

Cost implications of Equipment Failures using Life cost based Failure Modes and Effects Analysis (FMEA) on 365KVA Caterpillar Generator

Abstract

Equipment failures have implication on financial sustainability of the organization. This showcase the fact that equipment failures have cost implications and there is need to convert failures using Failure Modes and Effect Analysis, FMEA numerical analysis of 3parameters of severity, occurrence and detection that resulted to Risk Priority Number (RPN). The formula used in analyzing the results includes labour cost, material cost and opportunity cost. The labour cost is equals to the occurrence $\{[\text{Delay Time} \cdot \text{Labor rate} \cdot \text{no of Operators}]\}$ plus $[\text{Fixing Time} \cdot \text{Labor rate} \cdot \text{no of Maintenance of personnel} \cdot \text{Quantity}] + [\text{Detection Time} \cdot \text{Labor rate} \cdot \text{no of Operators}]$. Material Cost is equals to the occurrence \times Quantity of parts to replace \times Cost of Part. Opportunity Cost is equals to the Loss Time \times Hourly Opportunity Cost. Loss Time is equals to the $\{\text{Detection Time} + \text{Fixing Time} + \text{Delay Time}\}$. This researched have proven that since installation of 365kva caterpillar generator in NNPC Lokoja that every time the generator failed to run, we can easily calculate the cost of labour, material to replace failed parts and opportunity cost of those idle times of failed production. Using the concept of FMEA, Failure Modes, Effects Analysis which produces Risk Priority Number(RPN) that is being computed by multiplying severity, occurrence and detection in which occurrence was gotten from equipment history card and logbooks since year 2005 when the installation of 365kva caterpillar generator was made till date. Likert questionnaires from industry experts were collated and Delphi method used to arrive accepted severity and detection to aid in the analysis. Millions of naira are being lost whenever equipment failures occurs and engineers from all fields, should always carry out root cause analysis whenever equipment failure occurs in order to prevent further occurrence.

Keywords: Cost Implications, Equipment failure, Life cost, Failure Modes, Delay-time Detection, Effects Analysis, Financial sustainability

1. INTRODUCTION

Equipment failure, downtime and failed set target are key factors that require a more advance equipment optimization to address in order to have a very productive system. For engineering field to remain relevant in twenty first century there is the need for us all to embark on tangible research aim at reducing equipment failure to zero level. This will portray the spirit of seeing engineering works as means of measuring societal wealth and medium of saving treasures.

Much has happened in engineering since the industrial revolution a couple of hundred years ago but perhaps the most dramatic changes have occurred in the last fifty years. These changes have of course affected how industry's plant have been maintained. Prior to the Second World War (1939-1945) machinery was generally quite rugged and relatively slow running, instrumentation and control systems were very basic. The demands of production were not overly severe so that downtime was not usually a critical issue and it was adequate to maintain on a breakdown basis. This machinery was inherently reliable. Even today we can see examples of machines made in that period which have work very hard and are still essentially as good as the day they were made. From the 1950's with the rebuilding of industry after the war, particularly those of Japan and Germany there developed a much more competitive market place, there was increasing intolerance of downtime. The cost of labour became increasing significant leading to more and more mechanization and automation. Machinery was of higher construction and ran at higher speeds. They wore out more rapidly and were seen as less reliable. All equipment is designed to last for a period of time called the design life span. If the equipment does not last this long, major faults are attributed to the maintenance culture of the handler or equipment manager. In recent times research are geared towards developing models that would help select equipment maintenance intervals that are economical and have a low risk on losing the equipment. Some of the models that proved to improve the equipment maintenance culture and system reliabilities are convention(traditional) and life cost-based failure mode and effect analysis(FMEA). The two used models are highlighted below for more clarifications. The traditional FMEA process is a systematic method to identify: – Primary and secondary functions of the system and the failure modes that prevent the system from completing its designed purpose. To resolve the ambiguity of measuring detection difficulty and the irrational logic of multiplying 3 ordinal indices, a new methodology was created to overcome these shortcomings,

Life Cost-Based FMEA. Life Cost-Based FMEA measures failure/risk in terms of monetary cost. Cost is a universal parameter that can be easily related to severity by engineers and others.

2. LITERATURE REVIEW

FMEA was begun in 1940s by the U.S. military during World War II, FMEA was further developed by aerospace and automobile industries. Several Industries maintain formal FMEA standards. The process was also adopted early on by the Society for Automotive Engineers (SAE) in 1967. The use of FMEA spread rapidly to other industries during the 1970s and subsequent years and is now utilized in a variety of industries including military, semiconductors, and the foodservice industry. More recently FMEA has been adopted within the healthcare industry to assess the high risk process of care (Franklin, Shebl, & Barber, 2012). FMEA is useful in understanding the failure modes of systems or products, qualifying the effects of failure, and aiding in the development of mitigation strategies. It is a useful tool in improving quality, reliability, and the maintainability of designs, and is a critical analysis component in risk management. FMEA can be applied to almost any system or process and thus universally valuable. It became widely known within the quality community as a total quality management tool in the 1980s and as a Six Sigma tool in the 1990s. A team should apply FMEA to perform risk assessment to see what the customer will experience if a key process input (X) were to fail. The team should then take action to minimize risk and document processes and improvement activities. FMEA is living document that should be reviewed and updated whenever the process is changed (Jogger, 2002). It can be used in the define phase of the define, measure, analyze, improve and control strategy as a voice of the customer input, but is more commonly created in the measure phase, updated in the analyze and improve phases and is a vital element of the control phase. FMEA is one of the most efficient low-risk tools for prevention of problems and for identification of more efficacious system. Failure mode and effects analysis (FMEA) is an analysis method for systematic operations and a component of total quality management. It is a dynamic analysis and early prevention tool aimed at identifying potential failure modes (FM) in a specific scope of systematic operations and classifying these potential FMs based on their influence levels to confirmation of their impact on the system. FMEA is widely applied in the manufacturing industry to analyze the various stages of a product's lifecycle or provide preventative analysis for new products or engineering design processes.

The United States has endeavoured to standardize FMEA since the 1970s. Later, FMEA became widely used in the Japanese manufacturing sector. The purpose of FMEA in a planned manufacturing process is to convert design characteristics into clearly defined operating conditions and guarantee that the outcomes and performance of the final product satisfy client demands and expectations. Once a potential FM or failure effect is identified, corrective measures can be implemented to eliminate the potential FM or continue improving operations— thereby reducing the severity and frequency of the potential FM and improving detection—and to standardize the basic operations and regulations in the planned process, which can serve as a reference for future preventative and technical actions. Failure Modes and Effects Analysis (FMEA) is a step-by-step approach for identifying all possible failures in a design, manufacturing or assembly process, or a product or service. “Failure modes” means the ways, or modes, in which something might fail. Failures are any errors or defects, especially ones that affect the customer, and can be potential or actual. “Effects analysis” refers to studying the consequences of those failures. Failures are prioritized according to how serious their consequences are, how frequently they occur and how easily they can be detected. The purpose of the FMEA is to take actions to eliminate or reduce failures, starting with the highest-priority ones. Failure modes and effects analysis also documents current knowledge and actions about the risks of failures, for use in continuous improvement (Tague 2005; Wolniak 2011).

Life cost-based FMEA Steven Kmenta & Kosuke Ishii, (2000). Stated that risk contains two basic elements: chance and consequences. Probability is a universal measure of chance, and cost is an accepted measure of consequences (Gilchrist, 1993). For a given failure scenario, risk calculated as expected cost: the product of probability and failure cost (Rasmussen, 1981; Modarres, 1992). Expected cost is used extensively in the fields of Risk Analysis, Economics, Insurance, Decision Theory, etc. Cherrill & Seung (2003) posited thus all of the electromagnets and their power supplies must be highly reliable or quickly repairable. Improved reliability or repairability comes at a higher cost. We have developed a set of analysis procedures for magnet designers to use as they decide how much effort to exert, i.e. how much money to spend, to improve the reliability of a particular style of magnet. Availability for one particular magnet can be calculated. Next, labor and material costs to repair magnet failures are used in a Monte Carlo simulation to calculate the total cost of all failures over a 30-year lifetime. Opportunity costs are included. Engineers choose from

amongst various designs by comparing lifecycle costs. identifying technique, which involve life cycle costs, from design to operation. lifetime cost: a measure of risk, risk contains 2 basic elements (1) chance, measured by probability, and (2) consequence, measured by cost. A new methodology has been developed to overcome these shortcomings, it is called "Life Cost-based FMEA".

It measures risk of failure in terms of cost. Cost is a universal language understood by engineers without ambiguity. Expected failure cost is defined as the product of the probability of a particular failure and the cost associated with that failure. Lifetime failure cost is the sum of all the expected costs for all failure scenarios at all stages of a system component's life: design, manufacture, installation, and operation. Cost as a measure of failure Rhee S. & Spencer C. M., (2009) stated that to resolve the ambiguity of measuring detection difficulty and the irrational logic of multiplying 3 ordinal indices, a new methodology was created to overcome these shortcomings, Life Cost-Based FMEA

Hassan et al; 2009 opined the uses of ABC (Activity-Based Costing) method to estimate manufacturing cost. Finally, a cost-based FMEA method is carried out to estimate failure and alternative actions cost. Life Cost-Based FMEA, which measures risk in terms of cost. Life Cost-Based FMEA is useful for comparing and selecting design alternatives that can reduce the overall life cycle cost of a particular system. Next, a Monte Carlo simulation is applied to the Cost-Based FMEA to account for the uncertainties in: detection time, fixing time, occurrence, delay time, down time, and model complex scenarios (Seung & Kosuke . ;2003). Anette , 2008 posited that cost of faults are being categorized into cost of internal detected faults and cost of external detected faults. Hassan et al; 2008 stated that Cost-based FMEA and ABC methods were involved in selecting manufacturing resources, estimate manufacturing process risk cost and manufacturing cost. Cost-based process FMEA, the potential failure modes caused by the process are analysed and then their financial impacts are estimated. Macia et al; 2020. Stated that Risk analysis therefore gives considerable benefit to analytical validation, assessing and avoiding failures due to human errors, potential imprecision in applying protocols, uncertainty in equipment function and imperfect control of materials. Martyn & Carl, 2021 mentioned that 13 were not predicted by the identified failure modes, with six relating to delays in the process, three issues with appointment times, one communication error, two instances of a failure to image, and one technical fault deemed unpredictable by the manufacturer. The risk priority number (RPN) calculation

method is one of the critical subjects of failure mode and effects analysis (FMEA) researched (Xiaojun & Jing, 2021) and the high RPN value is above average due to unclean fuel resulting in a clogged system, as well as the impact of failure with the highest severity value (fire) this is due to unclean and moisture content on the fuel (Rahmad et al; 2018). Emovon et al; 2014 stated that RPN is the product of three risk criteria; probability of Occurrence (O), resulting level of Severity (S) and the inverse of the ability to Detect (D) the failure before it occurs. FMEA is an effective tool or technique used for identifying possible failures and mitigating their effects (faturachman et al, 2013) refers.

3. PROBLEM STATEMENT

Many production or manufacturing equipments (machines) failed to operate or breakdown intermittently while production is in process, thereby causing loss of man-hour, low production, poor revenue, failed business target etc. Lokoja Pump Station established in 1979 is one among the seven (7) Pump Stations on System 2C Pipeline Pumping/Boosting crude oil to Kaduna Refinery & Petrochemicals (KRPC) of Nigerian Pipeline and Storage Company, NPSC a subsidiary of Nigerian National Petroleum Corporation (NNPC). The Pump Station is carrying out the job of pumping crude oil with the help of these equipments: i. Pipeline ii. Allen Engine iii. Nuovo Pignone Pump iv. Valves v. Generators vi. Fan blowers vii. Compressors viii. Lighting fittings ix. Fire booster pumps etc. The pump station since from inception forty-one years (41yrs) ago solely depend on generator to accomplish its task of pumping crude oil to Kaduna Refinery and Petrochemical(KRPC). In light of above there is urgent need to carryout analysis of life cost-based FMEA (failure mode and effects analysis), on the 365kva caterpillar generator in order to established the cost involvement if the generator failed to operate(run).

4. METHODOLOGY

Life Cost-Based FMEA measures failure/risk in terms of monetary cost. Cost is a universal parameter that can be easily related to severity by engineers and others. Thus, failure cost can be estimated using the following simplest form:

$$\sum_{i=1}^n P_i C_i \quad (1)$$

Expected Failure Cost p: Probability of a particular failure occurring c: Monetary cost associated with that particular failure n: Total number of failure scenarios. Formation of team FMEA is most effective when there are inputs into it from all concerned disciplines of the product development team. However, FMEA is a long process and can become tedious and won't be effective if too many people participate. An ideal team should have 3 to 4 people from: design, manufacturing, and service departments if possible. Depending on how complex the system is, the entire process can take anywhere from one to four weeks working full time. Thus, it is important to agree to the time commitment before starting the analysis else, anxious managers might stop the procedure before it is completed. Labor Costs (Rhee & Spencer, 2009), Labor cost can be derived with the time information input in the cost-based FMEA table using the following equation:

$$\text{Labor Cost} = \text{Occurrence} \times \{ [\text{Detection Time} \times \text{Labor rate} \times \text{no. of Operators}] + [\text{Fixing Time} \times \text{Labor rate} \times \text{no. of Operators} \times \text{Quantity}] + [\text{Delay Time} \times \text{Labor rate} \times \text{no. of Operators}] \} \quad (2)$$

Material Costs (Rhee & Spencer 2009) is the component replacement due to failure is considered as material cost. Material cost is obtained using the following equation:

$$\text{Material Cost} = \text{Occurrence} \times \text{Quantity of parts to replace} \times \text{Cost of Part} \quad (3)$$

Opportunity Cost (Rhee & Spencer, 2009) Opportunity cost is the cost that incurs when a failure inhibits the main function of the system and prevents any value creation. Opportunity cost is calculated using the following equation:

$$\text{Opportunity Cost} = \text{Loss Time} \times \text{Hourly Opportunity Cost} \quad (4)$$

where, Loss Time = {Detection Time + Fixing Time + Delay Time}

5. RESULTS AND ANALYSIS

The results in tables 1 to 10 display the detailed results on cost-based FMEA for Ignition System Sub- System and Cylinder Liner in the Cylinder Block Assembly, oil filter for Lubricating System Sub-System, the Injector for the Fuel System Assembly Sub-System and Automatic Voltage Regulator (AVR) for the Alternator Sub-System.

Specifically, table 6 reveals the results integrity testing of piping network around the generator carried out to reduce the number of failure occurrence. The mitigation process of reducing the severity/failure occurrence or improving on the level of detection to reduce the RPN is less than 100 (< 100).

Table 7 show the result attained to reduce the frequency at which the equipment fail by servicing the generator every 250HRS. To reduce an equipment idle time, order original spare part from MANTRAC during overhaul process with proforma invoice fully investigated to ensure credibility of the spare parts.

This high cost recorded in table 8 indicates that material cost of running heavy duty on 24/7 operation is quite high, one drum of engine oil is over ₦250,000.00. Thus, there is need for alternative source of power supply that would be more economical is required.

Table 9 reveals that generator tank should be clean every 5years and thus, there should be proper inspection of AGO supplying tank, especially tanker (truck) that use their tank to convey yam/other food items from the North to elsewhere should not be used to convey AGO. The need for opt for better optimization process to reduce the occurrence of failure is also self-evident.

The results in table 10 reveals that load study analysis should be done before adding power consuming equipment to generator. This will enhance the life span of AVR and then reduce cost of material for repairs.

Table 1: Cost-based FMEA for Ignition System Sub- System

Failure mode	Root Cause of Failure	Effect of Failure	Input								Output				
			Origin	Detection phase	Frequency	Re-occurring	Detection Time(HRS)	Fixing Time(HRS)	Delay Time(HRS)	Loss Time(HRS)	Quantity	Parts Cost(₺)	Labour Cost(₺)	Material Cost(₺)	Opportunity Cost (₺) Cost(₺)
Does not ignite the air-fuel mixture	Batteries are dead	Engine will not start	INSTR	INSTR	2	6	0.03	0.3	2	2.33	2	85,000	4939	1,020,000	11,650
Low compression	Fuel delivery pipe is blocked/cracked	Engine will not start	MECH	MECH	0.001	20	0.03	2	1	3.03	1	1,600	4742	80,000	15,150

Table 2: Cost- based FMEA for Cylinder Liner in the Cylinder Block Assembly

Failure mode	Root Cause of Failure	Effect of Failure	Input										Output		
			Origin	Detection phase	Frequency	Re-occurring	Detection Time(HRS)	Fixing Time(HRS)	Delay Time(HRS)	Loss Time(HRS)	Quantity	Parts Cost(₦)	Labour Cost(₦)	Material Cost(₦)	Opportunity(₦)
Bad/Poor lubrication	Bad spray	Overheating	MECH	MECH	0.001	20	1	3	2	6	5	6000	75,120	150,000	30,000
Wear on the liner	Bad oil quality	Grinding of piston due to uneven lubrication	OPS	OPS	0.001	20	5	8	3	16	4	5,000	32,552	20,000	80,000
Very high operating temperature	Seizure in engine operation	Liner cracking	MECH	MECH	0.001	20	5	8	3	16	4	10,000	32,552	40,000	160,000

Table 3: Cost-based FMEA on oil filter for Lubricating System Sub-System

Failure mode	Root Cause of Failure	Effect of Failure	Input										Output		
			Origin	Detection phase	Frequency	Re-occurring	Detection Time(HRS)	Fixing Time(HRS)	Delay Time(HRS)	Loss Time(HRS)	Quantity(LITRES)	Parts Cost(₹)	Labour Cost(₹)	Material Cost(₹)	Opportunity(₹)
Rupture of the filter element	Wear of the filter element due to aging	Restriction of oil flow	MECH	MECH	2	1	0.03	2	3	5.03	40	200,000	152,137	16,000,000	25,150
Clogging	Blockage of oil passage(oilers) due to contaminants	Restriction of oil flow	MECH	MECH	0.001	1	0.03	2	3	5.03	40	200,000	152,137	16,000,00	25,120

Table 4: Cost based FMEA on the Injector for the Fuel System Assembly Sub-System

Failure mode	Root Cause of Failure	Effect of Failure	Input										Output		
			origin	Detection phase	Frequency	Re-occurring	Detection Time(HRS)	Fixing Time(HRS)	Delay Time(HRS)	Loss Time(HRS)	Quantity	Parts Cost(₹)	Labour Cost (₹)	Material cost (₹)	Opportunity (₹)
Dirty fuel in the tank	Poor fuel filtration	Seizure of the injector spindle/dripping of the fuel	OPS	OPS	0.001	2	2	5	5	12	6	7,000	91,083	126,000	60,000

Unstable output Voltage	Overloading of the generator	Low output voltage	OPS	OPS	4	20	0.3	3	3	6.3	1	150,000	3,850	150,000	31,500
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TABLE 6: Total Cost of Failed Ignition System Sub-System.

TOTAL COST OF PRODUCTION (LABOUR MATERIAL OPPORTUNITY COST) ₦	RPN	CRPN ₦	RECOMMENDATION
$4,939 + 1,020,000 + 11,650 = \mathbf{1,036,589}$	24	24,878,136	Material cost is high, Batteries required serious maintenance and there is need to replace the batteries make (Product) to (CAT batteries) to reduce the high occurrence of failure.

$4,742 + 80,000 + 15,150 = \mathbf{99,892}$	180	17,980,560	<p>Integrity Testing of piping network around the generator on 2years basis should be carried-out to reduce the number of failure occurrence.</p> <p>Mitigation process of reducing the Severity, Occurrence and improve on the level of Detection to reduce the RPN to less than 100 (< 100).</p>
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TABLE 7: Total Cost of Failed Cylinder Liner in the Cylinder Block Assembly.

TOTAL COST OF PRODUCTION (LABOUR MATERIAL OPPORTUNITY COST) ₦	RPN	CRPN ₦	RECOMMENDATION
$75,120 + 150,000 + 30,000 = \mathbf{255,120}$	280	71,433,600	<p>Mitigation process in order to reduce the Severity and Occurrence was applied, and there is the need to improve on</p>

			level of Detection in order to reduce RPN to less than 100 (<100). This will have positive effect on cost.
$32,552 + 20,000 + 80,000 = \mathbf{132,552}$	70	9,278,640	To reduce the frequency at which the equipment fail by servicing the generator every 250HRS.
$32,552 + 40,000 + 160,000 = \mathbf{232,552}$	7	1,627,864	To Reduce an equipment idle time, order original spare part from MANTRAC during overhaul process with proforma invoice fully investigated to ensure credibility of the spare parts.

TABLE 8: Total Cost of Failed Oil Filter for Lubricating System Sub-System.

TOTAL COST OF PRODUCTION (LABOUR MATERIAL OPPORTUNITY COST) ₦	RPN	CRPN ₦	RECOMMENDATION
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$152,137 + 16,000,000 + 25,150 = \mathbf{16,177,287}$	60	970,637,220	This high cost indicate material cost of running heavy duty on 24/7 operation is quite high, one drum of engine oil is over ₦250,000.00 , there is need for alternative source of power supply that would be more economical is required.
$152,137 + 16,000,000 + 25,150 = \mathbf{16,177,287}$	60	970,637,220	This high cost indicate material cost of running heavy duty on 24/7 operation is quite high, one drum of engine oil is over ₦250,000.00 , there is need for alternative source of power supply that would be more economical is required.

TABLE 9: Total Cost of Failed Injector for the Fuel System Assembly Sub-System.

TOTAL COST OF PRODUCTION (LABOUR MATERIAL OPPORTUNITY COST) ₦	RPN	CRPN ₦	RECOMMENDATION
$91,083 + 126,000 + 60,000 = \mathbf{277,083}$	42	11,637,486	Generator tank should be clean every 5years and there should be proper inspection of AGO supplying tank, especially tanker (truck) that use their tank to convey yam/other food items from the North to elsewhere should not be used to convey AGO.

$9,390 + 20,000 + 42,500 = \mathbf{71,890}$	64	4,600,960	The need for Optimization process to reduce the occurrence of failure.
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TABLE 10: Total Cost of Failed Automatic Voltage Regulator (AVR) for the Alternator Sub-System.

TOTAL COST OF PRODUCTION (LABOUR MATERIAL OPPORTUNITY COST) ₦	RPN	CRPN ₦	RECOMMENDATION
$3,850 + 150,000 + 31,500 = \mathbf{185,350}$	56	10,379,600	Load study analysis should be done before adding power consuming equipment to generator, this will enhance the life span of AVR and then reduce cost of material for repairs.

6. CONCLUSION

This research work have proven that since that installation of 365kva caterpillar generator in NNPC lokoja that every time the generator failed to run, we can easily calculate the cost of labour, material to replace failed parts and opportunity cost of those idle times of failed production. Using the concept of FMEA, Failure Modes, Effects Analysis which produces Risk Priority Number(RPN)

that is being computed by multiplying severity, occurrence and detection in which occurrence was gotten from equipment history card and logbooks since year 2005 when the installation of 365kva caterpillar generator was made till date. Likert questionnaires from industry experts were collated and Delphi method used to arrive accepted severity and detection to aid in the analysis.

Millions of naira are being lost whenever equipment failures occurs and engineers from all fields, should always carry out root cause analysis whenever equipment failure occurs in order to prevent further occurrence.

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