diesel engines and the opinions of experts. Choice probabilities are also estimated based on historical records.

3 RELIABILITY AND COST EVALUATION

The probabilistic maintenance model of the diesel engine is developed by transforming the state diagram illustrated in Fig. 2.1 to a semi-Markov model. That semi-Markov model is solved using analytical equations in MATLAB in order to find out costs and reliability indices [30, 31].

3.1 Performance Measures

Performance measures are computed as follows, using the probabilistic maintenance model described in section 2.1. These performance measures can be used to measure the effect of inspection and maintenance on cost and reliability of the diesel engine.

3.1.1 First Passage Time (FPT)

As per the Markov concepts, FPT is the mean time taken to reach a particular state of condition for the first time starting from any state of condition. It can be calculated using standard Markov equations [30]. With no inspection and maintenance activities are being carried out, the mean time from 'new' state of condition to failure state; could be calculated as follows:

$$FPT = (1/\lambda_{new} + 1/\lambda_{md} + 1/\lambda_{MD})$$

$$FPT = (1/1.47 + 1/0.5 + 1/0.72) = 4.06 \text{ years}$$

3.1.2 Life Cycle Cost (LCC)

LCC is comprised of inspection, maintenance and repair costs of the diesel engine per annum [32].

$$LCC = C_I * \sum_{i=1}^{3} \frac{P(Ii)}{d(Ii)} + C_M * \sum_{j=2}^{3} \frac{P(Mj)}{d(Mj)} + C_{MM} * \sum_{k=2}^{3} \frac{P(MMk)}{d(MMk)} + C_F$$

-where C_I, C_M, C_{MM} & C_F are costs of performing inspection, minor maintenance, major maintenance and repair activities respectively. P(D) and d(D) are the steady state probability of state D and mean duration in state D, respectively.

3.1.3 Unavailability (U)

Unavailability is the probability of which the particular equipment is not functioning. This can be calculated by simply adding the steady state probabilities of inspection, maintenance and failure states of the diesel engine where equipment is not in operation.

$$U = \sum_{i=1}^{3} P(Ii) + \sum_{j=2}^{3} P(Mj) + \sum_{k=2}^{3} P(MMk) + P(F)$$

-where P(D) and d(D) are the steady state probability of state D and mean duration in state D, respectively.

3.2 Reliability and cost measures for the existing practice

Reliability indices and annual costs obtained by solving the model for existing practice in MATLAB are shown in Table 3.1 and Table 3.2, respectively.

Table 3.1 Reliability Indices

Reliability Index	**Value (years)**
MTTF from S_1	31.95
MTTF from S_2	31.27
MTTF from S_3	26.46
MTBF	34.03

Table 3.2 Annual Costs

Annual Cost	**Value (LKR/year)**
Inspection Cost	0.3105 million
Maintenance Cost	8.1534 million
Repair Cost	2.3508 million
Life Cycle Cost	10.8147 million

3.3 Sensitivity Analysis

In this section, a sensitivity analysis is conducted order to perceive the behavior of the annual life cycle cost against the three inspection rates; γ_{new}, γ_{md} and γ_{MD}.

The annual life cycle cost is computed by adding the annual inspection, maintenance and the repair cost of the diesel engine. Then, each inspection rate is varied from zero to twenty per year, while retaining the other two inspection rates as per the values used in the existing maintenance practice. The variation of the annual life cycle cost with γ_{new}, γ_{md} and γ_{MD} is plotted in Figs. 3.1, 3.2 and 3.3, respectively.

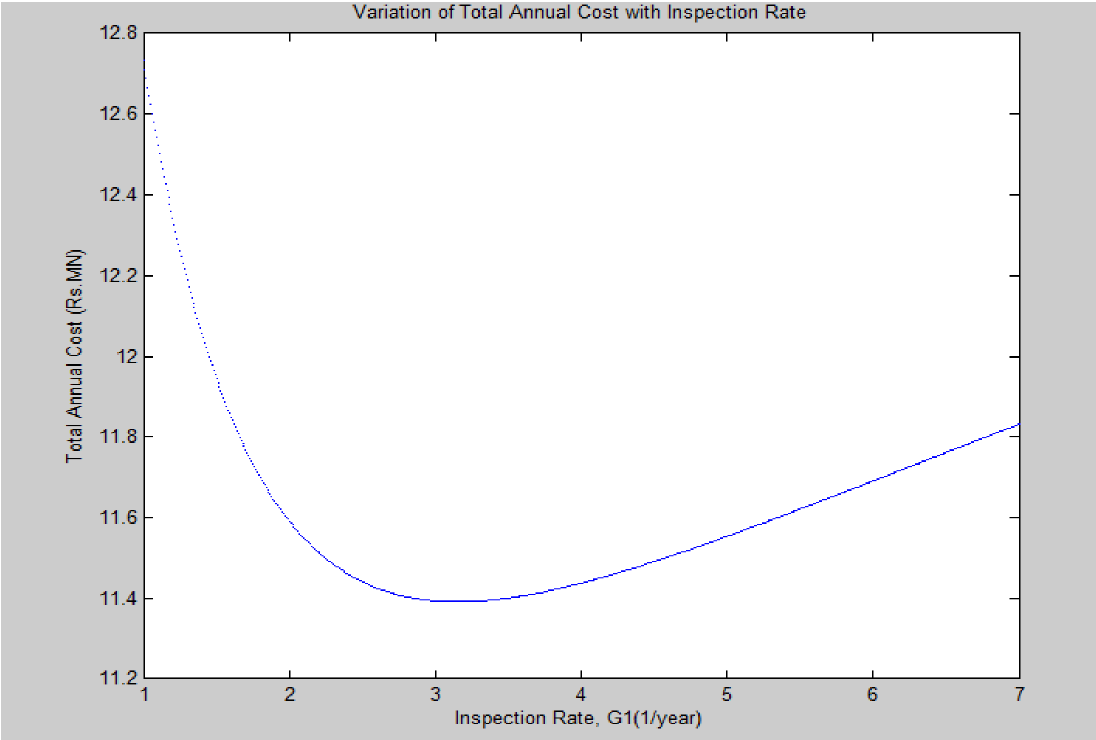

Figure 3.1 The variation of the life cycle cost of the diesel engine with γ_{new}

As illustrated in Fig. 3.1, the total annual cost gets minimized when γ_{new} equals to 3.2.

The variation of total annual cost against inspection rate γ_{md} is shown in Fig. 3.2.

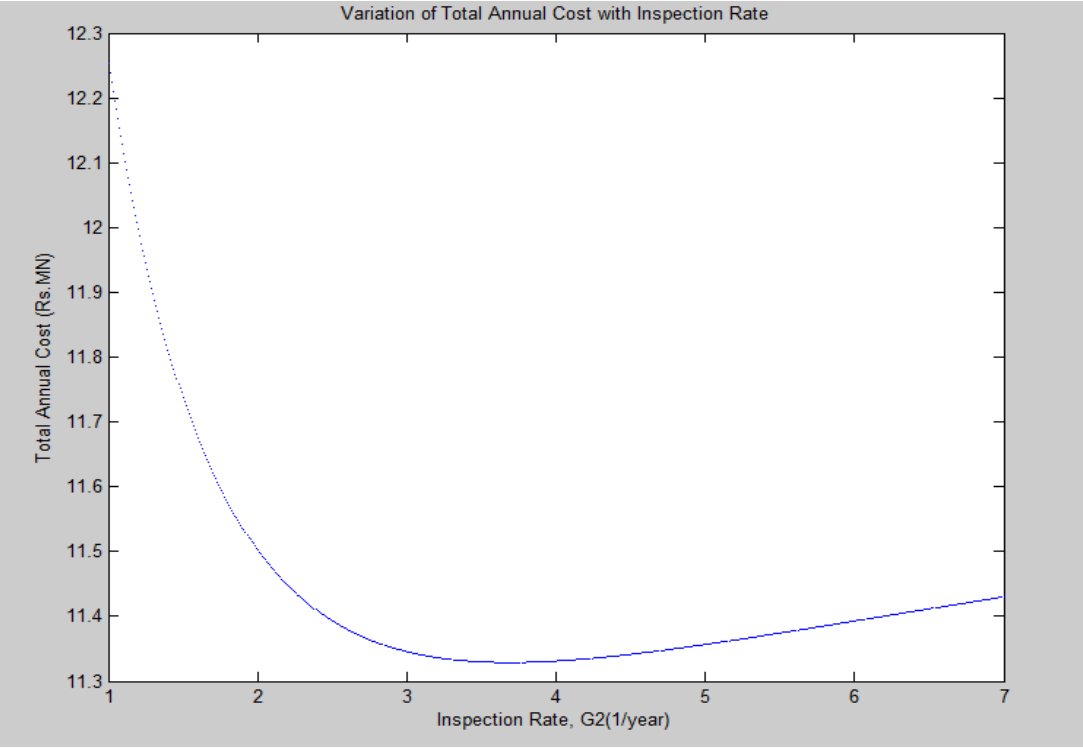

Figure 3.2 The variation of the life cycle cost of the diesel engine with γ_{md}

As illustrated in Fig. 3.2, the total annual cost gets minimized when γ_{md} equals to 3.6.

The variation of total annual cost against inspection rate γ_{MD} is shown in Fig. 3.3.

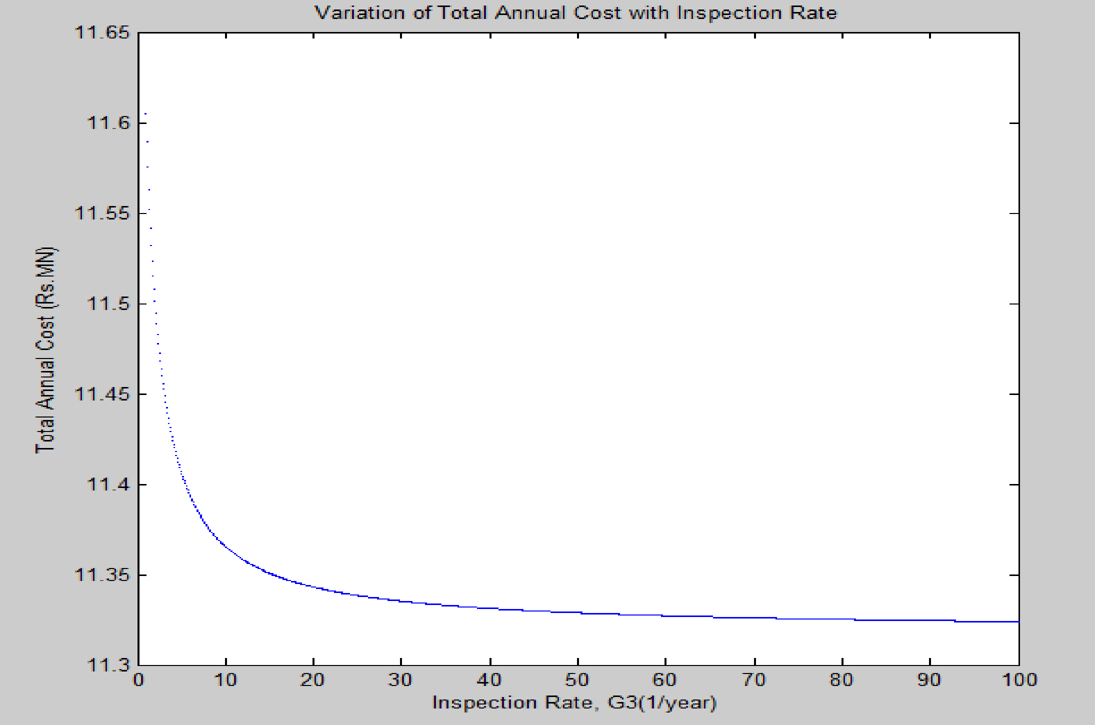

Figure 3.3 The variation of the life cycle cost of the diesel engine with γ_{MD}

As illustrated in Fig. 3.3, the total annual cost reduces when γ_{MD} increases.

The variation of unavailability against inspection rate γ_{new} is shown in Fig. 3.4.

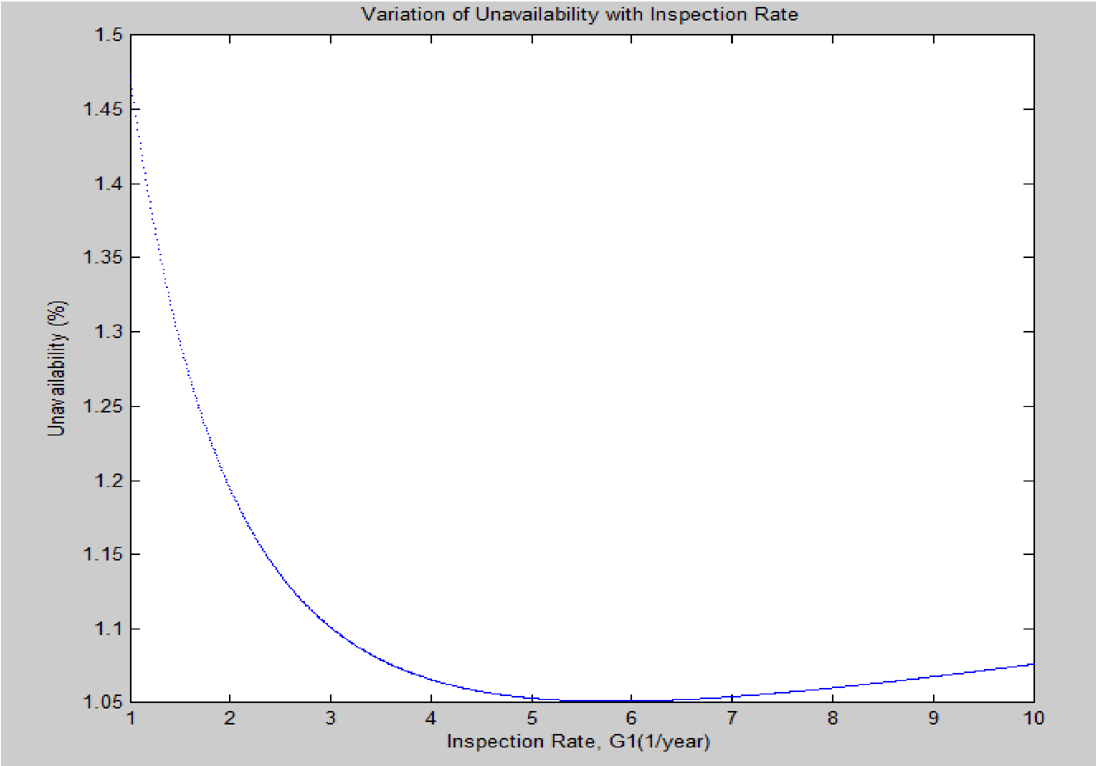

Figure 3.4 The variation of the unavailability of the diesel engine with γ_{new}

As illustrated in Fig. 3.4, the unavailability gets minimized when γ_{new} equals to 6. Unavailability is very less even when γ_{new} equals to 4 where total annual cost get minimized.

The variation of unavailability against inspection rate γ_{md} is shown in Fig. 3.5.

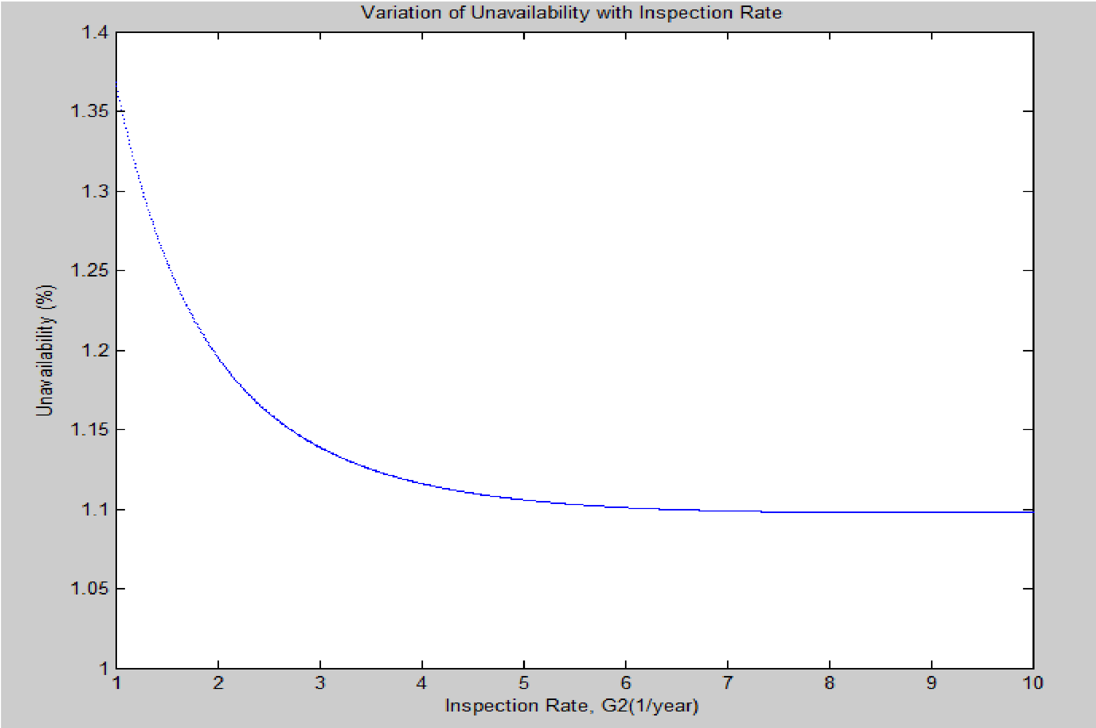

Figure 3.5 The variation of the unavailability of the diesel engine with γ_{md}

As illustrated in Fig. 3.5, the unavailability of the diesel engine reaches a fairly low value when γ_{md} equals to 4 where total annual cost get minimized.

The variation of unavailability against inspection rate γ_{MD} is shown in Fig. 3.6.

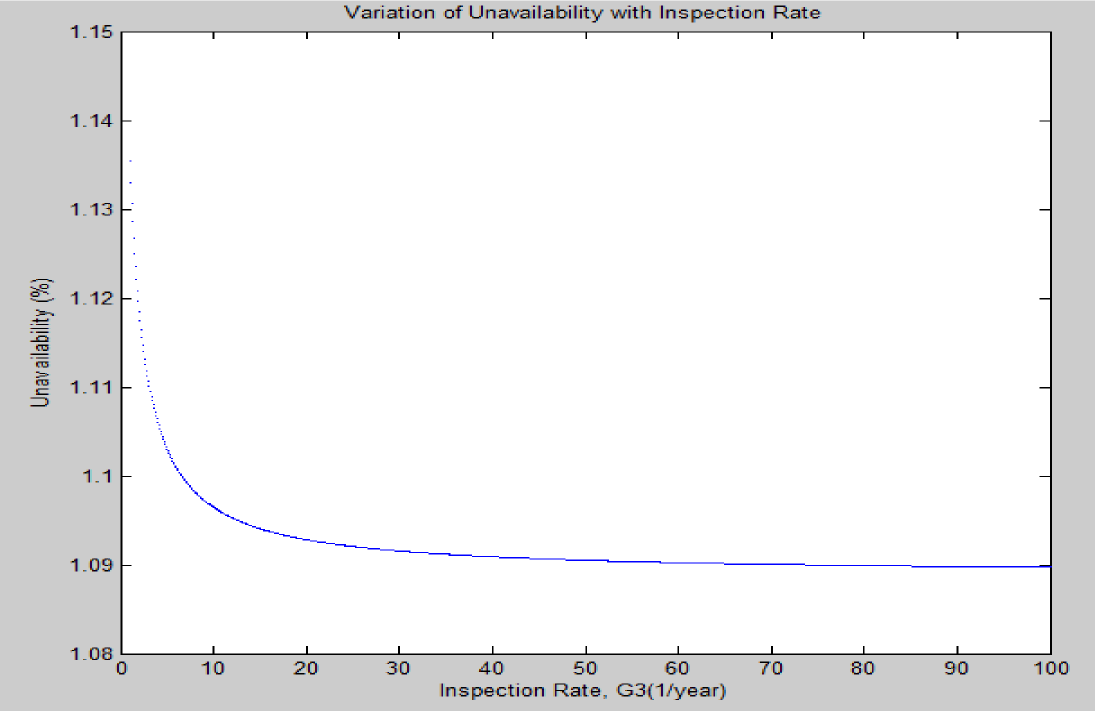

Figure 3.6 The variation of the unavailability of the diesel engine with γ_{MD}

As illustrated in Fig. 3.6, the unavailability of the engine reduces when γ_{MD} increases.

3.4 Discussion

In order to examine the suitability of existing maintenance practice; performance measure like First Passage Time, Life Cycle Cost and Unavailability etc. are calculated using the probabilistic maintenance model developed in chapter 2. Then, the effects of inspection and maintenance activities on those performance measures such as life cycle cost and unavailability are investigated using a sensitivity analysis.

4 MAINTENACE OPTIMIZATION

The aim of this chapter; is to ascertain the optimal inspection and maintenance policy for diesel engines using a grid search algorithm implemented in MATLAB. Unlike in the sensitivity analysis, in this algorithm, all three inspection rates are varied to find the set of optimal inspection rates in which the annual life cycle cost of diesel engines get minimized.

4.1 Problem Formulation

4.1.1 Objective Function

The objective of this optimization problem is to find out values of the variables that minimizes the total life cycle cost while satisfying the constraints.

The objective function:

- Minimize {Total Life Cycle Cost}

  Where total life cycle cost = annual inspection cost + annual maintenance cost + annual repair cost of the diesel engine

4.1.2 Decision Variables

Decision variables of this optimization problem are γ_{new}, γ_{md} & γ_{MD}.

4.1.3 Constraints

The following constraints were imposed based on practical limitations.

- Max { γ_{new} } = 20 per year
- Max { γ_{md} } = 20 per year
- Max { γ_{MD} } = 20 per year

4.2 Grid Search Algorithm

As deliberated in section 4.1.1, the total cost function of a diesel engine is a highly non-linear function of inspection rates; γ_{new}, γ_{md} & γ_{MD}. Hence, it would be challenging to find the optimal values for the inspection rates; γ_{new}, γ_{md} & γ_{MD} which minimize the total cost; using mathematical programing tools. Consequently, a grid search algorithm is utilized in order to ascertain the optimal inspection rates for diesel engines.

Grid search is an approach used for parameter tuning that will methodically evaluate a model for each combination of parameters in a grid. In Grid Search, every combination of the list of parameters are evaluated and the best combination of the parameters is chosen.

As such, a grid search algorithm is implemented in MATLAB in order to solve the optimization problem defined in section 4.1.1. The steps of the algorithm which gives optimal values thorough a discrete grid search; are as follows:

1. A discrete value set, i.e. (0,……, γ_{max}) is defined for the inspection rates, where γ_{max} is the maximum possible inspection rate. Inspections could not be practically performed at an extensively high rate due to constraints such as cost, time, and labour etc.
2. The defined discrete value set of inspection rates is assigned for grids of values of γ_{new}, γ_{md} & γ_{MD}. Let G_1=grid of values of γ_{new}, G_2=grid of values of γ_{md} and G_3=grid of values of γ_{MD}.
3. The Cartesian product of grids of values of inspection rates; γ_{new}, γ_{md} & γ_{MD} are computed as shown below.

   $\Omega = G_1 \text{ x } G_2 \text{ x } G_3$

   Each element set k ε Ω, which comprises of the inspection rate values of γ_{new}, γ_{md} & γ_{MD}; is corresponded to one possible maintenance scenario.
4. Using Markov Equations, the probabilistic maintenance model of the diesel engine is analytically solved for each k ε Ω in order to calculate the total annual life cycle cost (LCC).
5. By considering the total annual life cycle cost of each k ε Ω, k corresponded to the minimum total life cycle cost (which is denoted by k_{opt}), is obtained. k_{opt} represents optimal maintenance scenario and consists of the optimal inspection rate values of γ_{new}, γ_{md} & γ_{MD}.

Grid search could offer the best combination; but sometimes it could be a time consuming process.

4.3 Optimal Inspection Rates

In the grid search algorithm, values from zero to 20 (γ_{max}) per year, with a step size of one per year; are assigned to each inspection rate (i.e. for γ_{new}, γ_{md} and γ_{MD}). Then, the annual life cycle cost is computed for each set inspection rate value set of γ_{new}, γ_{md} and γ_{MD}. The particular set of values that gives the minimum life cycle cost (LCC) is considered as the optimal value set of inspection rates. Table 4.1 presents the optimal inspection rates.

Table 4.1 Optimal Inspection Rates

Rate	Value (1/year)
γ_{new}	4
γ_{md}	4
γ_{MD}	20

4.4 Reliability & costs for the optimal policy

For the optimal inspection rates, reliability indices are calculated. The reliability indices and costs corresponding to the optimal inspection and maintenance policy are tabulated in Table 4.2 and Table 4.3.

Table 4.2 Reliability Indices obtained for the optimal policy

Reliability Index	Value (years)
MTTF from S_1	37.6
MTTF from S_2	36.9
MTTF from S_3	31.9
MTBF	40.1

Table 4.3 Annual Costs obtained for the optimal policy

Annual Cost	Value (LKR/year)
Inspection Cost	0.3758 million
Maintenance Cost	8.3440 million
Repair Cost	1.9942 million
Life Cycle Cost	10.7140 million

4.5 Comparison between present maintenance policy and the optimal maintenance policy

As mentioned in Table 2.2, the values of γ_{new}, γ_{md} and γ_{MD} used in the current inspection based preventive maintenance practice are 3, 6 and 6 per year, respectively. As shown in Table 4.1, the optimal values for γ_{new}, γ_{md} and γ_{MD} are 4, 4 and 20 per year, respectively. The model suggests performing some more inspections at the new state, some less inspections in the minor deterioration state and a lot more inspections at the major deterioration state, than in the current practice.

When the reliability indices in Table 3.1 and Table 4.2 are compared with each other, it can be seen that the reliability is improved when inspection based preventive maintenance is conducted at optimal rates suggested by the model.

The annual costs of the present practice shown in Table 3.2 can be compared with the annual costs of the optimal policy shown in Table 4.3. In the current practice, the inspection and maintenance costs are less, when compared to the inspection and maintenance costs of the optimal policy. On the other hand, in the optimal policy, repair cost is significantly lower than that cost corresponding to the present maintenance practice. Performing more inspections at the new state and the major deterioration state could be the reason for getting a higher inspection cost and lower repair cost in implementing the optimal inspection and maintenance policy.

4.6 Discussion

Together with a grid search algorithm presented in this chapter, the model developed in Chapter 3, is used to suggest the optimal inspection and maintenance policy for diesel engines according to the optimization framework discussed in section 4.1.

The sensitivity analysis in section 3.3 also suggested maximizing of inspection rate γ_{MD} to minimize the annual life cycle cost of diesel engines. Even if the diesel engine is found in a major deterioration state; it would not be practical, to conduct inspections and maintenance activities at a very high rate; in terms of labour, time and cost etc.

As the existing practice has a higher inspection rate at the minor deterioration state, it also has a higher capability of reducing major deteriorations and failures of the diesel engine. Therefore, a massive reduction could not be observed in the annual life cycle cost of the optimal policy. However, the life cycle cost of diesel engines could be further reduced by adopting the optimal inspection and maintenance policy.

5 STATE PREDICTION OF DIESEL ENGINES

The prediction of states could be beneficial to forecast the condition of diesel engines in advance and act accordingly. When the diesel engine is forecasted to be in a higher deterioration state, the rate of condition monitoring of the same can be increased. The deterioration and maintenance process of diesel engines could be depicted by a simple state diagram as shown in Fig. 5.1

States S_1, S_2 and S_3 of this state diagram denote the deterioration condition of the diesel engine corresponding to states 1, 2 and 3, respectively and the engine failure state is denoted by F. When the diesel engine gets failed, it is restored back to state, S_1. λ_1 and λ_2 are deterioration rates of the diesel engine, and λ_3 is the transition rate from state, S_3 to failure state, F. Repair rates of the diesel engine corresponding to states 1,2, and 3 are denoted by μ_1, μ_2 and μ_3 respectively. Those repair rates are the reciprocal of the mean repair time. The past data of diesel engines, are analyzed in order to calculate these model parameters. Deterioration rates λ_1, λ_2 and λ_3 are

$$\lambda_c = \frac{1}{t_{S_c}}$$

calculated using the following equation; when c = 1, 2 and 3, correspondingly.

Here, t_{Sc} is the mean time spent in corresponding deterioration state c.

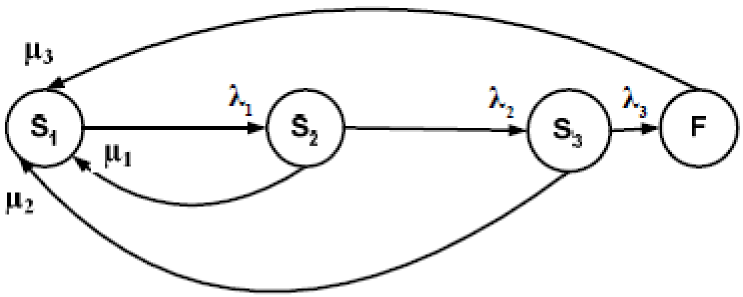

Figure 5.1 The state diagram of the state prediction model

A state diagram of a diesel engine could be represented mathematically by a Markov process. Then the transition probability matrix is computed using the transition rate matrix of this Markov process.

The deterioration states of the diesel engine are enumerated in MATLAB according to these transition probabilities. The average of 8 enumerations is considered as the predicted state of the diesel engine.

5.1 State Prediction tool for Diesel Engine

This proposed tool could be used by utilities to forecast the deterioration state of condition of the diesel engines. The ability to simulate the state of condition of a diesel engine could be used to predict the amount of deterioration of the diesel engine and alter the present maintenance policy accordingly. If the state of condition of the diesel engine could be predicted in advance; necessary preventive measures could be taken by the utilities, in order to avoid failures of the diesel engine.

5.2 Case Studies

5.2.1 Case 1: For present maintenance policy

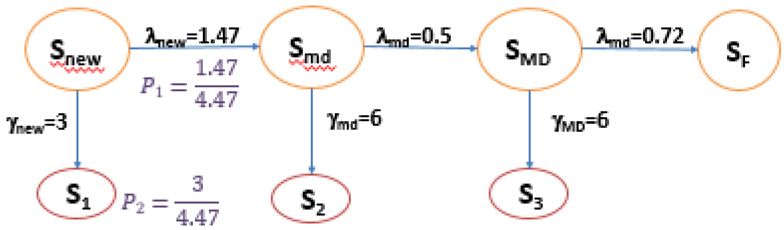

Figure 5.2 State Prediction Tool for present maintenance Policy

Results obtained for a diesel engine with present maintenance policy are shown in Table 5.1. Those results are obtained after executing state prediction tool in MATLAB.

Table 5.1 Current and predicted states for the present policy

Current State	**Predicted State**
S_1	S_2
S_1	S_1
S_1	S_1
S_2	S_3
S_2	S_2
S_3	S_3
S_3	S_4
S_3	S_3

5.2.2 Case 2: For Optimal maintenance policy

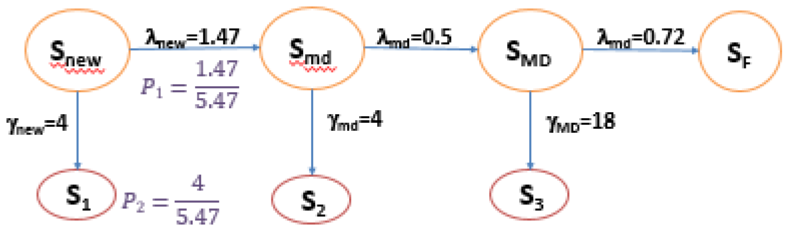

Figure 5.3 State Prediction Tool for optimal maintenance Policy

Results obtained for a diesel engine with optimum maintenance policy are shown in Table 5.2. Those results are obtained after executing state prediction tool in MATLAB.

Table 5.2 Current and predicted states for the optimal policy

Current State	**Predicted State**
S_1	S_1
S_1	S_1
S_1	S_2
S_2	S_2
S_2	S_3
S_3	S_3
S_3	S_3
S_3	S_4

5.3 Software Development

To develop the software tool with GUI interfaces and for computing purposes, Matlab is used. This is a desktop application which runs only on Windows operating system. System requirements to run this application are as follows.

- Operating System - Windows XP or higher
- Processor - Intel Pentium IV or higher
- Memory - 512 MB or higher
- Hard Disk Space - 20 GB

5.3.1 Stating a new project

Figure 5.4 shows the initial interface of the software.

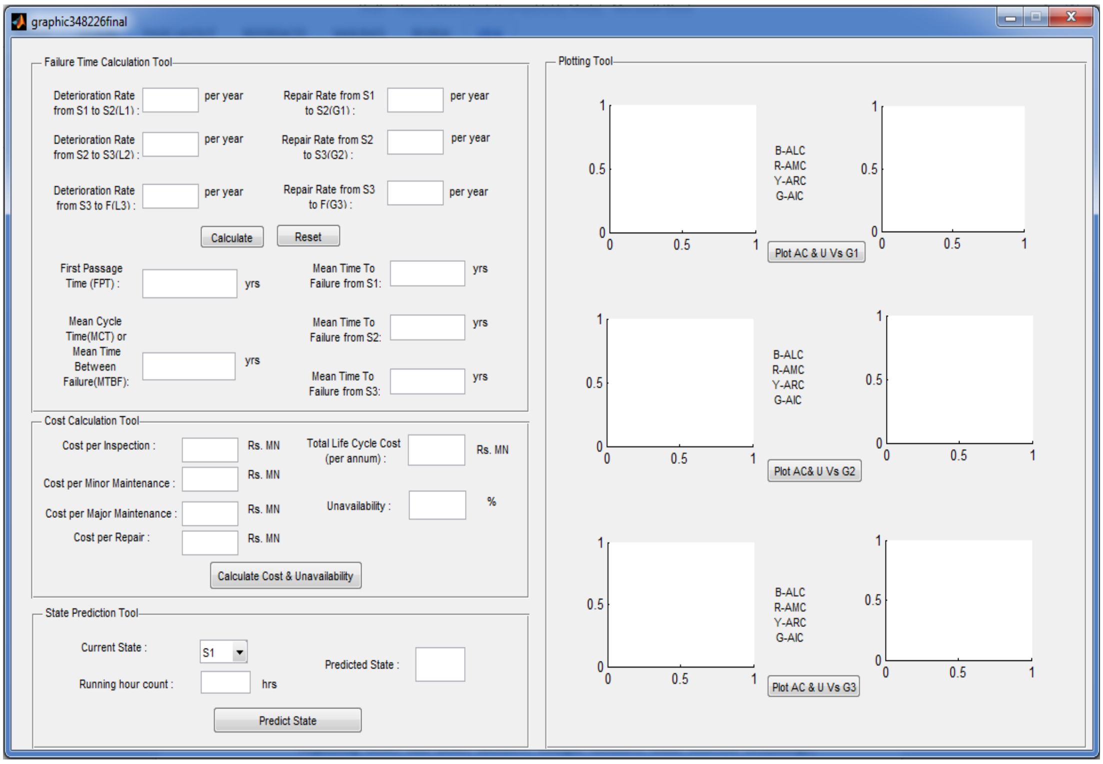

Figure 5.4 Initial interface

Deterioration rate from S1 to S2, deterioration rate from S2 to S3, deterioration rate from S3 to F, repair rate from S2 to S1, repair rate from S3 to S1 and repair rate from F to S1; have to be entered by the user. After inserting above details to the new project window, First Passage Time (FPT), Mean Cycle Time, Mean Time to Failure from state 1, Mean Time to Failure state 2, Mean Time to Failure from state 3 could be computed by pressing the calculate button as shown in Figure 5.5. Entered values can be cleared by pressing reset button, if it is required to edit or alter the values.

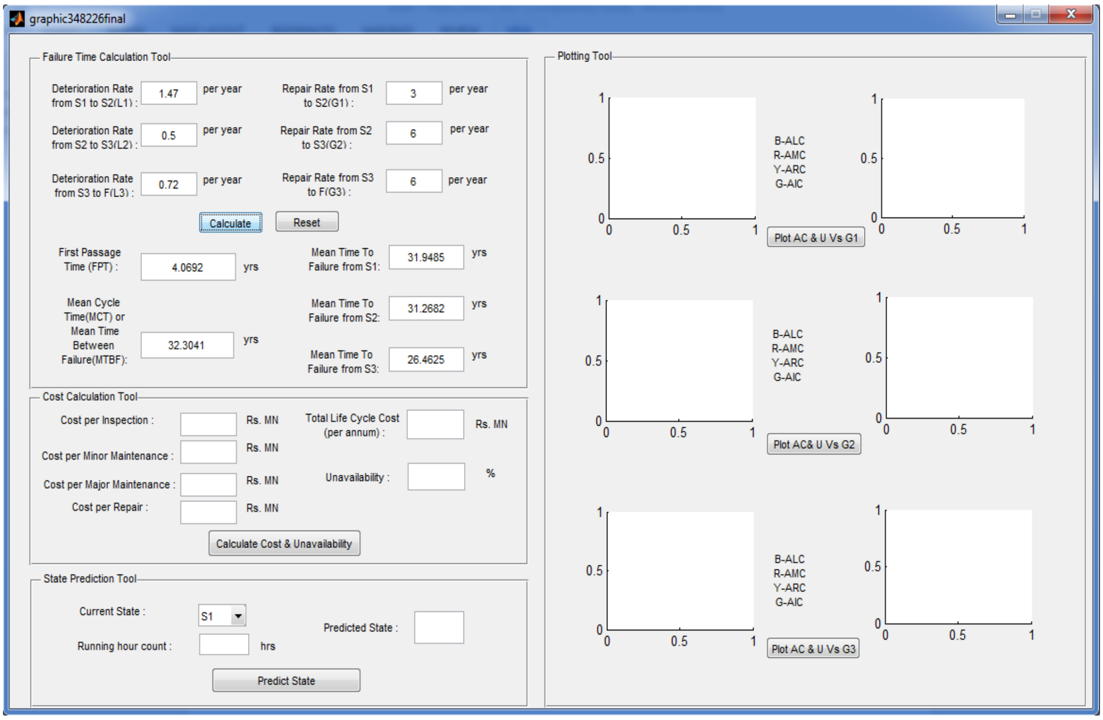

Figure 5.5: Failure time calculation tool

In the next sub-section cost calculation tool is developed. Here cost per inspection, cost per minor maintenance, cost per major maintenance and cost per repair needs to be entered by the user and Total Life Cycle Cost and Unavailability can be calculated by pressing the calculate button downstream as shown in Figure 5.6.

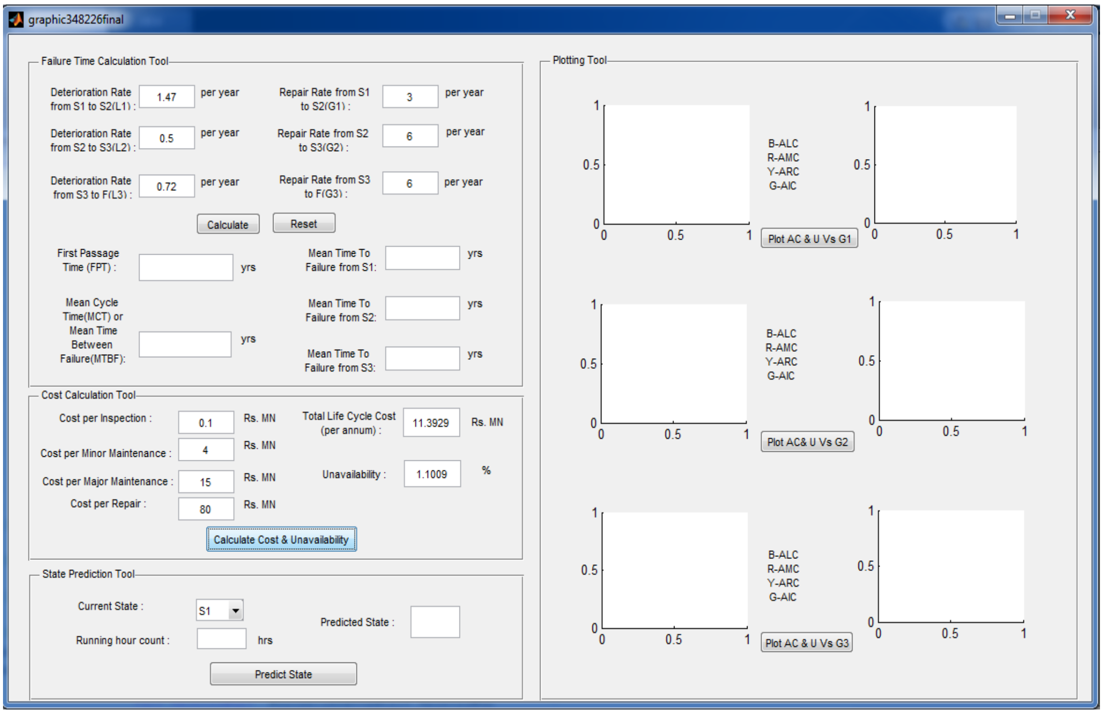

Figure 5.6: Cost calculation tool

In the plotting tool annual life cycle cost and the unavailability is plotted against inspection rates in order to find out optimum values of the same as shown in Fig. 5.7.

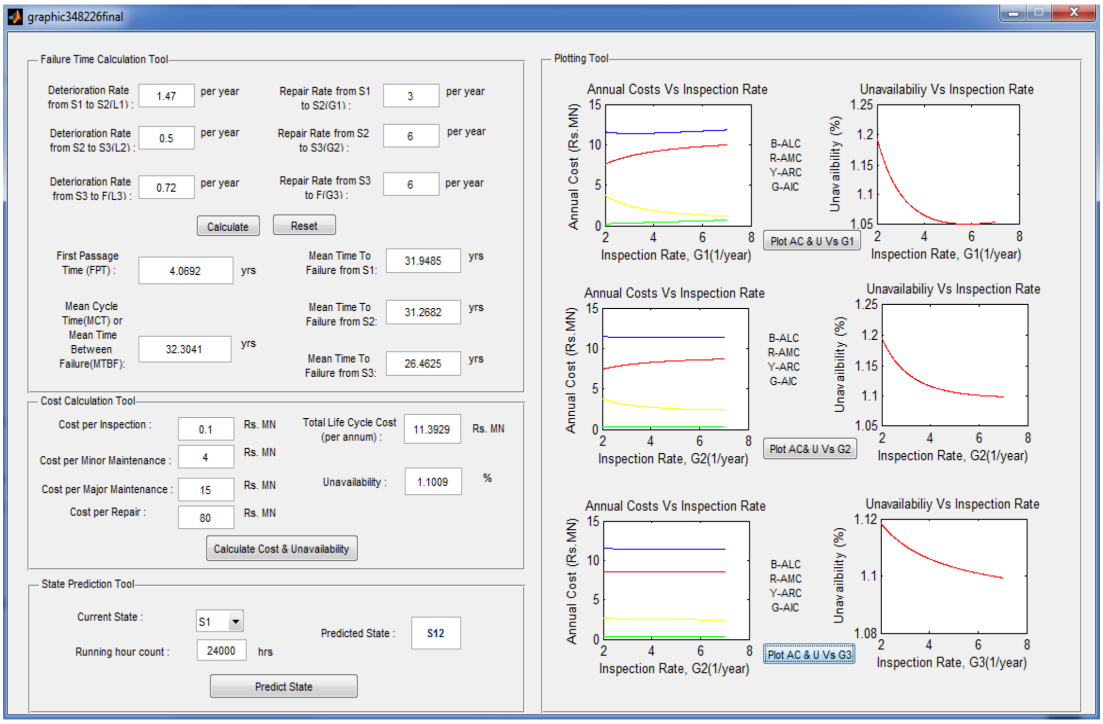

Figure 5.7: Plotting tool

The state prediction may be useful to forecast the condition of the diesel engines for utilities. For an example; the utility may escalate the condition monitoring rates of the diesel engine, if it is predicted to be found in a higher deterioration state of condition. The next section gives the predicted state based on inspection rates and maintenance rates as shown in Fig. 5.8.

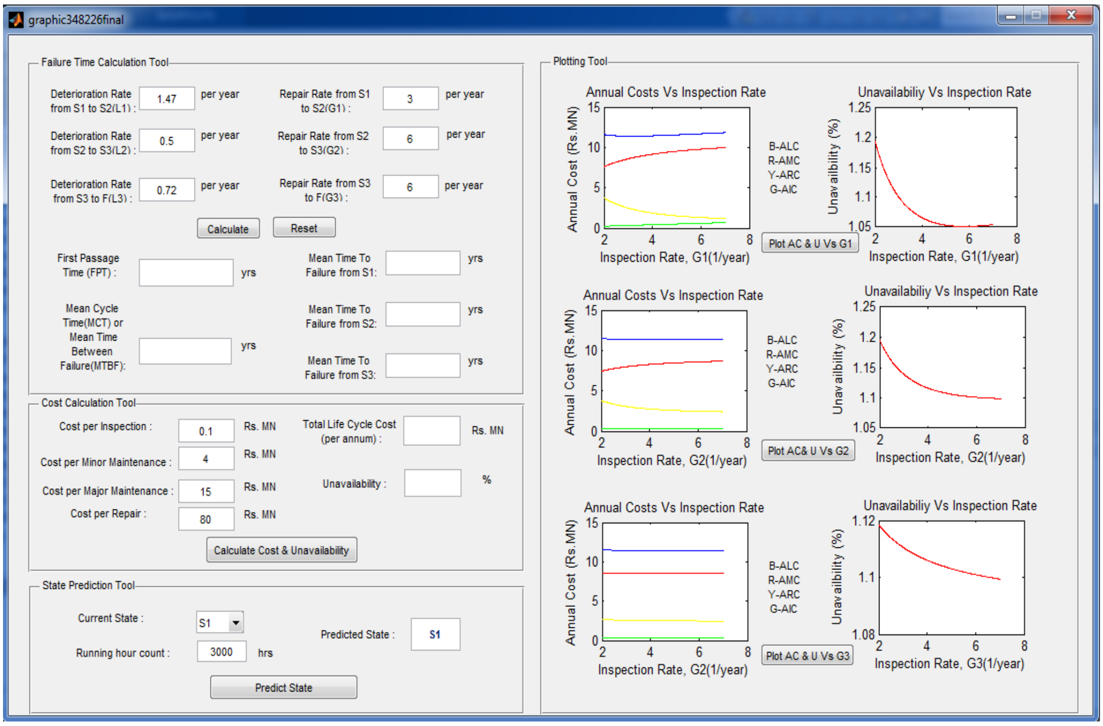

Figure 5.8 State prediction tool

For verification purposes, the predicted states could be compared with actual states.

6 CONCLUSION AND FUTURE WORK

6.1 Conclusion

State diagrams are commonly used in maintenance modelling and those maintenance models deliver precise results when the inspection rates are periodic. But in the actual world; these inspection rates are found non-periodic and the classical state diagram doesn't represent this maintenance condition accurately.

Then, a new state diagram is proposed to represent the maintenance model of diesel engines in real world, by introducing some new state of conditions to the classical state diagram; which eliminates the above mentioned error of generalized classical state diagram. In this proposed new state diagram, the inspection rate is usually established depending on the information about the state of condition of the diesel engine which is available merely after the inspection. The classical state diagrams are unable to characterize it; as the inspection rate get changed, whenever there is a transformation in the state of condition of the diesel engine without the knowledge of the operator.

Based on previous results; associated with maintenance and reliability records, a mathematical model is developed for inspection and maintenance activities of diesel engines in order to find out optimum maintenance policies [25]. The model is solved using real data obtained from historical records of diesel engines.

A reliability and cost evaluation is conducted to assess the suitability of existing maintenance practice of diesel engines, and those reliability and cost components are traded off in the optimization tasks.

The effect of inspection and maintenance activities on the annual life cycle cost and unavailability is examined through a sensitivity analysis. These sensitivity analyses show that it is more appropriate to impose a constraint on the inspection rate in terms of labour, time and cost etc.

Considering all, the objective of the maintenance optimization problem is set to minimizing total life cycle cost. A discrete grid search algorithm is utilized in MATLAB to ascertain optimal inspection rates in which minimize the objective function. When the reliability and cost measures calculated for the optimal policy are compared with those calculated values for the existing policy; it is found that the present maintenance practice of diesel engines is also a better policy which provides a lower life cycle cost and a higher reliability.

However, the annual life cycle cost could be further minimized and the reliability of diesel engines could be further improved by conducting inspection based preventive maintenance activities in an optimal manner as suggested by the model.

A state prediction tool is developed to forecast the state of condition of the diesel engine. This ability of simulating the state of condition of the diesel engine is useful for utilities to predict the next state of deterioration of the diesel engine and alter the present maintenance policy accordingly. For an example; when the state of the diesel engine is forecasted to be in a higher deterioration state, the condition monitoring rate of the diesel engine could be increased by the utility. If the state of the diesel engine could be predicted in advance; utility could take preventive measures in order to avoid failures.

A software tool is also developed which is capable of computing First Passage Time (FPT), Mean Cycle Time (MCT), annual cost components and unavailability based on user input parameters. It is also capable of plotting the annual total cost and unavailability against inspection rates.

In conclusion, it is essential to propose a motivational view of the study by presenting recommendations for further research. In this work, the interruption cost and the loss of profit are not considered, when conducting maintenance optimization. One of the upcoming research plans would be considering these costs by giving rational values.

6.2 Future work

- Evaluate the technical difficulties that can arise when developing the probabilistic maintenance model and investigate the solutions for each technical aspect.

- Considering ‘Frequency of Interruption’ and ‘Loss of Profit’, when conducting the maintenance optimization.

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