OPTIMIZING MARINE DIESEL ENGINE MAINTENANCE: A PROACTIVE COST-EFFICIENCY STRATEGY

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1. **ABSTRACT:** The world is currently working towards applying proactive maintenance, as it leads to reducing operating costs over time. As the previous studies didn't analyse the cost advantage of applicate proactive maintenance techniques compared to other maintenance approaches in the maritime industry. The aim of this paper is to show the benefits of using proactive maintenance on marine diesel engines which are highlighted by a reduction in maintenance costs. A mathematical model has been created to show the cost reduction of using proactive maintenance in comparison to other maintenance types depending on downtime cost, spare parts cost, and services cost. The results show the benefits of using proactive approaches to reduce maintenance costs with an average of $2815.22 compared to predictive maintenance.

2. INTRODUCTION

Marine engines are the heart of any vessel, and their reliable operation is essential for smooth sailing and efficient transportation. Given the cruel working conditions of the marine environment, engines face challenges like operating hours, corrosive saltwater, and fluctuations in temperature and pressures. To keep engines working in proper conditions, maintenance of engines must be applied periodically to ensure operation efficiency. Maintenance provides freedom from breakdown during operations, which is essential to keep the equipment in a satisfactory condition for safe operations which in turn reduces maintenance costs. According to findings in The Swedish Club's report, damages to main engines contributed to 34.4% of total marine machinery claims from 2012 to 2020, resulting in a financial impact exceeding 87 million USD [1].

Forms of maintenance defer a long time that overhaul and maintenance of marine engines are critical aspects of ensuring reliable and efficient vessel operation. Technology advancements have led to an evolution in marine maintenance practices, producing strategies and regulations that are broadly relevant across all domains. The maritime industry has seen a shift in maintenance tactics from corrective (reactive) to preventive, then predictive, and most recently proactive. At the early stages of maintenance, corrective maintenance was applied as a fix of failures occurring to equipment after the issue is detected during operation. The downside of this program is that it increases costs and downtime [2].

Preventive maintenance was the required choice for scientists early on given the problems of corrective maintenance. Preventive maintenance (PM) can be defined as the process of carrying out planned maintenance tasks on a regular basis to help avoid future unplanned malfunctions. Equipment maintenance needs to be planned and scheduled in advance for a maintenance strategy to be successful. This maintenance approach also stores records of previous equipment servicing and inspections [3].

As technology develops, predictive maintenance (PdM) appears, as it employs data analysis to spot possible equipment flaws and operational irregularities, allowing for prompt repairs before failures occur. By reducing the frequency of maintenance, it seeks to reduce unplanned outages and needless preventive maintenance expenses. The current approach to maintenance is condition-based maintenance which triggers maintenance when it is necessitated by the condition of the target system and can lead to more downtime caused by late-detected failures, causing an increase in operating cost. However, this program still has some disadvantages as the performance and efficiency of the engine decrease over time which leads to losing time and money and satisfactory engine condition [4].

Maintenance in the maritime transport sector is a multifaceted undertaking that calls for a wide range of methods and strategies, according to Dragos, S., et al. [5], even though maintenance is vital, the methods currently in use don't produce the best results. This deficiency is manifested in malfunctions and downtime, which interferes with ships' operational efficiency [6]. The marine industry's current maintenance strategies are not effective in tackling the complex issues that ships encounter [7].

However, the global maritime fleet's greenhouse gas emissions have increased by 4.7% in 2021 compared to 2020 [8]. Comprehensive research and the creation of guidelines that consider the special difficulties faced by the marine industry are required to address these urgent concerns [9]. Diesel engines are widely used in power generation due to their high thermal efficiency. However, using diesel engines presents serious difficulties due to harmful emissions especially nitrogen oxides (NO_x) [10].

Up till now, current programs in marine maintenance have not achieved the desired goal, and so far, there are problems and delays in the maintenance stages, increases in time and cost, and a decrease in engine performance and efficiency. All these problems interest finding a new maintenance approach to be more sufficient and have a better solution for engine problems to reduce losses and allow ships to keep their lifetime. Proactive maintenance is the new approach that finds solutions for engine problems.

However, as technology develops, more people are realizing how machine learning (ML) and artificial intelligence (AI) algorithms can enhance maritime maintenance procedures. These technologies present the chance to improve reliability, reduce downtime, and optimize maintenance decision-making. Predictive models that anticipate and prevent potential failures before they occur can be developed by analyzing historical and real-time engine data. The maritime industry could achieve greater operational efficiency if machine learning and artificial intelligence algorithms are incorporated into current maintenance procedures [11].

The integration of various systems into a cohesive embedded operational system within the engine presents a significant challenge for the application of AI algorithms and ML in the maritime sector. The machine learning process and computer programming that allow for fault detection and learning are key components of this integration. Data analysis then makes it possible to estimate the likelihood of future failures and predict when they will occur by considering a variety of factors, including working routines, usage patterns, and other frequently disregarded aspects. The algorithm's ability to assess anomalies' severity and recommend appropriate actions is crucial for scientific and engineering applications but can be challenging due to differing personal experiences and knowledge.

Furthermore, there are some researches that employed various methods to investigate the effectiveness of different maintenance approaches and their impact on efficiency and performance thus explaining the trend towards the use of machine learning-based maintenance, its importance, and the trend towards proactive maintenance. The goal was to simplify the process to conclude judgements about the best mixture of corrective and proactive maintenance to save money. Depending on the many variables in the model, maintenance cost savings can vary. However, with 8.33% of proactive repairs given, maintenance expense was reduced by 3.71% [12]. According to this survey, there is still an expectation that data will be used to handle unforeseen problems. It provides an illustration of the Honeywell turbofan engines' oil pressure transducer (OPX) algorithm in operation as well as the proactive measures implemented to resolve this issue [13]. In order to give principles and guidelines for marine engine maintenance operations, it is necessary to define and focus on these practices because maintenance operations for marine engines frequently involve various operations across several practices. A total of 32 critical practices are prioritized for the operation of marine diesel engines [14]. It was discovered that, in order to potentially benefit from proactive maintenance, which includes keeping an eye on the health of machines and examining the likelihood that individual machine units would survive, examination of engine faults is a significant maintenance expense [15]. Low user experience awareness when it comes to distributed network applications was discovered by this survey. The Proactive Automatic Semantic Engine (PAS Engine) is the engine they conceptualized. The proposal takes proactive action after learning about the current user's experience using a service. Its goal is to prevent the deterioration of Quality of Experience (QoE) by employing supplemental information kept in a Knowledge Base (KB). The experiment's findings showed that proactive behavior could improve network resource utilization and dramatically lower packet loss rates [16].

A comprehensive thermodynamic model of a two-stroke, low-speed, 13.6 MW marine diesel engine from Winterthur Gas & Diesel was developed using the Ricardo WAVE engine simulation programmer. First, experimental data was used to validate the model. After that, a Low Pressure (LP) EGR architecture was implemented to evaluate the engine's performance in compliance with IMO Tier III regulations. The study's conclusions show that cutting-edge emission reduction techniques, like LP EGR, along with waste heat recovery systems, like ORC, can be used to develop marine diesel engines that significantly reduce pollutant emissions while exhibiting fuel consumption levels comparable to Tier II operation [17].

Most of these researchers concurred that there are a lot of issues that need to be resolved and that proactive maintenance should be used in place of reactive and predictive maintenance because the latter still costs more money, takes longer, and negatively impacts engine performance. Certain industrial machinery uses machine learning to approve production and lower maintenance costs. The financial costs associated with predictive, preventive, and corrective maintenance are thought to be extremely high and still result in losses in terms of time, money, and engine performance. However, proactive maintenance is thought to be more effective in maintaining the working condition of the engine and reducing the need for maintenance because it uses accessories to keep an eye out for any changes. As of yet, though, no application has been made to compare the reduction of maintenance costs through proactive maintenance with other kinds of maintenance programs. If implemented, a proactive maintenance strategy can save the marine industry's economic return.

3. METHODOLOGY

The methodology employed in this research aims to assess the financial implications of proactive maintenance strategies for optimizing the cost of maintenance in marine diesel engines. The systematic approach includes data collection with a specific focus on marine diesel engines, and the utilization of specific equations for calculations encompassing spare parts costs, downtime effects, and services costs. By collecting and analyzing data from real-life situations, this research aims to provide valuable insights into the cost optimization of maintenance in marine diesel engines. A flowchart illustrating the stages of the methodology is provided in Figure 1.

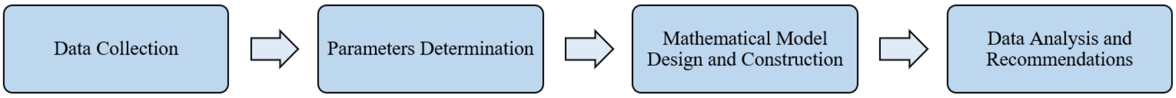

Figure 1: Research Methodology Layout

The data collection phase included the collection of historical datasets from maintenance engineers and case studies within the maritime industry to obtain comprehensive information regarding the lifetime, maintenance rate, and number of changes for specific parts of the engine. This in turn led to the determination of factors affecting maintenance cost which were found to be: downtime cost, replacement parts costs, and failure costs. To carry out a reliable cost analysis, equations were used to produce an unfailing calculation of the corrective, preventive, predictive, and proactive maintenance cost. It is recommended to gather data variations to assess the effectiveness of proactive maintenance strategies compared to other maintenance techniques. By modifying the data to simulate different scenarios, a comprehensive analysis of the benefits of proactive maintenance can be conducted.

The data collection process involved acquiring these datasets and placing emphasis on obtaining detailed information about the lifetime, maintenance rate, and number of changes for each specific part of the engine. The acquired datasets will serve as the foundation for the calculations and analysis carried out in this research [18]. Table 1 includes the maintenance data of a 500 kV diesel generator.

Table 1. Data from a 500 kV diesel generator

Component	*Lifetime (days)*	*Failure cost ($)*	*Replacement cost ($)*	*Maintenance cost ($)*
Injection pump	950	160	113.75	85
Valve Calibration	1080	425	225	40
Ring Cutting	1090	262.5	212.5	100
Cylinder top gasket	1170	325	228.75	100
Radiator	1050	120	45	20
Oil pump	1005	100	100	20
Injector nozzle	900	337.5	337.5	100
Air filter	1160	150	100	50
Alternator	250	192.5	106.25	57.5
Water pump	1050	108.75	67.5	50

Another dataset was obtained for a 600 kV diesel generator that was used in maintenance cost calculations as shown in Table 2.

Table 2. Data from a 600 kV diesel generator

Component	*Lifetime (days)*	*Failure cost ($)*	*Replacement cost ($)*	*Maintenance cost ($)*
Injection pump	1100	160	113.75	85
Valve Calibration	800	425	225	40

Ring Cutting	470	300	237.5	100
Cylinder top gasket	1020	387.5	236.25	100
Radiator	1020	120	45	20
Oil pump	800	100	100	20
Injector nozzle	900	337.5	337.5	100
Air filter	1200	200	137.5	50
Alternator	990	262.5	143.75	95
Water pump	780	108.75	87.5	50

A final dataset of an 800 kV diesel generator, shown in Table 3, was used for the calculation to ensure the validity of the results on the various models obtained.

Table 3. Data from an 800 kV diesel generator

Component	*Lifetime (days)*	*Failure cost ($)*	*Replacement cost ($)*	*Maintenance cost ($)*
Injection pump	900	160	113.75	85
Valve Calibration	1050	425	225	40
Ring Cutting	1050	262.5	212.5	100
Cylinder top gasket	980	42	36	8.4
Radiator	1010	387.5	236.25	100
Oil pump	1015	120	45	20
Injector nozzle	1020	100	100	20
Air filter	1030	337.5	212.5	100
Alternator	1010	337.5	212.5	100
Water pump	1110	150	100	50

A machine or piece of equipment's maintenance factor (α) indicates how frequently it needs to be repaired which is fixed at 0.00025 at this case, while system reliability indicators include the number of expected failures over the part's lifetime (F), its lifespan (T), and its mean time between failures (MTBF). Mean downtime (MDT) represents the average time required to restore a system or piece of equipment after a failure, and failure rate (λ) is a measure of the expected frequency of failures over a given time period. The costs of replacement parts (C_{rp}), failure (C_f), maintenance operations (C_m), and downtime (C_{dt}) are other factors, including the reliability function (R(t)) and mean time to repair (TTR).

4. Mathematical Model

The main maintenance service parameters are to be calculated using the following equations [19]. Number of failures over the total lifetime of the part (F):

$$F = T \times \alpha \tag{1}$$

Mean time between failures (MTBF):

$$MTBF = \frac{T}{F} \quad (2)$$

Failure rate (λ):

$$\lambda = \frac{1}{MTBF} = \frac{F}{T} \quad (3)$$

To determine cost of corrective maintenance (CM), significant cost factors contributing for the total cost should be considered such as cost of repairs (C_m), average cost of downtime (C_{dt}), mean downtime (MDT), failure rate (λ), and lifetime in hours (T).

$$C_{cor} = \left(C_m + \left(C_{dt} \times MDT\right)\right) \times \lambda \times T \quad (4)$$

Similarly, the cost of preventive maintenance (PM) over a given time depends on various substantial parameters such as average maintenance cost (CM) and the annual number of repairs (M).

$$C_{pm} = \left(C_m + \left(C_{dt} \times MDT\right)\right) \times M \quad (5)$$

The following exponential law can give the reliability function because it describes events that can be considered as occurring at random, such as breakdowns [20].

$$R(t) = e^{-\lambda(t)} \quad (6)$$

To consider the cost of predictive maintenance (PdM), the cost of repairs (C_m), function of reliability (R(t)), cost of replacement parts (C_{rp}), annual number of repairs (M), failure cost (C_f), mean downtime (MDT), and downtime cost (C_{dt}) are so essential which makes PdM a changeable variable.

$$C_{pdm} = \left(C_m \times R(t)\right) + \left(C_{rp} \times M\right) + \left(C_f \times \left(1 - R(t)\right)\right) + \left(MDT \times C_{dt}\right) \quad (7)$$

For proactive maintenance (PA), it was found from explicit research that proactive maintenance saves about 5 to 10 percent of the total cost of the predictive maintenance [21], So cost of proactive maintenance (C_{pa}) is obtained by multiplying Cost of Predictive Maintenance (C_{pdm}) by the cost reduction factor which ranges from 0.9 to 0.95 .

$$C_{pa} = factor \times C_{pdm} \quad (8)$$

To simplify the calculations, the following assumptions were implemented:

a) constant maintenance factor (α) of 0.00025.
b) 2 times of parts replacement per year (M).
c) an initial reliability factor of 0.995.
d) cost per downtime of 100$ per hour.

5. RESULTS AND DISCUSSION

This section shows the cost of corrective, preventive and predictive maintenance strategies if applied to diesel generators. The cost was calculated using the previous equations to estimate the cost of each strategy if implemented for exactly one year on each component. All components have a lifetime of more than one year except the alternator in the 500 kV diesel generator, which has a lifetime of 250 days. However, it was calculated with the same equation assuming it would last for one year to be able to compare it to other components.

As shown in Table 4, for the 500 kV diesel generator when switching from corrective maintenance strategy to preventive maintenance strategy, it is noticed that the cost decreases by (8% - 9%). However, when predictive maintenance strategy is implemented, a significant drop in maintenance cost with an average of 46% decrease is noticed when compared with corrective maintenance. Comparison with preventive maintenance shows a decrease of an average of 46%. It was also observed that the cost of predictive maintenance is higher than that of preventive maintenance for the alternator.

Table 4. Cost of different maintenance strategies for 500 kV diesel generator

Component	*Corrective maintenance cost ($)*	*Preventive maintenance cost ($)*	*Predictive maintenance cost ($)*
Injection pump	1988	1815	902
Valve Calibration	3013	2752	1955
Ring Cutting	3352	3061	1731
Cylinder top gasket	4414	4031	2090
Radiator	1355	1237	528
Oil pump	1930	1762	850
Injector nozzle	3443	3144	2201
Air filter	2088	1907	935
Alternator	696	635	637
Water pump	1496	1366	712

Table 5 shows that switching from corrective maintenance to preventive maintenance in 600 kV diesel generator yields a cost decrease of (8% - 9%). When predictive maintenance strategy is implemented, the maintenance cost decreases by an average of 46% when compared to corrective maintenance, while a decrease of 41% is achieved when compared to preventive maintenance. The 600 kV generator has a higher ROI than the 500 kV diesel generator.

Table 5. Cost of different maintenance strategies for 600 kV diesel generator

Component	*Corrective maintenance cost ($)*	*Preventive maintenance cost ($)*	*Predictive maintenance cost ($)*
Injection pump	2302	2102	995
Valve Calibration	2232	2038	1609
Ring Cutting	1516	1384	1111
Cylinder top gasket	3894	3556	2007
Radiator	1316	1202	521
Oil pump	1536	1403	738
Injector nozzle	3443	3144	2201

Air filter	2430	2219	1253
Alternator	3200	2923	1341
Water pump	1112	1015	582

As demonstrated in Table 6, the 800kV diesel generator experiences an (8% - 9%) decrease in maintenance cost when switching from corrective maintenance to preventive maintenance. When adopting predictive maintenance, a cost saving of 51% is achieved compared to corrective maintenance which is the highest among the three diesel generator models. When comparing predictive maintenance cost to preventive maintenance cost, it is found that an average cost decrease of 46% is achieved.

Table 6. Cost of different maintenance strategies for 800 kV diesel generator

Component	*Corrective maintenance cost ($)*	*Preventive maintenance cost ($)*	*Predictive maintenance cost ($)*
Injection pump	1883	1720	871
Valve Calibration	2930	2675	1918
Ring Cutting	3229	2949	1684
Cylinder top gasket	2025	1849	535
Radiator	2947	2691	1844
Oil pump	1614	1474	570
Injector nozzle	1958	1788	859
Air filter	2858	2610	1686
Alternator	3712	3390	1812
Water pump	1665	1521	858

According to a report from Deloitte, the implementation of proactive maintenance can reduce overall maintenance costs by (5% - 10%). The percentage of reduction in cost depends on many factors including how efficient the proactive maintenance strategy is applied, skill of workers inside the factory, maintenance management system, etc.

The cost of proactive maintenance is estimated for the 500 kV diesel generators at each level of efficiency the plant can achieve as illustrated in Table 7.

Table 7. Cost of maintenance for 500 kV diesel generator within (5% - 10%) efficiencies

Component	*Efficiency percentage*					
	5% ($)	*6% ($)*	*7% ($)*	*8% ($)*	*9% ($)*	*10% ($)*
Injection pump	857	848	839	830	821	812
Valve Calibration	1857	1837	1818	1798	1779	1759
Ring Cutting	1644	1627	1610	1592	1575	1558
Cylinder top gasket	1986	1965	1944	1923	1902	1881
Radiator	502	497	491	486	481	476
Oil pump	808	799	791	782	774	765

Injector nozzle	2091	2069	2047	2025	2003	1981
Air filter	888	879	870	860	851	842
Alternator	606	599	593	586	580	574
Water pump	676	669	662	655	648	641

Table 8 shows the proactive maintenance costs for each efficiency value for the 600 kV diesel generator.

Table 8. Cost of maintenance for 600 kV diesel generator within (5% - 10%) efficiencies

Component	*Efficiency percentage*					
	5% ($)	*6% ($)*	*7% ($)*	*8% ($)*	*9% ($)*	*10% ($)*
Injection pump	945	936	926	916	906	896
Valve Calibration	1529	1513	1497	1481	1465	1449
Ring Cutting	1055	1044	1033	1022	1011	1000
Cylinder top gasket	1906	1886	1866	1846	1826	1806
Radiator	495	490	485	479	474	469
Oil pump	701	694	686	679	672	664
Injector nozzle	2091	2069	2047	2025	2003	1981
Air filter	1191	1178	1166	1153	1141	1128
Alternator	1274	1261	1248	1234	1221	1207
Water pump	553	547	542	536	530	524

Table 9 shows the proactive maintenance costs for the 800 kV diesel generator at each given efficiency.

Table 9. Cost of maintenance for 800 kV diesel generator within (5% - 10%) efficiencies

Component	*Efficiency percentage*					
	5% ($)	*6% ($)*	*7% ($)*	*8% ($)*	*9% ($)*	*10% ($)*
Injection pump	827	818	810	801	792	784
Valve Calibration	1822	1803	1783	1764	1745	1726
Ring Cutting	1600	1583	1566	1550	1533	1516
Cylinder top gasket	508	503	498	492	487	482
Radiator	1751	1733	1715	1696	1678	1659
Oil pump	541	536	530	524	519	513
Injector nozzle	816	807	798	790	781	773
Air filter	1601	1585	1568	1551	1534	1517
Alternator	1722	1704	1686	1667	1649	1631
Water pump	815	806	798	789	781	772

Figure 2 shows the cost for all maintenance strategies in comparison with each other for the 500 kV diesel generator. Maintenance costs decrease for each equipment as illustrated. For corrective maintenance, the highest equipment maintenance cost was $4413 while with proactive maintenance, the highest equipment maintenance cost is $1980. The total cost for corrective maintenance for 500 kV diesel generator for all equipment is $23773 while the total cost for preventive maintenance for all equipment is $21710, and the total cost for predictive maintenance for all equipment is $12541. On the other hand, the total cost for proactive maintenance at an efficiency of 10% for all equipment is $11287.

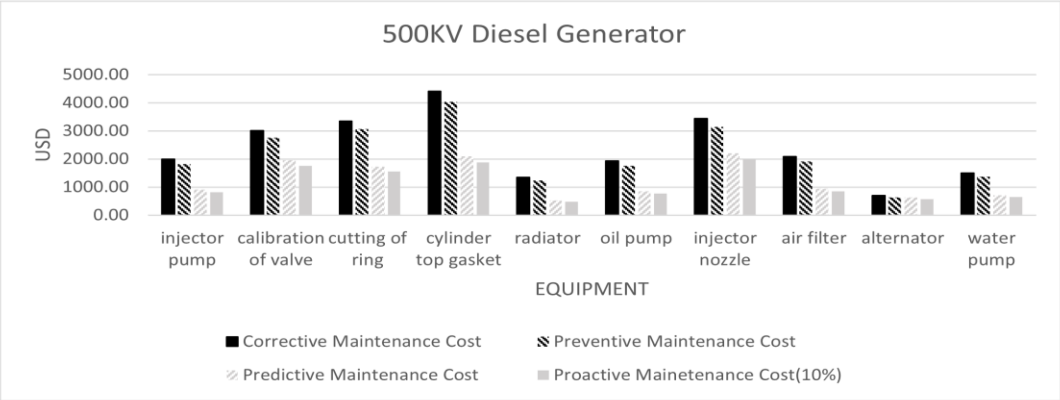

Figure 2: Cost of Different Maintenance Strategies for 500 kV Diesel Generator

Figure 3 shows a decrease in maintenance costs for the 600 kV diesel generator. For corrective maintenance, the highest equipment maintenance cost was $3894 while with proactive maintenance, the highest equipment maintenance cost is $1981. The total cost for corrective maintenance for 600 kV diesel generator for all equipment is $22979 while the total cost for preventive maintenance for all equipment is $20985 and the total cost for predictive maintenance for all equipment is $12359. On the other hand, the total cost for proactive maintenance (10% efficiency) for all equipment is $11123.

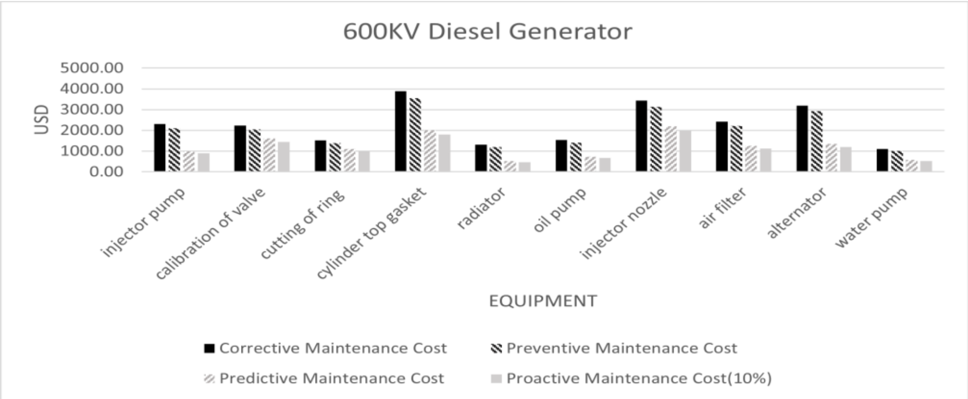

Figure 3: Cost of Different Maintenance Strategies for 600 kV Diesel Generator

As shown for the 800 kV diesel generator in Figure 4, maintenance costs decrease. For corrective maintenance the highest equipment maintenance cost was $3711, while with proactive maintenance, the highest equipment maintenance cost is $1725. The total cost for corrective maintenance for 800 kV diesel generator for all equipment is $24820, while the total cost for preventive maintenance for all equipment is $22667, and the total cost for predictive maintenance for all equipment is $12635. On the other hand, the total cost for proactive maintenance (10% efficiency) for all equipment is $11371.

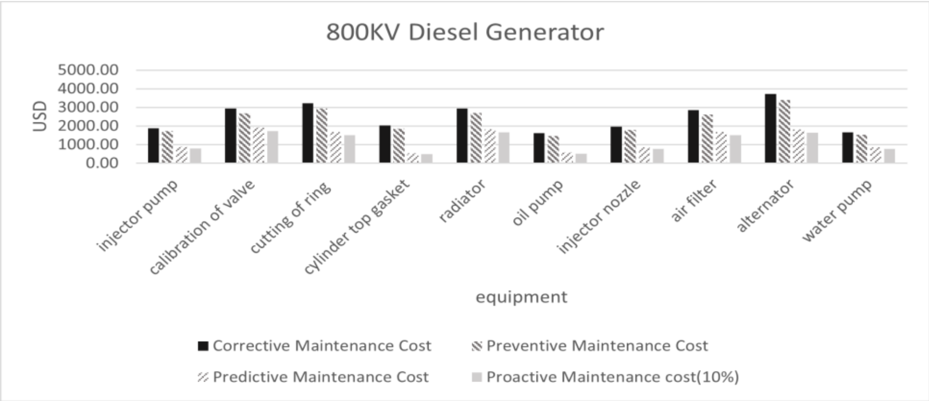

Figure 4: Cost of Different Maintenance Strategies for 800 kV Diesel Generator

6. CONCLUSION

The main objective of this research is to present a mathematical model to determine the cost benefits of implementing proactive maintenance. The research was conducted by applying the mathematical model on 500 kV, 600 kV and 800 kV diesel generators. Calculating the maintenance cost for each type of maintenance strategy on each equipment. By comparing the obtained results, it was found that:

- predictive maintenance saved approximately 9% when compared to corrective maintenance.
- while implementing predictive maintenance reduced maintenance costs by an average of:
    a) 47% for 500 kV diesel generator.
    b) 46% for 600 kV diesel generator.
    c) 49% for 800 kV diesel generator
- implementing proactive maintenance with a maximum efficiency of 10% will save:
    a) $1254 for 500 kV diesel generator.
    b) $1236 for 600 kV diesel generator.
    c) $1264 for 800 kV diesel generator.

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