1. Chapter One : Introduction

1-1 Introduction

Reliability emerged with a technological meaning just after World War I and was then used in connection with comparing operational safety of one-, two-, and four-engine airplanes. The reliability was measured as the number of accidents per hour of flight time. At the beginning of the 1930s, Walter Shewhart, Harold F. Dodge, and HarryG. Romig laid down the theoretical basis for utilizing statistical methods in quality control of industrial products. Such methods were, however, not brought into use to any great extent until the beginning of World War II. Products that were composed of a large number of parts often did not function, despite the fact that they were made up of individual high-quality components.

After World War II, the development continued throughout the world as increasingly more complicated products were produced, composed of an ever-increasing number of components (television sets, electronic computers, etc.). With automation, the need for complicated control and safety systems also became steadily more pressing.

Reliability is the probability that a component or a system is performing its role satisfactorily, for the intended period of time, under the intended operating conditions. Reliability can be measured through the mathematical model of probability by identifying the probability of successful performance with the degree of reliability .The mean time to failure

Reliability and maintainability engineering attempts to study, characterize, measure, and analyze the failure and repair of systems in order to improve upon their operational use by increasing their design life, eliminating or reducing the likelihood of failures and safety risks, and reducing downtime thereby increasing available operating time.

Traditional approach to safety in engineering is to design into a product a high safety margin or safety factor, a deterministic method in which a safety of factor of perhaps 4 to 10 times the expected load or stress would be allowed for in the design.

Safety factors often result in overdesign thus increasing costs or less frequently in under design when an unanticipated load or a material weakness results in a failure. [1]

Normally, a component or system is said to perform satisfactorily if it does not fail during the time of service. On the other hand, many components are expected to experience failures, be repaired and then returned to working state during their entire useful life. In this case a more suitable measure of reliability is the availability of the component.

A reliability study can be useful in areas of risk analysis, optimization of operations and maintenance. The risk analysis is a way of identifying causes and consequences of failure events, and the optimization is a way of telling how failures can be prevented and how to improve the availability of a system. One can see reliability theory as a tool for analyzing and improving the availability of the system.

Diesel engines are designed to last longer and to give reliable and durable source of power. Commercial businesses can depend on them when a storm arrives or a crisis crop up with the local power network. A good, solid diesel generator can give any commercial business a safe, secure backup power source that can save a possible loss of production. All important industries such as construction, marine, manufacturing, forestry, and mining, to name a few, needs a reliable backup power in cases of blackouts. With a diesel generator, commercial industries can continue functioning normally with little to no downtime

1.2 Problem Statement

Diesel engines must be overhauled periodically to maintain optimum performance levels and to guard against engine failure. The determination of when to complete the overhaul is a matter of significant importance. The goal of maintenance scheduling is to minimize maintenance cost by reducing unneeded labor and downtime, internal components should be used for as long as possible without sacrificing overall engine performance or incurring a high risk of engine failure.

1-3 Objectives

- To study diesel engine failure information
- To use reliability techniques for analyzing the diesel engine
- To determine exactly what must be done to ensure that the diesel engine continues to operate at an expected level of performance

1-4 Scope

- The research considers one power generation unit **(Cummins KTA 50-G3 ,serial number 33141235)**

2. Chapter Two: literature Review

2-1 Maintenance:

Maintenance is defined as a combination of all technical and associated administrative activities required to keep equipments, installations and other physical assets in the desired operating condition or restore them to this condition.

The Maintenance Engineering Society of Australia (MESA) gives a definition that indicates that maintenance is about achieving the required asset capabilities within an economic or business context. They define maintenance as the engineering decisions and associated actions, necessary and sufficient for optimization of specified equipment ‘capability’. The ‘‘capability’’ in this definition is the ability to perform a specified function within a range of performance levels that may relate to capacity, rate, quality and responsiveness
Charged with this responsibility of ensuring that the plant achieves the desired performance, maintenance managers need a good track of performance on maintenance operations and maintenance results. In addition, it is in the interest of asset managers to know the relationship between the input of the maintenance process and the outcome in terms of total contribution to manufacturing performance and business strategic objectives can be realized through development and implementation of a rigorously defined performance measurement system and indicators that are able to measure important elements of maintenance function performance [1]

In the beginning of the 1980s had many systematic concepts been proposed, such as Total Productive Maintenance (TPM) and Reliability Centered Maintenance (RCM).

The middle and corporate level management have until recently, ignored the impact of the maintenance operation on production costs, bottom-line profit and product quality. The general opinion has been that “nothing can be done to impact maintenance costs” or “maintenance is a necessary evil”. The developments of computer-based instrumentation or microprocessors have provided the means to manage the maintenance operation due to that it can be used to monitor the operating condition of plant equipment and systems. Unnecessary repairs can with this technique be reduced or even eliminated, catastrophic machine failures can be prevented and the negative impact of the maintenance operation on the profitability can be reduced. [2]

An increasingly number of companies replace the current reactive, “fire-fighting” maintenance strategy with proactive strategies such as predictive and preventive maintenance and also with aggressive strategies such as TPM in order to achieve world-class performance.

Companies undertake efforts to reduce costs and at the same time improve quality and productivity, a part of these efforts commonly includes an examination of the maintenance function. For many operations within a producing company are effective maintenance critical due to the fact that it extends equipment life, increase equipment availability and retains equipment in proper condition. Poorly maintained equipment may conversely lead to more frequent failures of the equipment, low utilization rate of the equipment and delayed production schedules. Equipment that is malfunctioning or misaligned may cause a higher scrap rate or produce products with a questionable quality. In addition does the equipment need to be replaced more often due to shorter life-cycles, which also is a consequence of poor maintenance. [3]

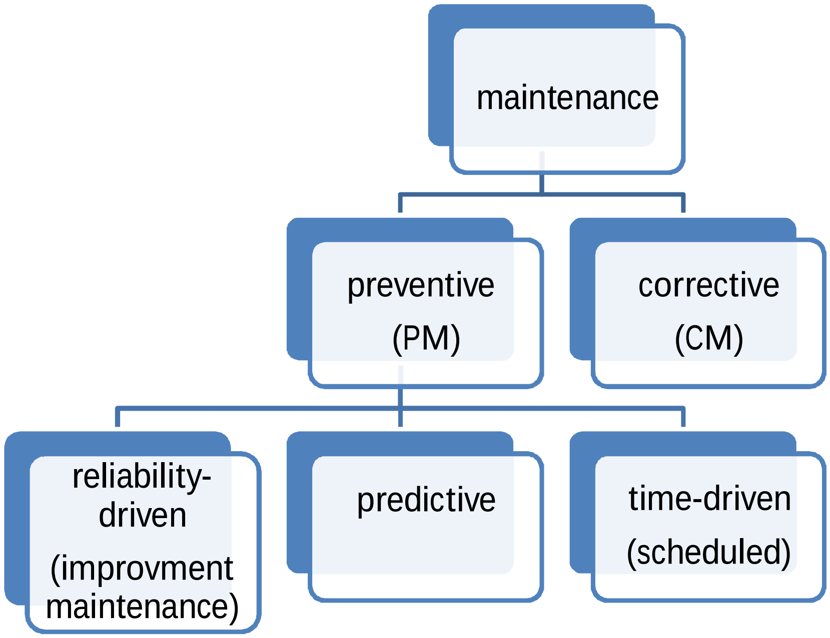

Figure 2.1: Types of Maintenance [3]

2-1-1 Corrective (Reactive) Maintenance:

Reactive maintenance is basically: "run it till it breaks" maintenance mode. No actions or efforts are taken to maintain the equipment as the designer originally intended to ensure design life is reached, we can also call it "fire fighting".

Studies indicate this is still the predominant mode of maintenance.

Advantages to reactive maintenance can be viewed as a double-edged sword. If we are dealing with new equipment, we can expect minimal incidents of failure. If our maintenance program is purely reactive, we will not expend manpower dollars or incur capitol cost until something breaks. Since we do not see any associated maintenance cost, we could view this period as saving money.

In reality, during the time we believe we are saving maintenance and capitol cost, we are really spending more than we would have under a different maintenance approach.

Advantages:

- Low cost.
- Less staff.

Disadvantages:

- Increased cost due to unplanned downtime of equipment.
- Increased labor cost, especially if overtime is needed.
- Cost involved with repair or replacement of equipment.
- Possible secondary equipment or process damage from equipment failure.
- Inefficient use of staff resources.

2-1-2 Preventive Maintenance:

Preventive maintenance can be defined as follows:

Actions performed on a time- or machine-run-based schedule that detect, preclude, or mitigate degradation of a component or system with the aim of sustaining or extending its useful life through controlling degradation to an acceptable level.

By simply expending the necessary resources to conduct maintenance activities intended by the equipment designer, equipment life is extended and its reliability is increased. it does have several advantages over that of a purely reactive program. By performing the preventive maintenance as the equipment designer envisioned, we will extend the life of the equipment closer to design. Preventive maintenance (lubrication, filter change, etc.) will generally run the equipment more efficiently resulting in money savings. While we will not prevent equipment catastrophic failures, we will decrease the number of failures. Minimizing failures translate into maintenance and capitol cost savings.

Advantages:

• Cost effective in many capital intensive processes.

• Flexibility allows for the adjustment of maintenance periodicity.

• Increased component life cycle.

• Energy savings.

• Reduced equipment or process failure.

Disadvantages:

• Catastrophic failures still likely to occur.

• Labor intensive.

• Includes performance of unneeded maintenance.

• Potential for incidental damage to components in conducting unneeded maintenance. [4]

2-1-3 Predictive Maintenance:

Predictive maintenance can be defined as follows: measurements that detect the onset of a degradation mechanism, thereby allowing causal stressors to be eliminated or controlled prior to any significant deterioration in the component physical state.. Basically, predictive maintenance differs from preventive maintenance by basing maintenance need on the actual condition of the machine rather than on some preset schedule is used to define needed maintenance task based on quantified material/equipment condition.

A well-orchestrated predictive maintenance program will all but eliminate catastrophic equipment failures. We will be able to schedule maintenance activities to minimize or delete overtime cost. We will be able to minimize inventory and order parts, as required, well ahead of time to support the downstream maintenance needs. We can optimize the operation of the equipment, saving energy cost and increasing plant reliability.

Advantages:

• Increased component operational life/availability.

• Allows for preemptive corrective actions.

• Decrease in equipment or process downtime.

• Decrease in costs for parts and labor.

• Better product quality.

• Improved worker and environmental safety.

• Improved worker moral.

• Energy savings maintenance program.

Disadvantages:

• Increased investment in diagnostic equipment.

• Increased investment in staff training.

• Savings potential not readily seen by management. [4]

2-1-4 Reliability Centered Maintenance:

Reliability centered maintenance (RCM) magazine provides the following definition of RCM: “a process used to determine the maintenance requirements of any physical asset in its operating context.”

Basically, RCM methodology deals with some key issues not dealt with by other maintenance programs.

It recognizes that all equipment in a facility is not of equal importance to either the process or facility safety. It recognizes that equipment design and operation differs and that different equipment will have a higher probability to undergo failures from different degradation mechanisms than others. It also approaches the structuring of a maintenance program recognizing that a facility does not have unlimited financial and personnel resources and that the use of both need to be prioritized and optimized. In a nutshell, RCM is a systematic approach to evaluate a facility’s equipment and resources to best mate the two and result in a high degree of facility reliability and cost-effectiveness.

RCM is highly reliant on predictive maintenance but also recognizes that maintenance activities on equipment that is inexpensive and unimportant to facility reliability may best be left to a reactive maintenance approach.

Advantages:

• Can be the most efficient maintenance program.

• Lower costs by eliminating unnecessary maintenance or overhauls.

• Minimize frequency of overhauls.

• Reduced probability of sudden equipment failures.

• Able to focus maintenance activities on critical components.

• Increased component reliability.

• Incorporates root cause analysis.

Disadvantages

• Can have significant startup cost, training, equipment, etc.

• Savings potential not readily seen by management. [4]

2-1-5 Role of maintenance:

The mission of maintenance in a world-class organization is to achieve and sustain optimum availability.

Optimum Availability:

The production capacity of a plant is, in part, determined by the availability of production systems and their auxiliary equipment. The primary function of the maintenance organization is to ensure that all machinery, equipment, and systems within the plant are always on line and in good operating condition.

Optimum Operating Condition:

Availability of critical process machinery is not enough to ensure acceptable plant performance levels. The maintenance organization has the responsibility to maintain all direct and indirect manufacturing machinery, equipment, and systems so that they will be continuously in optimum operating condition.

Minor problems, no matter how slight, can result in poor product quality, reduce production speeds, or affect other factors that limit overall plant performance.

Maximum Utilization of Maintenance Resources:

The maintenance organization controls a substantial part of the total operating budget in most plants. In addition to an appreciable percentage of the total plant labor budget, the maintenance manager, in many cases, controls the spare parts inventory, authorizes the use of outside contract labor, and requisitions millions of dollars in repair parts or replacement equipment. Therefore, one goal of the maintenance organization should be the effective use of these resources.

Optimum Equipment Life

One way to reduce maintenance cost is to extend the useful life of plant equipment.

The maintenance organization should implement programs that will increase the useful life of all plant assets.

Minimum Spares Inventory

Reductions in spares inventory should be a major objective of the maintenance organization. However, the reduction cannot impair their ability to meet goals 1 through 4. With the predictive maintenance technologies that are available today, maintenance can anticipate the need for specific equipment or parts far enough in advance to purchase them on an as-needed basis.

Ability to React Quickly

Not all catastrophic failures can be avoided. Therefore the maintenance organization must maintain the ability to react quickly to the unexpected failure. [2]

2-2 Failure:

Failure is defined as the inability of any asset to do what its users want it to do,

Every time a failure occurs, the organization which uses the asses is affected in some way .some failures affect output, product quality or costumer service. Other threatens safety or the environment .some increase operating costs, for instance by increasing energy consumption, while a few have an impact in four, five or even six of these areas. Still others may appear to have no effect at all if they occur on their own, but may expose the organization to the risk of much more serious failures.

If any of these failures are prevented, the tie and effort which need to be spent correcting them also affects the organization, because repairing failures consumes resources which might be better used elsewhere.[5]

Failure can be defined on several different levels. The simplest form of a failure is a system or component that operates, but does not perform its intended function. This is considered a loss of function.

The next level of failure involves a system or component that performs its function but is unreliable or unsafe .In this form of failure, the system or component has sustained a loss of service life.

In the next level of severity of failure, a system or component is inoperable.

A logical failure analysis approach first requires a clear understanding of the failure definition and the distinction between an indicator (i.e., symptom), a cause, a failure mechanism, and a consequence.

Although it may be considered by some to be an exercise in semantics, a clear understanding of each piece of the situation associated with a failure greatly enhances the ability to understand causes and mitigating options and to specify appropriate corrective action. [6]

Figure 2.2 exemplify a possible shape of the failure function. There are some other shapes of failure function curves as well, but the bathtub curve generally represents the failure rates for mechanical components. Since majority of the mechanical components goes through wear and tear, the failure function curve shows a little escalating trend during the useful life period, consequently their actual curves may vary to some extent from the one shown in Figure 2.2. [10]

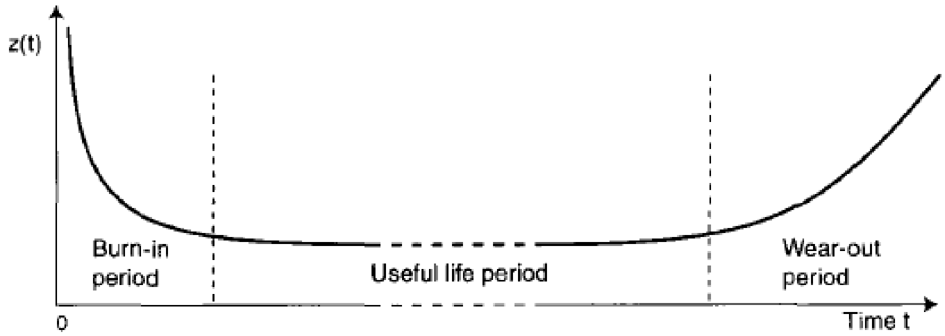

Figure 2.2: Bathtub curve [10]

2-2-1 Failure Prevention:

Failure prevention begins with a state of mind in the specification, design, manufacture/fabrication, installation, operation, and maintenance of any component. However, before failure prevention measures are taken, the degree of reliability required in a specific situation must be determined.

There is a cost associated with failure prevention, and of course there is a cost associated with accepting failures. As shown in Figure 2.3, many times it may be reasonable to accept failures should the cost of reliability enhancement outweighs the benefits. [6]

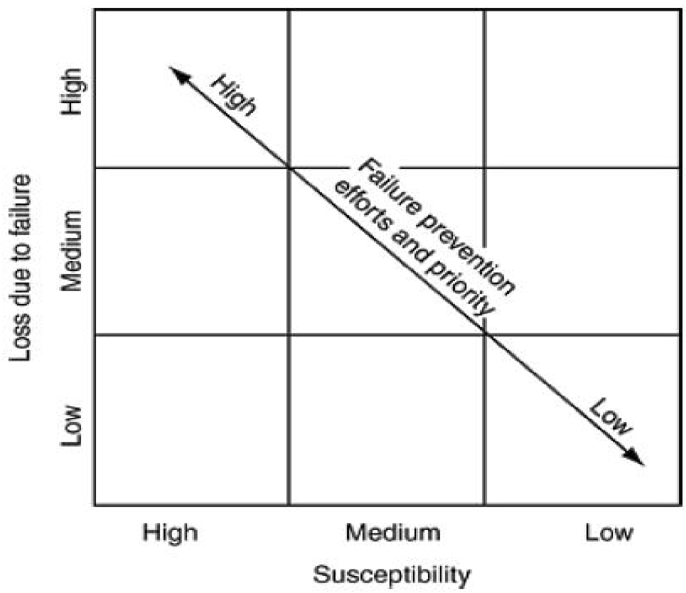

Figure 2.3: Failure prevention effort prioritization [6]

2-3 Diesel engines:

Diesel engines are generally used as mechanical engines, power generators and in mobile drives. They are extensively utilized in automobiles, locomotives, construction equipment, and numerous other industrial applications. Industrial diesel engines and diesel powered generators are widely used in construction, marine, mining, hospital, forestry, telecommunications, underground, and agricultural applications. Power generation for prime or standby backup power is a major application of today's diesel engines.

Diesel powered electrical generators are used in many industrial and commercial organizations. These generators can be used in homes for small loads, as well as in hospitals, industrial plants, and commercial buildings for big loads. They can be used both as a source of prime power or standby power back-up. They are available in various specifications and sizes. Diesel generator sets rating 5-30KW are normally used in simple home and personal applications. Industrial applications cover a wider range of power ratings (from 30 kW to 6 Megawatts) and are used in different industries all over the world.

For home use, single-phase power generators are sufficient. Three-phase power generators are mainly used for industrial purpose

Modern diesel generators are extremely powerful and advanced. They are designed to last longer and to give reliable and durable source of power. Commercial businesses can depend on them when a storm arrives or a crisis crop up with the local power network. A good, solid diesel generator can give any commercial business

a safe, secure backup power source that can save a possible loss of production. All important industries such as construction, marine, manufacturing, forestry, and mining, to name a few, needs a reliable backup power in cases of blackouts. With a diesel generator, commercial industries can continue functioning normally with little to no downtime. [7]

In specialized applications of small autonomous power systems the reliability of the power units is a crucial factor affecting even the survivability of their users i.e. helicopter's power system. The unavailability of a power unit is quantified by the

Forced Outage Rate (FOR), which is the number of hours the unit is on forced outage over the total number of hours in a year. The use of different power units affects the unavailability rate of the power system which is expressed by two indicators: the expected loss of load power (LOLP), which is the equivalent time per year for which the load demand is not covered by the generation power system completely, the expected loss of load energy (LOLE), which is the total active energy not supplied in a year. They are practical measures of a "black-out" probability. Ideally, these indicators should be equal to zero; practically they should be as small as possible. The respective indicators are calculated by classical reliability assessment methods. The knowledge of the FOR of each power unit is satisfactory for the design and the operation of the power system. But the thermal electric power unit is a complex system of several sub-systems and components. The operator of the power unit needs more information about the reliability of each sub-system and its components, so as the most frequently malfunctioning parts of the system are identified. Afterwards, techno economical study should be carried out comparing the possible measures, which can be taken, i.e. replacement of a component, use of parallel element in case of a sensitive component, etc. [8]

The main components of a diesel engine are:

- **Cylinder block**: rigid structure that keeps the cylinders in an appropriate alignment;
- **Injection pump**: responsible for the fuel pressurization at the moment of injection;
- **Cylinders**: pipes where the pistons slide up and slide down inside;
- **Cylinder head**: delimits with the piston the combustion chamber volume;
- **Oil carter**: rigid structure situated at the inferior part of the engine which allows the lubrication system to feed the engine mobile elements;
- **Piston**: it assures a tight blockade between the combustion chamber and the block. When the piston is submitted to the gases pressure, it transmits the explosion force to the connecting rod through its shaft;
- **Connecting rod**: transmits the force exerted by the piston when the mixture air-fuel burns;
- **Crank shaft**: transforms the alternated movement of the pistons in rotating movement and transmits the engine power for the gearbox, which relays for the wheels;
- **Flywheel**: maintain the uniformity of the rotation movement of the winches tree, assuring the constant speed of the crankshaft;
- **Valves**: each cylinder has an admission valve where the mixture to be burnt enters and an expulsion valve to leave the burnt gases escape; and
- **Camshaft**: responsible for opening and closing the valves.[16]

2-3-1 Faults in diesel engines:

Many articles and books are dedicated to the subject of diesel engine faults. Some of them refer to one specific fault and others construct lists of possible faults. Most of the lists are composed from expert experiences.

In [17] there are many fault lists in the book for different types of mechanical systems including one dedicated to diesel engine faults. As in table 2-1 the list consists of defect classes and their occurrences as reported from 410 stoppages in industrial diesel engines around 1970.

Table 2-1: List of industrial diesel engine defects and their occurrences

Class of defect	**Occurrence (%)**
Fuel-injection equipment and fuel supply	27.0
Water leakages	17.3
Valves and seats	11.9
Bearings	7.0
Piston assemblies	6.6
Oil leakages and lubrication systems	5.2
Turbochargers (excluding damage by intruding foreign bodies)	4.4
Gearing and drives	3.9
Governor gear	3.9
Fuel leakages	3.5
Gas leakages	3.2
Breakages and fractures, other than mentioned	2.5
Miscellaneous	2.5
Foundations	0.9
Crankshafts	0.2
	100.0

The article in [18] states that faults in a diesel engine can be roughly divided in two groups: combustion related faults, concerning the fuel injection system, inlet/exhaust valve system, and cylinder/piston system, and non combustion related faults, including faults in all auxiliary devices such as the cooling system, gear, bearing, and turbocharger.

It listed some of the most common fault symptoms of diesel engines:

• Misfire

• Knocking

• Insufficient power

• Overheating

• Poor fuel efficiency

• Excessive noise and vibration

• Excessive exhaust smoke

• Engine not starting

The authors in [19] constructed a list of symptoms and the possible corresponding faults. The symptoms were:

• Power loss

• Emission changes

• Lubrication system fault

• Noise and vibration

• Wear

• Thermal overload

• Leakages

• Other faults

2-4 Reliability:

Reliability is the probability that an item will perform its stated mission satisfactory for the specified time period when used under the stated condition.

Reliability and maintainability engineering attempts to study, characterize, measure, and analyze the failure and repair of systems in order to improve upon their operational use by increasing their design life, eliminating or reducing the likelihood of failures and safety risks, and reducing downtime thereby increasing available operating time.

Traditional approach to safety in engineering is to design into a product a high safety margin or safety factor, a deterministic method in which a safety of factor of perhaps 4 to 10 times the expected load or stress would be allowed for in the design.

Safety factors often result in overdesign thus increasing costs or less frequently in under design when an unanticipated load or a material weakness results in a failure.

Approach taken in reliability is to treat failures as random or probabilistic occurrences. In theory, if we were able to comprehend the exact physics and chemistry of a failure process, many internal failures of a component could be predicted with certainty.

With limited data on the physical state of a component, and an incomplete knowledge of the physical, chemical (and perhaps biological) processes which cause failures, failures will appear to occur at random over time, this random process may exhibit a pattern which can be modeled by some probability distribution.

Random phenomena Observed in practice when dealing with large numbers of components statistically can predict the failure or of these components. Failures caused by events external to the component, such as environmental conditions like excessive heat or vibration, hurricanes or earthquakes, will appear to be random. with sufficient understanding of the conditions resulting in the event as well as the effect such an event would have on the component, then we should also be able to predict these failures deterministically, This uncertainty, or incomplete information, about a failure process is therefore a result of its complexity, imprecise measurements of the relevant physical constants and variables, and the indeterminable nature of certain future events. [8]

2-4-1 Basic Reliability Theory:

Statistical methods are used to determine part reliability using part failure data. Probability methods are used to determine system reliability using knowledge of part reliability and system structure. Commonly used distributions include the exponential, Weibull, lognormal, and gamma distributions.

Systems will fail through various means resulting from different physical phenomena leading to different failure characteristics of parts. A useful approach is to separate these failures according to the mechanisms or parts causing the failures. For example, as a result of improper machining, a gear-tooth in a vehicle's transmission breaks causing the transmission to lock up and the vehicle to crash, injuring the driver. The failure mode in this case is the jammed transmission.

A failure density distribution that has a constant failure rate has an exponential reliability distribution. Many systems exhibit constant failure rates and the exponential reliability distribution is the simplest to analyze. [9]

2-4-2 Reliability analysis methods:

There are many methods that can be used to perform reliability analysis of engineering systems. Those are three of the commonly used methods:

2-4-2-1 Failure Modes and Effect Analysis (FMEA):

Failure modes and effect analysis (FMAE) is a widely used method in the industrial sector to perform reliability analysis of engineering systems. It may simply be described as an approach used to conduct analysis of each potential failure mode in the system under consideration to examine the effects of such failure modes on that system .Furthermore, the approach demands listing of all potential failure modes of all parts on paper and their effects on the listed subsystems and the system under consideration. When this approach (i.e., FMEA) is extended to classify each potential failure effect according to its severity, then it is called failure mode, effects, and criticality analysis (FMECA) The history of FMEA goes back to the early 1950s when the U.S. Navy's Bu-reau of Aeronautics developed a requirement called "Failure Analysis". In the 1970s, the U.S. Department of Defense developed military standards entitled "Procedures for Performing a Failure Mode, Effects, and Criticality Analysis". The six main steps followed in performing FMEA are shown in Figure 3.5. Some of the main characteristics of the FMEA method arc as follows:

- It is a routine upward approach that starts from the detailed level.
- By determining all possible failure effects of each pan, the entire system is screened completely.
- It identifies weak spots in a system design and highlights areas where further or detailed analyses are required.
- It improves communication among individuals involved in design.

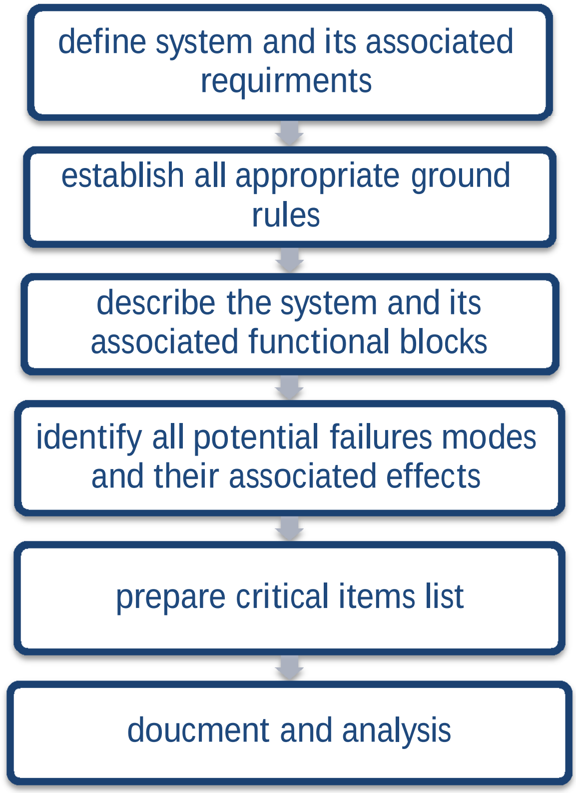

Figure 2.4: Main steps of conducting FMEA [8]

Objectives of an FMECA:

According to IEEE **Std.** 352, the objectives of an FMECA are to:

1. Assist in selecting design alternatives with high reliability and high safety potential during the early design phase.

2. Ensure that all conceivable failure modes and their effects on operational success of the system have been considered.

3. List potential failures and identify the magnitude of their effects.

4. Develop early criteria for test planning and the design of the test and checkout systems.

5. Provide a basis for quantitative reliability and availability analyses.

6. Provide historical documentation for future reference to aid in analysis of field failures and consideration of design changes.

7. Provide input data for tradeoff studies.

8. Provide basis for establishing corrective action priorities.

9. Assist in the objective evaluation of design requirements related to redundancy, failure detection systems, fail-safe characteristics, and automatic and manual override.

Since all failure modes, failure mechanisms, and symptoms are documented in the FMECA, this also provides valuable information as a basis for failure diagnostic procedures and for a repairman's checklists.

An FMECA may be very effective when applied to a system where system failures most likely are the results of single component failures. During the analysis, each failure is considered individually as an independent occurrence with no relation to other failures in the system.

A second limitation of FMECA is the inadequate attention generally given to human errors. This is mainly due to the concentration on hardware failures.

Perhaps the worst drawback is that all component failures are examined and documented, including those that do not have any significant consequences. For large systems, especially systems with a high degree of redundancy, the amount of unnecessary documentation work is a major disadvantage.

The FMECA analysis may be performed according to the following scheme:

1. Definition and delimitation of the system (which components are within the boundaries of the system and which are outside).
2. Definition of the main functions (missions) of the system.
3. Description of the operational modes of the system.
4. System breakdown into subsystems that can be handled effectively.
5. Review of system functional diagrams and drawings to determine interrelationships between the various subsystems. These interrelations

may be illustrated by drawing functional block diagrams where each block corresponds to a subsystem.

6. Preparation of a complete component list for each subsystem.
7. Description of the operational and environmental stresses that may affect the system and its operation. These are reviewed to determine the adverse effects that they could generate on the system and its components.[10]

2-4-2-2 Markov Method:

The Markov method is a powerful reliability analysis tool that is named after Russian mathematician Andrei Andreyevich Markov (1856-1922). It can handle both repairable and non-repairable systems. In analyzing large and complex systems, a problem may occur in solving a set of differential equations generated by this method. Nonetheless, the Markov method is based on the following assumptions:

• The transitional probability from one state to the next state in the finite time interval Δt is given by $\lambda \Delta t$, where λ is transition rate (e. g., failure or repair rate) associated with Markov states.

• The probability of more than one transition occurrence in finite time interval Δt from one state to the next is negligible (e. g., $(\lambda \Delta t)(\lambda \Delta t) \rightarrow 0$).

• All occurrences are independent of each other. [8]

2-4-2-3 Fault tree Analysis:

The fault tree technique was introduced in 1962 at Bell Telephone Laboratories, in connection with a safety evaluation of the launching system for the intercontinental ***Minuteman*** missile. The Boeing Company improved the technique and introduced computer programs for both qualitative and quantitative fault tree analysis. Today fault tree analysis is one of the most commonly used techniques for risk and reliability studies. In particular, fault tree analysis has been used with success to analyze safety systems in nuclear power stations, such as the Reactor safety study (NUREG-0492).

A fault tree is a logic diagram that displays the interrelationships between a potential critical event (accident) in a system and the causes for this event. The causes may be environmental conditions, human errors, normal events (events that are expected to occur during the life span of the system), and specific component failures.

A fault tree analysis may be qualitative, quantitative, or both, depending on the objectives of the analysis. Possible results from the analysis may, for example, be

- **A** listing of the possible combinations of environmental factors, human errors, normal events, and component failures that may result in a critical event in the system.
- The probability that the critical event will occur during a specified time interval.

Fault tree analysis is a *deductive* technique where we start with a specified system failure or an accident. The system failure, or accident, is called the TOP *event* of the fault tree. The immediate causal events A_1 A_2 . . . that, either alone or in combination, may lead to the TOP event are identified and connected to the TOP event through a *logic gate*. Next, we identify all potential causal events $A_{i,1}$ $A_{i,2}$, . . . that may lead to event A_i for i = 1,2, ... These events are connected to event Ai through a logic gate. This procedure is continued deductively (i.e., backwards in the causal chain) until we reach a suitable level of detail. The events on the lowest level are called the basic events of the fault tree.

Fault tree analysis is a binary analysis. All events are assumed either to occur or not to occur; there are no intermediate options. [10]

2-4-2-4 Reliability block diagram:

A reliability block diagram is a success-oriented network describing the function of the system. It shows the logical connections of (functioning) components needed to fulfill a specified system function. If the system has more than one function, each function must be considered individually, and a separate reliability block diagram has to be established for each system function.

Reliability block diagrams are suitable for systems of nonrepairable components and where the order in which failures occur does not matter. When the systems are repairable and/or the order in which failures occur is important. [10]

2-4-2-5 Event tree analysis:

In many accident scenarios, the initiating (accidental) event, for example, a ruptured pipeline may have a wide spectrum of possible outcomes, ranging from no consequences to a catastrophe. In most well-designed systems, a number of safety functions, or barriers, are provided to stop or mitigate the consequences of potential accidental events. The safety functions may comprise technical equipment, human interventions, emergency procedures, and combinations of these. Examples of technical safety functions are: fire and gas detection systems, emergency shutdown (ESD) systems, automatic train stop systems, fire-fighting systems, fire walls, and evacuation systems. The consequences of the accidental event are determined by how the accident progression is affected by subsequent failure or operation of these safety functions, by human errors made in responding to the accidental event, and by various factors like weather conditions and time of the day.

The accident progression is best analyzed by an inductive method. The most commonly used method is the event tree analysis. An event tree is a logic tree diagram that starts from a basic initiating event and provides a systematic coverage of the time sequence of event propagation to its potential outcomes or consequences.

In the development of the event tree, we follow each of the possible sequences of events that result from assuming failure or success of the safety functions affected as the accident propagates. Each event in the tree will be conditional on the occurrence of the previous events in the event chain. The outcomes of each event are most often assumed to be binary (true or false -yes or no) but may also include multiple outcomes
(e.g., yes, partly, and no).

Event tree analyses have been used in risk and reliability analyses of a wide range of technological systems. The event tree analysis is a natural part of most risk analyses but may be used as a design tool to demonstrate the effectiveness of protective systems in a plant. Event tree analyses are also used for human reliability assessment, for example, as part of the THERP technique (NUREGKR-1278).

The event tree analysis may be qualitative, quantitative, or both, depending on the objectives of the analysis. In quantitative risk assessment (QRA) application, event trees may be developed independently or follow on from fault tree analysis.[10]

2-5 Related works:

In [11] the authors has validated FMETA method by an application to an automotive heavy-duty diesel engine, FMETA allows the designer to find the most critical characteristic of the product from a reliability point of view and provides the designer with a set of possible changes, FMETA allowed the designer to save about 50% of the time usually needed for reliability growth.

The FMETA applied to the case study has produced a reliability improvement of about 40% in the product.

In [12] the study has focused mainly on the estimation of the reliability of a specific Railway Locomotive Engine, Reliability analysis is performed using the Weibull Distribution and the various data plots as well as failure rate information helped in achieving the results. From the Reliability prediction of the engine component it is found that the reliability of the component is 59.999%. As the system of the Engine is found to be moderate Reliability it is needed to upgrade its maintenance process.

In [13] Research efforts related to the development of diesel engine diagnostic systems have typically been guided by a thorough knowledge of component. Failure Mode and Effects Analysis (FMEA) has been conducted. Comparisons of component failure rates obtained from studies of twenty similar marine diesel engines are shown in Figure 2.4; failures of the fuel oil valve represent greater than 30% of the recorded failures, while twelve components account for roughly 90%. from the study on marine diesel engines, a comparison was made between the amount of maintenance attention given to engine components versus their corresponding failure rates. Figure 2.5 shows that the high failure rates of individual components described in Figure 2.4 are not caused by lack of proper maintenance attention. It also shows that preventative maintenance (PM) is properly distributed to those parts that are most prone to failure or are critical to engine performance.

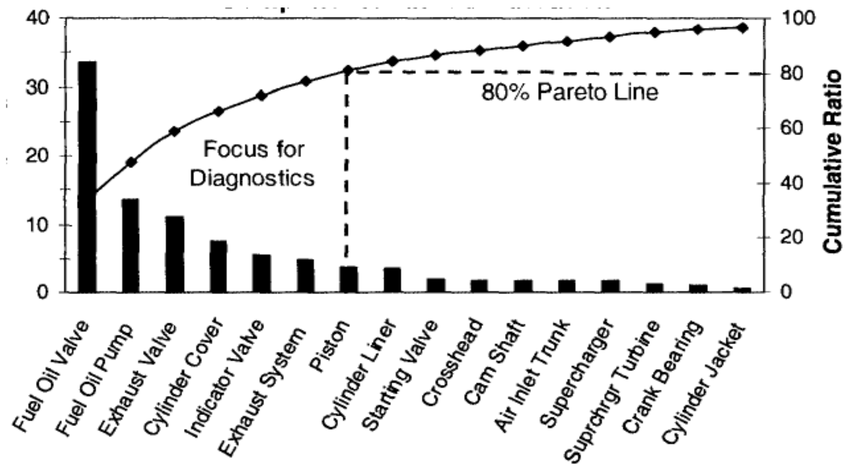

Figure2.5: Marine Diesel Engine Component Failure Distribution [13]

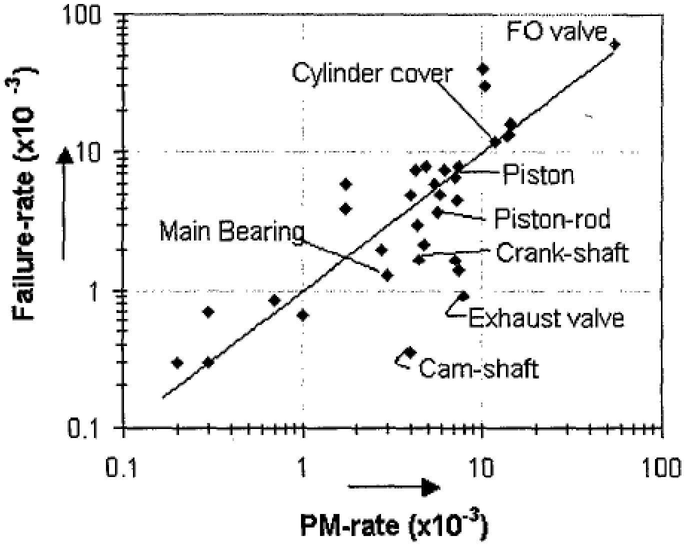

Figure 2.6: Main Diesel Engine Components, Failure-rate vs. PM-rate [13]

In [14] the reliability prediction method discussed in this paper utilizes FMEA to increase the efficiency of reliability prediction. Through comparing FMEA of existing and new design, changes of failure modes and of failure modes occurrence scales are obtained. Then the factor which characterizes the change of failure rate can be calculated.

In [15] the study has been conducted on locomotive diesel engine. The field failure data for current three consecutive years (i.e. from 2006 to 2009) has been collected from Loco shed, Motibagh, Nagpur. It is arranged in tabular form in which the date of failure of loco along with loco number is given. The system and its sub-system which is failed are also mentioned. The cause of failure of that system/sub-system is stated. FMEA has been implemented in order to identify the parts of the process that are most in need of change, From the analysis, the most common causes of failure in four major area of maintenance were detected. These failures were due to the misplaced steps in the present schedule i.e. steps which should have been performed in the earlier part of the schedule were delayed to the latter parts. The critical components are identified and the causes for their failure are also discussed.

3. Chapter Three: FMECA Analysis

3-1 Preface

This chapter will present a brief overview of the site (power generation through diesel generators) in Portsudan, Sudan and will discuss the criteria used to make the reliability analysis of the diesel engine (Cummins KTA50 G3)

3-2 Site overview

The site is owned by the Sudanese Thermal Power Generation Company, this power generation site actually started up in September 2003; the objective was to supply electric power to support the national electricity grid through diesel generator sets which acted as a source of secondary power for Portsudan town, The reason for using diesel power as the secondary source is the unreliable power supply transmission line and instability of the national electricity grid.

It is observed that they are following conventionally framed scheduled maintenance system; a study is performed, to identify the wastage of process in the form of misplaced steps in their schedules to avoid the repetitive failure of diesel generators.

3-3 Diesel generator specifications

The engine is of the heavy duty industrial type with 4 stroke compression ignition and is fitted with all accessories to provide a reliable power supply.

Table 3.1: diesel generator specifications

Model name	**Cummins KTA50 G3**
Installed capacity	**900 KW**
Maximum available capacity	**850 KW**

Number of cylinders	**16**
R.P.M	**1500**
frequency	**50 Hz**
KVA rating	**947 kva**

3-4 Methodology

Reliability analysis (FMECA method) will be achieved by identifying the most critical components in the various systems of the diesel generator. Present practices of maintenance schedule, past failure data and their experiences will be taken into consideration for identifying the critical components, Failure modes will be observed and represented by occurrence and failure modes will be considered as defects representations of the subsystem (assembly or components).

3-5 Reliability analysis of the diesel engine

3-5-1 System construction:

Here, the typical construction of a diesel engine is analyzed; specifically, it consists of the following sub-systems and major component:

- Cylinder block.
- lubricating oil circuit
- fuel circuit
- Cooling circuit.
- Electrical equipments
- Electrical control system

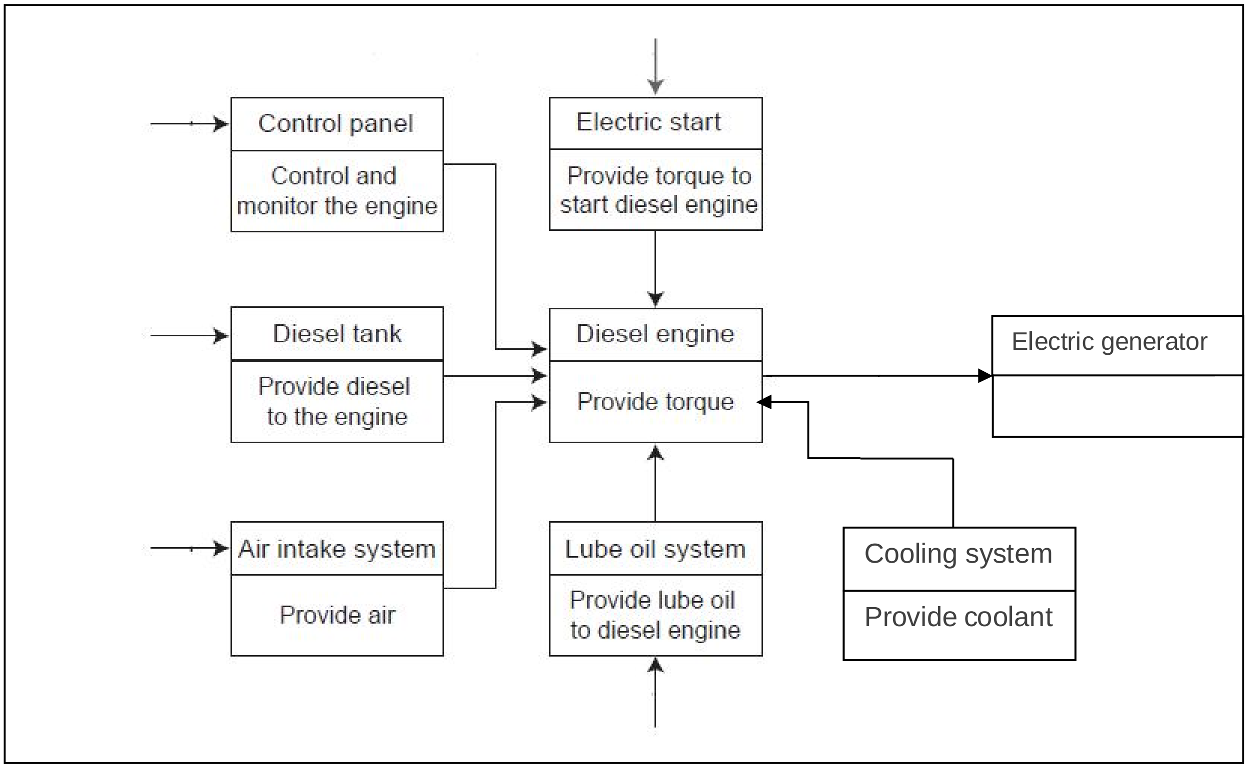

Figure 3.1: functional diagram of the system

3-5-2 Evaluation and Ranking of Equipment Failure Modes (Criticality/Risk Ranking):

To provide a consistent means to evaluate the relative criticality of the diesel engine subsystem and equipment failures and to help judge the adequacy of activities performed to prevent and detect the failures, a Risk Priority Number (RPN) ranking scheme based the following factors was employed:

- Frequency of Failure of the Equipment Failure Mode
- Ability to Detect and Prevent the Failure Mode via system monitoring and practices
- Severity of the End Effect for each Functional Failure

A RPN ranking for each functional failure associated with an equipment-level failure mode was based on the product of the following three independent factors:

- Severity Rating – This rating assesses the severity of worst-case end effect for a given functional failure. (Note: The functional failure end effects documented in the functional level FMECA were used to determine this rating assuming no redundancies are present.).
- Occurrence Rating – This rating assesses the likelihood of the failure mode resulting in the functional failure and its stated end effect. Such an assessment is made by evaluating the causes listed for the failure mode. The presence of redundant components and systems is explicitly considered in this rating.
- Detection Rating – This rating assesses the likelihood of the current applicable activities and system monitoring techniques to detect the failure mode before it results in the functional failure.

The severity, occurrence, and detection ratings are provided in Tables 3-2 through 3-5, respectively.

These ratings were then used to calculate a single RPN ranking for each functional failure effect & equipment failure mode pair (i.e., RPN ranking for each functional failure associated with an

equipment-level failure mode) using the following equation:

RPN = Severity Rating X Occurrence Rating X Detection Rating

The individual RPN rankings provide a relative ranking of the risk associated with a given functional failure effect-equipment failure mode pair. Thereby, providing a means to identify the most critical equipment-level failure modes in overall diesel engine performance, as well as identifying the more critical failure modes associated with a specific diesel engine functional failure.

Severity classes:

By the severity of a failure mode we mean the worst potential consequence of the failure, determined by the degree of injury, property damage, or system damage that could ultimately occur

Table 3.2: table of severity

Severity Rank	class	Description
10	Catastrophic	Any failure that prevent performance of the intended mission
7,8,9	Critical	Any failure that will degrade the system beyond acceptable limits
4,5,6	Major	Any failure that will degrade the system beyond acceptable limits but can be adequately counteracted or controlled by alternate means
1,2,3	Minor	Any failure that does not degrade the overall performance beyond acceptable limits

Failure rate classes:

Table 3.3: table of occurrence

Occurrence Rank	class	Occurrence frequency
1	Very unlikely	Once per year or more seldom

2,3,4	Remote	Twice per year
5,6	Occasional	Once per 3 months
7,8,9	Probable	Once per month
10	Frequent	More than once per month

Detection classes:

It is the likelihood that the failure will be detected before the system reaches the end-user/customer.

Table 3.4: Table of detection

Detection Rank	class	Description
1	Extremely likely	Very high probability that the defect will be detected. Verification and/or controls will almost certainly detect the existence of a deficiency or defect
2,3,4	Highly likely	High probability that the defect will be detected. Verification and/or controls have a good chance of detecting the existence of a deficiency/defect
5,6,7	likely	Moderate probability that the defect will be detected. Verification and/or controls are likely to detect the existence of a deficiency or defect.
8,9	unlikely	Low probability that the defect will be detected. Verification and/or control not likely to detect the

		existence of a deficiency or defect.
10	Extremely unlikely	Very low (or zero) probability that the defect will be detected. Verification and/or controls will not or cannot detect the existence of a deficiency/defect.

3-6 FMECA assessment:

3-6-1 Fuel system:

The fuel is supplied to the engine from intermediate daily service tank located under the generating set which is automatically refilled from a bulk storage tank.

Fuel circuit elements are: fuel tank, pipes, Shut-off valve, fuel pump, fuel filters (two are used in parallel connection), fuel injectors, fuel governor and fuel pre-filter

Table 3.5: fuel system FMECA table

	Description of unit	**Description of failure**			**S**	**O**	**D**
item	**Function**	**Failure mode**	**Failure cause**	**Effect of failure**			
fuel tank	Restore fuel	Fuel contaminated	Strange materials or dirt in the tank	Engine will not start or hard to start	6	7	3

Fuel pump	flow the Fuel from service tank to main engine and Raise the pressure of fuel	Less pressure and the resulting lack of capacity.(Low output)	Mechanical failure	Reduce the fuel flow Main engine Performance decrease	8	6	4
governor	Control the fuel amount						
Shut-off valve	Open and close the fuel flow	Does not respond to controller:					
		• Fails closed	Electrics are not working probably	• Engine cannot start	6	6	3
		• Fails open	Electrics are not working probably	• Engine cannot shut down	8	6	3
fuel filters	Separate the fuel from dirt (from service tank to engine)	Filter clogged by the dirt	• Water contamination • Debris contamination	• Fuel supply to main engine stopped • Unstable load • Damage Pump • Damage Injectors	7	8	5

		Air in the fuel system	Filters not tightened	• Sudden loss of power • Engine not keep running	8	3	7
fuel injectors	atomize fuel in combustion chamber and to ensure that it mixes with sufficient air for complete combustion in cycle time available	incorrect atomization	choked atomizer due to contaminated fuel debris and hot gas from cylinder forming carbon	• incorrect combustion • misfiring • Poor Idle performance engine	7	7	5
		malfunctioning	Injectors adjusted wrong	• Engine speed surges at low or high idle speed • exhaust smoke	8	7	6

				excessive under load • engine misfires			
Fuel pre-filter	Separate from the fuel dirt (from main tank to service tank)	Filter clogged by the dirt	Debris contamination	• Dirty fuel • Fuel supply to service tank stopped	5	8	3
fuel line	Transfer fuel	Fuel line restricted	lops, crimps or clamped points	The flow of fuel decreased exhaust smoke excessive under load engine will not shut off engine misfires	5	4	6

3-6-2 Cooling system:

The engine cooling system is water cooled. The water cooled system is comprised of a radiator a pusher fan and thermostat

Table 3.6: cooling system FMECA table

	Description of unit	Description of failure					
item	**Function**	**Failure mode**	**Failure cause**	**Effect of failure**	**S**	**O**	**D**
radiator	Lowering coolant temperature	Radiator fins obstructed with debris	Choked or dirty plates Dirty tubes	High coolant temperature High engine temperature Engine shutdown	8	7	5
		Coolant loss	• Internal leak • Radiator cap is not correct	• High coolant temperature • High engine temperature • Engine shutdown	8	7	2
thermostat	Open and close coolant flow corresponding to the temperature	Thermostat is malfunctioning	Thermostat is not correct	High coolant temperature	7	2	5
Coolant system hose	Linking between radiator and	Coolant system hose is collapsed	Hose damage	High coolant temperature	8	3	3

	cylinder block						
Water pump	flow the water from radiator to cylinder block and Raise the pressure of water	Water pump is malfunctioning	Pump failure	Temperature rise Engine shutdown	9	2	6
Fan drive	Fan rotation	fan drive belt is loose fan shroud is damaged	Belt not tightened corrosion	High coolant temperature	8	5	2

3-6-3 Lubricating oil system:

Oil system of diesel engine is one of the most important elements of the engine; it has five main oil filters and two bypass filters

The engine have a lubricating oil pump which is mounted to the bottom at the rear of the cylinder block, the pump is driven by a gear that is mounted on the rear of the crankshaft.

Table 3.7: lubricating oil system FMECA table

	Description of unit	**Description of failure**					
item	**Function**	**Failure mode**	**Failure cause**	**Effect of failure**	**S**	**O**	**D**
Oil pump	flow the oil from	Not functioning	Failure in service	Low oil pressure	10	3	8

	oil pan to cylinder block and Raise the pressure of oil		Mechanical failure	alarm Loss of engine			
Oil filters	Separate the oil from dirt	Filters are plugged	contamination	Low oil pressure	5	6	6
Piston cooling nozzle		damage	Cooling nozzles are not installed correctly	Low oil pressure	6	2	8
Oil pan	Reserve oil	Lubricating oil level is above specifications	Failure in service	Crank case gases excessive	4	7	1
				High coolant temperature	7	6	3
		Lubricating oil is contaminated	Contamination with coolant or fuel	High oil temperature	8	8	1
		Lubricating oil level is below specifications	Oil leaks	Low oil pressure			
Oil pressure regulator	Regulate oil pressure	Oil pressure regulator Is malfunctioning	Mechanical failure	• High oil pressure • Low oil pressure	8	4	3
Lubricating oil cooler	Cooling oil	Lubricating oil cooler is plugged	Contamination	Low oil pressure	7	2	5

		Lubricating oil cooler is leaking	damage	High oil temperature Low oil pressure	8	2	4
Lubricating oil lines	Transfer lubricating oil	Leaking	damage	• Low oil pressure • High coolant temperature	7	9	1
		restriction	Debris contamination	Low oil pressure	7	6	3

3-6-4 Cylinder block:

The engine cylinder block is cast in one piece cast iron, V- type cylinders inline overhead valves and camshafts in block; the cylinder heat is made of special cast iron. The thermally loaded flame plate is efficiently water cooled.
The crankshaft is forged in one piece in high tensile steel.

Table 3.8: cylinder block FMECA table

	Description of unit	**Description of failure**					
item	**Function**	**Failure mode**	**Failure cause**	**Effect of failure**	**S**	**O**	**D**
Main	Guide rotation	• Abrasion	• long-term	• Wear	9	2	8

bearing	of crank shaft about its own longitudinal axis	and scoring of bearing surface • fatigue	operation with very fine debris in the oil and short-term operation with coarser contaminant • combination of load, high temperature, and inconsistency of white metal structure resulting from direct lining of a large variable-cross-section housing	and scoring of the crank shaft • Overhe at-ing • Damag ed bearing	10	2	7
Connectin g rod bearings	support movement of connecting rod bearing	• Abrasion and scoring of bearing surface	• long-term operation with very fine debris in the oil and short-term operation with coarser contaminant	• Wear and scoring of the crank shaft	9	3	8

		• fatigue	• combination of load, high temperature	• Overhe at-ing • Damag ed bearing	10	3	8
Cylinder head gasket	Prevent oil leakage	Oil leaking	Gasket damage	Lubricating oil in the coolant Low oil pressure	5	7	2
Cylinder block		Cylinder block is cracked	Mechanical failure	Lubricating oil or fuel in the coolant	10	1	4
pistons	Transmit gas load to connecting rod and crank shaft system carries gas and oil sealing elements	piston seizure	Leaky piston rings Damaged valves Over fueling Ring breakage Over load on cylinders Distorted rings	liner breakage springing or twisting of crankshaft	9	6	6
		piston blow-by		crankcase explosion poor combustion	9	6	5

				hence loss in power			
		scratching			7	6	8
				liner damage burning of piston wall			
Piston rings	control blow-by and oil flow from crankcase to combustion chamber	Leakage	insufficient lubrication worn, broken, stuck or poorly maintained piston rings excessive cylinder liner wear overloading of engine	piston seizure low compressio n, hence loss in engine power gas blow-by afterburnin g liner damage burned piston walls	8	5	3
		worn		crank case gases blow-by	9	5	5
Cylinder liner		overheated cylinder liner	insufficient cooling water	piston seizure	7	6	8

		worn liner	insufficient lubrication broken rings insufficient cylinder lubrication	breakage of piston rings ring scuff crank case gases blow-by	8	6	5
Exhaust and insert valves		Leakage	Improper lubrication	low compression and peak firing pressure	8	8	5
		Burned exhaust valves	excessive thermal stress	exhaust blow-by	8	7	3
Turbocharger	increases mass of air trapped in combustion chamber by raising air density, hence permitting more fuel to be burnt, and ultimately increasing power output of engine	Fouling	excessive lubrication	loss in engine power	7	7	3
		Surging	filter and fuel path obstructions	loss in engine power	7	7	3
		damaged	mechanical failure	engine noise excessive	8	8	1

3-6-4 Electrical equipment:

The engine electrical system is 24 volts DC, negative ground/earth. This system includes an electric engine starter, a battery and a battery charging alternator

Table 3.9: Electrical equipment FMECA table

	Description of unit	**Description of failure**					
item	**Function**	**Failure mode**	**Failure cause**	**Effect of failure**	**S**	**O**	**D**
alternator	Charge the batteries	Malfunctioning	Mechanical failure	Alternator is not charging	6	3	2
Batteries	Provide DC	failure	Bad condition	Insufficient charging Engine not crank	6	6	2
Alternator drive belt	to drive the alternator	Alternator belt is loose	Belt is not tightened	Alternator is not charging	6	8	1
Starting motor	Start the engine from the battery	Malfunctioning Starting motor ring is damaged	Mechanical failure	Engine not crank	7	3	1
generator	Generate output voltage	Loss of excitation Fail to synchronize	Fail to operate Improper synchronizing adjustments	No power output Engine shutdown			

3-6-5 Electrical control system:

To control and monitor the generating set, an electronic control system has been used; PCC model control system is fitted. Control panel provides a means of starting and stopping the generating set, monitoring its operation and output and automatically shutting down the set in the event of critical condition arising such as low oil pressure or high engine temperature.

Table 3.10: Electrical control system FMECA table

	Description of unit	**Description of failure**					
item	**Function**	**Failure mode**	**Failure cause**	**Effect of failure**	**S**	**O**	**D**
Magnetic pickup	Speed sensor	Speed does not match generator set	Speed is not being sensed Damaged magnetic pickup	Engine shutdown	6	3	1
Engine interface board	Reads user control inputs Monitors engine ,generator and system status	Fail to operate	Bad condition	Engine does not crank	7	3	1
		The run signal is not being processed	Connectors failed	Engine does not start	7	3	2
				High AC voltage			
				Engine shutdown			

Customer interface board		Customer fault	Bad customer interface board	Engine shutdown High AC voltage	7	3	1
Digital board	Contains the microprocessor and the operational software for the control	Fail to operate	Bad condition Connectors failed	Engine does not crank Engine does not start Engine shutdown High AC voltage Under frequency	7	4	1
		The run signal is not getting out			7	4	1
OPE regulator auto volt							
Governor output module	Sends and amplified signal to drive the governor actuator	Signal fault	Bad Governor output module	Engine shutdown Engine over speed Under frequency	8	2	1

4. Chapter four: Results and Discussion:

4-1 Failure Modes– Sorted by RPN:

The RPN results are presented to reflect the criticality of the failures that were assessed during the FMECA. Table 4-1 lists the highest average RPN for all of the equipment failures. RPN scores from the FMECA range from 16–336, with the top 25% ranging from 192–336. These are considered to be the most critical failure modes.

Table 4-1: Failure Modes– Sorted by RPN

item	Failure mode	RPN	Number of functional failures
Cylinder liner	overheated cylinder liner	336	3
pistons	scratching	336	3
fuel injectors	malfunctioning	336	6
pistons	piston seizure	324	4
Exhaust valves	Leakage	320	4
Intake valves	Leakage	320	3
radiator	Radiator fins obstructed with debris	280	4
fuel filters	Filter clogged	280	9

	by the dirt		
pistons	piston blow-by	270	1
fuel injectors	incorrect atomization	245	4
Oil pump	Not functioning	240	1
Cylinder liner	worn liner	240	2
Connecting rod bearings	fatigue	240	1
Piston rings	worn	225	2
Connecting rod bearings	Abrasion and scoring of bearing surface	216	1
Fuel pump	Less pressure and the resulting lack of capacity.(Low output)	192	2
Oil filters	Filters are plugged	180	6
fuel filters	Air in the fuel system	168	2
Exhaust valves	Burned exhaust valves	168	1

Turbocharger	Fouling	147	4
Turbocharger	Surging	147	5
Main bearing	Abrasion and scoring of bearing surface	144	1
Shut-off valve	Fails open	144	3
Lubricating oil lines	restriction	126	3
Oil pan	Lubricating oil is contaminated	126	2
fuel tank	Fuel contaminated	126	3
fuel line	Fuel line restricted	120	2
Fuel pre-filters	Filter clogged by the dirt	120	9
Piston rings	Leakage	120	1
radiator	Coolant loss	112	6
Shut-off valve	Fails closed	108	1
Water pump	Water pump is malfunctioning	108	1
Fails closed	Oil pressure regulator Is malfunctioning	96	1
Piston cooling nozzle	failure	96	1
Fan drive	fan drive belt is loose	80	1
Coolant system	Coolant system hose is	72	1

hose	collapsed		
Batteries	failure	72	3
Cylinder head gasket	Oil leaking	70	5
Lubricating oil cooler	Lubricating oil cooler is plugged	70	2
thermostat	Thermostat is malfunctioning	70	1
Oil pan	Lubricating oil level is above specifications	64	1
Turbocharger	damaged	64	3
Lubricating oil cooler	Lubricating oil cooler is leaking	64	2
Lubricating oil lines	Leaking	63	3
Alternator drive belt	Alternator belt is loose	48	3
Engine interface board	The run signal is not being processed	42	2
Cylinder block	Cylinder block is cracked	40	1
alternator	Malfunctioning	36	2
Oil pan	Lubricating oil level is above specifications	28	1
Digital board	Fail to operate	28	2

Digital board	The run signal is not getting out	28	3
Starting motor	Malfunctioning	21	2
Engine interface board	Fail to operate	21	1
Customer interface board	Customer fault	21	3
Magnetic pickup	Speed does not match generator set	18	2
Governor output module	Signal fault	16	2

4-2 Discussion

The Cylinder liners were assessed as one of the top equipment whose failure could potentially have a severe effect. This is owing to the fact that these liners are the items where combustion occurs, where failure can lead to the worst case consequences. It was assessed that the cylinder liners to have mechanical damage every 12000 hours of service to once in every 24000 hours of service caused by damage to the piston, connecting rod or cooling deficiency. However, it is to be noted that these liners are replaced every 24000 hours of service. The high RPN rating is also due to the overheating caused by seal wear, oil leakage and other mechanical damage discussed above.

The pistons scratching and seizure were assessed as one of the top 10% of critical equipment failures. The piston failure may lead to worst consequences. It was assessed that scratching and seizure caused by leaky piston rings, damaged valves, over fueling, Ring breakage, over load on cylinders or distorted rings to occur three to four times a year. It is also to be noted that these scratching will not be detected until the function is fired. A review of maintenance practices shows that these pistons are replaced every 24000 hours of service.

Malfunctioning and incorrect Atomization were assessed to be in the top 25% of the criticality rankings. Such failures were attributed to mechanical failure of these plungers and barrels, restriction of orifice screen or damage of seals.

Such failures were assessed to occur twice to four times a year. A review of maintenance practices shows that these injectors are calibrated every 12000 hours of service.

The FMECA results show the intake and exhaust valves to be in the top 25% of the critical equipment list. The possibility of leaking to the valves was assessed to occur three to four times a year .Such damages caused either by improper lubrication or wear of the valve seat due to normal operation. The valves are checked every 12000 hours.

The radiator was also assessed as one of the top 25% of the critical equipment, owing to the severity of the failure of the functions associated with their operation. The failure of the radiator was assessed to have the likelihood of occurrence four times a year. Such damages caused either by debris in the water, or any corrosion or erosion issues specific to the water environment.

The fuel filter clogging by the dirt caused by water contamination or debris contamination place these equipment items in the top 15% of the criticality list. It causes unstable load, damage pump or damage Injectors. The fuel filters have to be replaced every 250 hours of service.

Owing to the mechanical damage and subsequent failure, the oil pump was assessed as one of the top 25% of critical equipment. Such damage can only be detected when the oil pump is pulled for inspections. The assessments did not show high failure occurrences.

Fatigue, abrasion and scoring of connecting rod bearing surface were assessed as one of the top 25% of critical equipment failures. Such damages will only be detected during visual inspection of the connecting rod bearing. The causes were assessed are operation with very fine debris in the oil, short-term operation with coarser contaminant and combination of load, high temperature. The connecting rod bearing are replaced every 12000 hours of service.

Less pressure and the resulting lack of capacity (Low output) of the fuel pump is also one of the most critical equipment failures. The causes were assessed as a mechanical failure that reduces the fuel flow and decrease the engine performance. It was assessed it occurs twice a year.

4-3 Maintenance plan for the improvement of components whose failure is critical:

It was possible to establish suitable maintenance activities for each failure mode. As a result, the maintenance actions are a combination of corrective and preventive means. The distribution of maintenance tasks is displayed below, Run to failure maintenance tasks is mainly dependent on spare part management. This is apparent since the decision of applying these actions in the first place, is based on the idea that it is safe and economically efficient to let the item fail instead of using preventive means. In other words, spare parts must be available to replace the component or its parts when it fails. The remainder of maintenance tasks is considered as preventive. Applying this sort of maintenance necessitates more planning concerning how and when the activities should be executed

Table 4-2 shows the proposed maintenance strategy meant for the most critical components covered by the FMECA. Failure modes are referred to using the notation from the FMECA worksheets in the previous sections. The table list maintenance tasks type, a description of the procedure which should be executed

Table 4-2: Maintenance tasks description for the top critical items

item	failure	action	Type of maintenance
Cylinder liner	overheated cylinder liner	• Systematic Changing the seals • Lubrication grooves each disassembly • State checking after 1500 h of service • Change in the case of wear	• Preventive • corrective
pistons	scratching	• State checking after 6000 hours of service • Lubrication every disassembly • Change in the case of wear	• Preventive • corrective

fuel injectors	malfunctioning	Check and calibrate every 6000 hours of service	Preventive
pistons	piston seizure	• State checking after 6000 hours of service • Cleaning the bore • Lubrication every disassembly • Change in the case of wear	• Preventive • corrective
Exhaust valves	Leakage	Change valve with a new one every 12000 hours of service	Overhaul
radiator	Radiator fins obstructed with debris	• Perform water sampling • Systematic cleaning of the plates	Condition monitoring
fuel filters	Filter clogged by the dirt	Prevent fuel filter blockage	Condition monitoring
pistons	piston	• State checking	• Preventive

	blow-by	after 1500 h of service • Lubrication every disassembly • Change in the case of wear	• corrective
fuel injectors	incorrect atomization	Check and calibrate every 6000 hours of service	Preventive
Oil pump	Not functioning	Mechanical indicator showing the pressure drop through the filter	Condition monitoring
Cylinder liner	worn liner	• Systematic Changing the seals • Lubrication grooves each disassembly • State checking after 1500 h of service • Change in the case of wear	• Preventive • corrective
Connecting	fatigue	• Change the	

rod bearings		bearings after 12000 hours of operation • Systematic Lubrication	Preventive
Piston rings	worn	Systematic Changing the ring after 5000 hours of service	preventive
Connecting rod bearings	Abrasion and scoring of bearing surface	• Change the bearings after 12000 hours of operation • Systematic Lubrication	Preventive
Fuel pump	Less pressure and the resulting lack of capacity.(Low output)	Perform standard measurements after 3000 hours of service	Preventive

The presented results have established maintenance tasks that consistently aim to handle the sources of a potential failure, which is the best way of proactively avoid the failure from occurring in the first place.

In the long run, by implementing the resulting maintenance program operational costs is very likely to be reduced

. Specifically, the economic winnings would be a decrease in repair costs, less off-hire, less costs of maintenance and unforeseen spare parts

5. Chapter five: Conclusions and Recommendations:

5-1 Conclusions:

In terms of system reliability, our work helps to identify the components on which special attention should be paid while also determining the critical failures and the improvements that need to be implemented. We must note that the FMECA analysis is a logical and structured approach to better control the system studied while identifying the weak links and to know the types of maintenance applied to each subsystem and component. It is a real process of optimizing maintenance costs and ensures maximum availability for production tools

The initial assessment showed that based on the criticality ranking, the following equipment and their failure modes were identified as the top 25% of the critical items:

- Cylinder liner
- Pistons
- Fuel injectors
- Exhaust valves
- Radiator
- Fuel filters
- Oil pump
- Connecting rod bearings
- Piston rings
- Fuel pump

5-2 Recommendations:

- The results of this research can be used to implement computerized maintenance management system
- A new task should involve more parts and components
- A new task should involve preventive replacements costs

References:

[1] Muchiri, Peter, Liliane Pintelon, Ludo Gelders, and Harry Martin. "Development of Maintenance Function Performance Measurement Framework and Indicators." International Journal of Production Economics 131.1 (2011): 295-302

[2] Mobley, R. Keith. Maintenance Fundamentals. 2nd ed. Amsterdam: Elsevier/Butterworth Heinemann, 2004. Print

[3] Swanson, Laura. "Linking Maintenance Strategies to Performance." International Journal of Production Economics 70.3 (2001): 237-44. Web.

[4 Sullivan, G. P., R. Pugh, A. P. Melendez, and W. D. Hunt. "Operations & Maintenance Best Practices." A guide to achieving operational efficiency, Release 2 (2004).

[5] John Moubray. Reliability Centered Maintenance. 2nd ed. New York: Industrial, 1992

[6] Scutti, J. J., and W. J. McBrine. "Introduction to failure analysis and prevention." Materials Park, OH: ASM International, 2002. (2002): 3-23.

[7] Industrial Diesel Generators and Engines, “Types and Applications”, website:

http://www.dieselserviceandsupply.com/ (accessed in April 2016)

[8] R. Billinton, R. N. Allan. Reliability

Evaluation of Power Systems. Plenum Press, New York and London, 1996

[9] Narang, Ramesh V. "Introducing Reliability and Maintainability in Engineering and Technology." American Society for Engineering Education. American Society for Engineering Education, 2010. Web. 18 May 2016. <https://www.asee.org/public/.../download>.

[10] Høyland, Arnljot, and Marvin Rausand. System Reliability Theory: Models and Statistical Methods. New York: Wiley, 2004. Print.

[11] Arcidiacono, G., and G. Campatelli. "Reliability Improvement of a Diesel Engine Using the FMETA Approach." Qual. Reliab. Engng. Int. Quality and Reliability Engineering International 20.2 (2004): 143-54. Web.

[12] Bose, D., G. Ghosh, K. Mandal, S.P. Sau, and S. Kunar. "Measurement and Evaluation of Reliability, Availability and Maintainability of a Diesel Locomotive Engine." IOSR-JMCE IOSR Journal of Mechanical and Civil Engineering 8.1 (2013): 31-46. Web

[13] Banks, Jeffrey, et al. Failure modes and predictive diagnostics considerations for diesel engines. PENNSYLVANIA STATE UNIV UNIVERSITY PARK APPLIED RESEARCH LAB, 2001.

[14] Ling, Dan, Wei Song, and Rui Sun. " A RELIABILITY PREDICTION METHOD FOR DIESEL ENGINE COMPONENTS BASED ON FMEA." Maintenance and Reliability nr (2011): 63-67.

[15] Gandhare, S. N., T. A. Madankar, and D. R. Ikhar. "Re–Scheduling Of Maintenance Tasks for Diesel Locomotive (ZDM) Maintenance Work Using FMEA Technique–An Industrial Engineering Approach for Saving the Resources." OSR Journal of Mechanical and Civil Engineering (IOSR–JMCE) International Conference on Advances in Engineering & Technology–2014 (ICAET–2014). 2014.

[16] Estorilio, Carla, and Marcelo César Simião. "Cost reduction of a diesel engine using the DFMA method." Product Management & Development 4.2 (2006): 95-103.

[17] Collacott, R.A. Mechanical Fault Diagnosis and Condition Monitoring. Chapman and Hall,1977.

[18] Lin, T.R., Tan, A.C.C., Mathew, J. Condition Monitoring and Diagnosis of Injector Faults
in a Diesel Engine using In-Cylinder Pressure and Acoustic Emission Techniques. 14th Asia

Pacific Vibration Conference Hong Kong, 2011.

[19] Jones, N.B., Li, Y.H. A Review of Condition Monitoring and Fault Diagnosis for Diesel Engines. Tribotest Journal Vol. 6, 2000.