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Optimization of Maintenance Schedule for Rotating Equipment Using the Total Expected Cost and Cost-Variance Criteria

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Abstract
Inspection and maintenance of rotating equipment have gained credit in petrochemicals, refineries and oil and gas industries over the past decades due to the hazard failures resulting from overpressures and fluctuated temperatures surrounding the industrial zone. Therefore, any equipment operating under the harsh operational conditions should take the cost and time of inspection and maintenance into account. Maintenance of rotating equipment is an expensive event in terms of the cost and time, which are the driving forces to improve the maintenance performance. The paper aimed at optimizing the maintenance schedule for the grouped pumps in the refinery plant using the expected cost criterion and expected cost-variance criterion. This is characterized by the application of techniques to prolong equipment life, minimize downtimes, and enhance all aspects of reliability, availability and maintainability. The results showed that the cost and time of maintenance could optimize based on the rotating equipment, which could implement according to the preventive and corrective maintenance policy. The results analysis has revealed that applying optimization of maintenance schedule could help practitioners in decision-making to estimate the optimal cost and time, and reduce planning efforts in the future.
Keywords: Pumps equipment, Maintenance policy, Cost and time of maintenance.

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تحسين جدول صيانة المعدات الدوارة باستخدام معيار التكلفة المتوقعة الكلية ومعيار تباين التكلفة

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الملخص

لقد اكتسب فحص وصيانة المعدات الدوارة أهمية كبيرة على مدى العقود الماضية في الصناعات البتروكيميائية والمصافي وصناعة النفط والغاز بسبب الأعطال الخطيرة الناتجة عن الضغوط الزائدة والتقلبات في درجات الحرارة المحيطة بالمنطقة الصناعية. لذلك، يجب أن يؤخذ في الاعتبار تكلفة ووقت الفحص والصيانة لأي معدات تعمل تحت ظروف تشغيل قاسية. تعد صيانة المعدات الدوارة حدثًا مكلفًا من حيث التكلفة والوقت، وهما القوى الدافعة لتحسين أداء الصيانة. هدفت هذه الورقة إلى تحسين جدول صيانة المضخات المجمعة في مصنع التكرير باستخدام معيار التكلفة المتوقعة ومعيار تباين التكلفة المتوقع. يتميز هذا بتطبيق تقنيات لإطالة عمر المعدات، وتقليل فترات التوقف، وتعزيز جميع جوانب الموثوقية والتوافر وقابلية الصيانة. أظهرت النتائج أن تكلفة ووقت الصيانة يمكن تحسينها بناءً على المعدات الدوارة، والتي يمكن تنفيذها وفقًا لسياسة الصيانة الوقائية والتصحيحية. كشف تحليل النتائج أن تطبيق تحسين جدول الصيانة يمكن أن يساعد الممارسين في اتخاذ القرار لتقدير التكلفة والوقت الأمثل، وتقليل جهود التخطيط في المستقبل.

الكلمات المفتاحية: معدات المضخات، سياسة الصيانة، تكلفة ووقت الصيانة.

Introduction

Pump is a critical part at any processing plant. Pumps are rotating equipment designed to accelerate the transference of fluid from one location to another at any processing plant. Without pumps, gas, petrochemical and refinery plants cannot operate. Therefore, many different pumps are classified according to their operational functions. These pumps need inspection and maintenance activities to prolong their lifetime.

Pumps represent a greater part of any processing plant where any failure of a pump can result in serious consequences [1]. Despite the design life of a pump, these pumps have to undergo inspection and maintenance activities once every period to avoid any unexpected mechanical failures that may occur. Mechanical failures can occur due to a number of different parts of the pump, including [2]:

- Seals failure,
- Bearing failure,
- Lubrication Failure,
- Excessive vibrations,
- Blockages in the pump,
- Corrosion and
- Fatigue.

Maintenance activities of rotating equipment sometimes generate high uncontrollable costs. The controllable costs in these costs should be so crucial for any processing company due to equipment reliability fluctuation. Therefore, the main challenge is to find a balance between a decrease in the cost of maintenance and an increase in the interval of maintenance. A review of inspection and maintenance records for pumps is needed to reach the aim of the study and to be able to master and optimize the maintenance schedule.

There are many refinery plants in Libya. These plants include the Ras Lanuf, Gulf of Sirte, Azzawiya, Tobruk and Brega refineries. This study focuses on the used pumps in Brega refinery plant. These pumps are a good example, which can be considered the worst rotating equipment due to the oldest refinery plant and the geographical location in Libya.

Many questions are often posed to the maintenance department in order to optimize maintenance performance. The paper aims to answer the following questions:

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(i) What approach is used to reduce the maintenance cost?
(ii) What is the optimal interval of maintenance?

2. Maintenance Policy

The maintenance schedules of most processing plants have been implemented in a random manner [3]. In practice, an unbalance has been found between the cost and time of maintenance for most rotating equipment. This means there is a need to review inspection and maintenance records of rotating equipment in order to optimize the cost and time of maintenance. Both Preventive Maintenance (PM) and Corrective Maintenance (CM) can provide a relatively high level of reliability for the refinery plant.

2.1 Corrective Maintenance (CM)

CM is a set of remedial actions taken after a failure occurs to return equipment to its normal condition because of unexpected failures that occur during the normal operation process of a plant. CM is one of planned maintenance activities according to the time required for shutdown due to deferred activities (running-to-failure). CM is also considered unplanned maintenance from an immediate maintenance perspective. Furthermore, it can be easily performed. According to CIBSE Guide [4], this type of maintenance is called reactive maintenance because the system is operated until it fails. According to the British Standards Institution [5], this is "maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function". Kumar and Maiti [6] agree that CM can be effective for some complex processes, but there are some cases of deterioration that require an entire shutdown to carry out the planned maintenance program that depends on many factors, such as operational and environmental conditions. Hence, these types of maintenance are not able to overcome all failures, which justifies the widespread adoption of PM in the real application of maintenance.

2.2 Preventive Maintenance (PM)

PM usually accounts for a major part of the maintenance function because of its relative cost, which gives it acceptance between

production sectors and industrial organizations. PM is a premature activity that replaces components or equipment before the defects occur to avoid unscheduled failures. Any component or equipment can be replaced or repaired based on the predetermined period to apply PM. In the predetermined period, the component should be replaced even if the item is still active. This period can be identified according to a scheduled time for each item. PM includes a set of activities that contribute in reducing the number of failures and avoiding the occurrence of CM. This enhances system performance and meets minimum costs [7]. According to the British Standards Institution [5], PM can be defined as "maintenance carried out at predetermined intervals or according to failure replacement and intended to reduce the probability of failure or the degradation of the functioning of an item". Therefore, the key goals of the execution of PM are to improve the reliability of a system in the long term [8] by minimizing frequent equipment failure, reducing total inspection and maintenance costs, and decreasing downtime of equipment to avoid production losses and prolong equipment life [9].
Despite sophisticated maintenance styles being implemented in the oil and gas sector, PM cannot be avoided altogether.

3. Maintenance Costs

Many processing companies have suffered from the increase in maintenance costs that have thwarted companies' forecasts.This has indicated a shift towards postponing maintenance activities, which has led to the cancellation or delay of some predominant maintenance activities. Consequently, this poses several threats to the reliability and maintainability of the system.
Maintenance cost is a direct measure of maintenance performance. The immensity of the costs associated with the maintenance of refinery plants is one of the challenges faced by most processing companies. Arunraj and Maiti [10] report that critical equipment for any processing plant requires high maintenance costs, which may reach up to 50% of total production costs. As Sahoo [11] states, the costs of maintenance for the refinery plant exceed 30%

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of the allocated budget, in addition to the production losses during the shutdown period of the plant. Thus, these plants incur losses in the profit margin due to maintenance activity.

The fluctuation of Preventive Maintenance Cost (PMC) of the refinery plant from cycle to cycle is due to the extra activities. Most processing companies allocate a PM budget randomly predetermined based on the decision of top management of the company, not according to pre-planned. The Corrective Maintenance Cost (CMC) is considered one of the main elements that should be taken into account when estimating the total cost of maintenance in order to estimate the success of the maintenance program. The CMC may not be accurately estimated due mainly to the unexpected or contingency works that can occur during the normal operation conditions. Thus, CMC can be calculated including PMC during the planning phase.

Every maintenance action performed on an item incurs some cost, in the form of craftsmen or spare parts. Previous studies show how optimization in maintenance activities can lead to cutting maintenance costs based on failures of rotating equipment. Figure 1 shows a trade-off between PMC and CMC. In the beginning, PMC approaches zero, then increases, but CMC decreases. Sundberg [12] explains that reducing the costs in CM can increase the costs in PM due to raising the direct costs, which leads to reducing the indirect costs. Therefore, maintenance management needs to find the optimal point related to the cost and time of maintenance.

4. Maintenance Cost Models

This study presents a set of equations representing the model to determine the CM and PM costs, which can be applied to a set of pumps grouped in Brega refinery plant. These costs can be categorized under CMC and PMC [13].

$$CMC = RCN \times CC \times MTTR + \sum SC + PL \quad (1)$$

Where; CMC is the cost of corrective maintenance, RCN is the number of repairing craftsmen, CC is the cost of a craftsman per

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hour = $30, MTTR is the mean time to repair (hrs), and SC is the cost of spare parts.

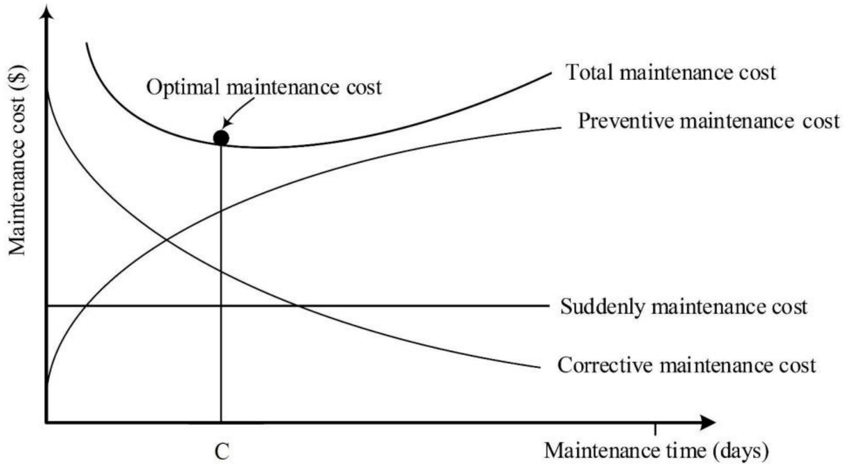

Figure 1.Preventive and corrective maintenance costs

$$PMC = IT \times IN \times IC + RC \tag{2}$$
$$RC = NPC \times RT \times CC + SC \tag{3}$$

Where PMC is preventive maintenance cost, RC is replacement cost, IT is inspection time (hr), IN is number of inspectors, IC is inspector cost, NPC is number of replacing craftsmen and RT is replacing time.

The total cost between two maintenance types can be evaluated as the sum of the costs related to preventive and corrective maintenance. The Total Expected Cost Criterion (TEC) and the Total Expected Cost- Variance Criterion (TECV) represent the model to optimize the cost and time of maintenance, which could be applied to a set of equipment pieces grouped in a particular way at Brega refinery plant. This model can deal with the critical and complex equipment pieces that run under harsh conditions. Also, these equations represent the model to estimate the service life of components in the short term based on the analysis of the data sheets of each equipment with consideration of the replacement

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policy that is used in the plant and without considering the repair policy if possible [14].

The proposed equations have two important features to apply this model: the collection of statistical data of maintenance and then the probabilistic analysis of equipment pieces. Equations 4 and 5 can be expressed as follows [15]:

$$\mathrm{TEC(T)} = \mathrm{N}\,[\mathrm{CMC}\,(1 - \mathrm{R(t)}) + \mathrm{PMC}\,\mathrm{R(t)}] / \int_0^t \mathrm{R(x)dx}$$

$$\mathrm{TEC(T)} = \mathrm{N}\left[\frac{[\mathrm{CMC}\sum \mathrm{PoB} + \mathrm{PMC}]}{\mathrm{T}}\right] \qquad (4)$$

$$\mathrm{TECV(T)} = \mathrm{N}\,[(\frac{\mathrm{CMC}}{\mathrm{T}} + \left(\frac{\mathrm{CMC}}{\mathrm{T}}\right)^2 \mathrm{K})\sum_1^{t-1}(1 - \mathrm{R(t)}) - (\mathrm{K}\left(\frac{\mathrm{CMC}}{\mathrm{T}}\right)^2 \sum_1^{t-1}(1 - R(t))^2 + \frac{\mathrm{PMC}}{\mathrm{T}})]$$

$$\mathrm{TECV(T)} = \mathrm{N}\,[(\frac{\mathrm{CMC}}{\mathrm{T}} + \left(\frac{\mathrm{CMC}}{\mathrm{T}}\right)^2 \mathrm{K})\sum_1^{t-1}\mathrm{PoB} - (\mathrm{K}\left(\frac{\mathrm{CMC}}{\mathrm{T}}\right)^2 \sum_1^{t-1}\mathrm{PoB}^2 + \frac{\mathrm{PMC}}{\mathrm{T}})] \qquad (5)$$

N is the number of equipment, K is the degree of importance, PoB is the probability of breakdown, R(t) is the reliability function and T is the expected life of equipment(months).

5. Results and Discussion

Maintenance of pumps in any processing plant can cause huge financial costs and pose environmental risks, making the reliability of the system extremely important. This is a part of the many indicators that should be taken into account when scheduling maintenance for pumps used in any processing plant that operate continuously under harsh operating conditions. Table 1 shows a set of pumps used in Brega refinery plant.

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Table 1. Some of pumps grouped in Brega refinery plant

Rotating M/Cs	M/Cs No	M/C Code
Gas recycle pumps (GRP)	3	J110, J111A, J111B
Intermediate pumps (IP)	6	IP-5,26,27,28,29,30
Gas condensate pumps (GCP)	2	GCP-112AB
Main oil line pumps (MP)	10	MP-25, 26, …... 34
Water supply pumps (WSP)	3	WSP- 11ABC
Water disposal pumps (WDP)	2	WDP- 11AB
Domestic water pumps (DWP)	2	DWP-33AB
Chemical injection pumps (CIP)	8	CIP-20, 21, … 27
New water disposal pumps (NWDP)	6	NWDP-16ABC, 17ABC

This study focuses on the repairing and replacing policy of GRP in order to optimize CM and PM schedules associated with the cost and time of maintenance as shown in Tables 2 and 3, respectively.

Table 2. Repairing policy of GRP information on Dec 2001

Equip Code	Breakdown Date	MTTR (hrs)	MTTF (mths)	RCN	CC ($/hr)	RPC ($)	CMC ($)	CMC per mth
J110	Jul-03	8	19	2	20	100	420	22
J111A	Feb-03 Oct-02 Feb-02	160 96 40	14	2 2 2	20	392 636 2660	6792 4476 4260	1109
J111B	Jul-03 Oct-02	18 35	19	2 3	20	222 1000	942 3100	213

Table 3. Replacing policy of GRP information

Equip Code	Inspection date	IN	IT (min)	IC ($/hr)	MTTF per mth	RC ($)	PMC ($)	PMC per mth
J110	Sep-02 Mar-02 Oct-01	1 1 1	271 161 271	20	11	1426 792 636	1516 846 726	281
J111A	Jul-02 Dec-01	1 1	161 161	20	7	774 1238	828 1292	303
J111B	Sep-02 Mar-02 Oct-01	1 1 1	271 161 271	20	11	394 2062 1090	484 2116 1180	344

Table 4 shows the average CMC and PMC of GRP based on the Mean Time to Failure for repairing policy ($MTTF_{RP}$) and Mean Time to Failure for replacing policy ($MTTF_R$), respectively.

Table 4. Average of CMC and PMC per month for GRP

Eq. Code	CMC ($)	$MTTF_{RP}$ (mth)	CMC per mth	PMC ($)	$MTTF_R$ (mth)	PMC per mth
J110	420	19	22	3088	11	281
J111A	15528	14	1109	2120	7	303
J111B	4042	19	213	3780	11	344
GRP	Average CMC		448	Average PMC		309

The average of CMC and PMC for 12 months can be determined as follows:

- The average of CMC for 12 months = 12 x 448 = $5376
- The average of PMC for 12 months = 12 x 309 = $3708

5.1 Degree of importance (K)

The degree of importance is the significance level that is used to calculate the expected cost variance criterion. It can be expressed as:

$$K = \frac{\text{Number of running equipment pieces}}{\text{Total equipment pieces}} \quad (6)$$

Table 5. Degree of importance for working pumps

Rotating M/Cs	working equip	standby equip	M/Cs No	K
GRP	1	2	3	0.33
IP	3	3	6	0.5
GCP	1	1	2	0.5
MP	2	8	10	0.2
WSP	1	2	3	0.33
WDP	1	1	2	0.5
DWP	1	1	2	0.5
CIP	3	5	8	0.38
NWDP	3	3	6	0.5

5.2 Probability of Breakdown (PoB)

GRP equipment consists of three pieces: J110, J111A and J111B. The breakdown date of J110 occurs between December 2001 and July 2003. This means that the MTTF of J110 is 19 months. The breakdown date of J111A occurs in four periods: Dec 2001, Feb 2002, Oct 2002 and Feb 2003. This means that the MTTFs of J111A are 2, 8 and 4 months, respectively. The breakdown date of J111B occurs in three periods: December 2001, October 2002 and July 2003. This means that the MTTFs of J111B are 10 and 9 months, respectively. Table 5 shows PoB for GRPs for 12 months.

- $P(t)_{J110}$: $P(1) = \frac{1}{19} = 0.0526$, $P(2) = \frac{2}{19} = 0.1052$, ………….. $P(12) = \frac{12}{19} = 0.6315$
- $P(t)_{J111A}$: Three breakdowns of J111A.

This means that each breakdown has a probability ($\frac{1}{3} = 0.333$). However, there are three scenarios of breakdown for J111A. They can be explained as shown in Figure 2.

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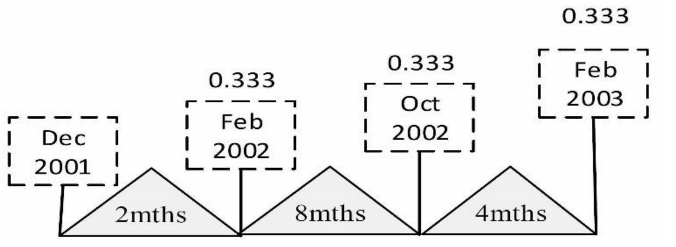

Figure 2. Breakdowns Scenarios for GRP equipment

Scenario Ioccurs from Dec-2001 to Feb-2002 (2mths),
$P(1\text{-}2)_{J111A} = \frac{0.333}{2} = 0.166$
Scenario II occurs from Feb-2002 to Oct-2002 (8mths),
$P\ (3\text{-}10)_{J111A} = \frac{0.333}{8} = 0.0416$
Scenario III occurs from Oct-2002 to Feb-2003 (4mths),
$P(11\text{-}12)_{J111A} = \frac{0.333}{4} = 0.0832$

- $P(t)_{J111B}$: Two breakdowns of J111B. This means that each breakdown has a probability ($\frac{1}{2}$ = 0.5). However, there are two scenarios of breakdown for J111B.

ScenarioIoccurs from Dec-2001 to Oct-2002 (10mths),
$P(1\text{-}10)_{J111A} = \frac{0.50}{10} = 0.05$
Scenario II occurs from Oct-2002 to July-2003 (9mths),
$P(11\text{-}12)_{J111A} = \frac{0.5}{9} = 0.055$

Table 6 shows the probability of breakdown for J110, J111A and J111B.

Table 6. PoB of GRP for 12 months

T (mth)	P(t) J110	P(t) J111A	P(t) J111B	PoB
1	0.0526	0.1665	0.05	0.0897
2	0.1052	0.3333	0.1	0.1794
3	0.1579	0.3746	0.15	0.2275
4	0.2105	0.4162	0.2	0.2755

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5	0.2631	0.4578	0.25	0.3236
6	0.3157	0.4994	0.3	0.3717
7	0.3684	0.5410	0.35	0.4198
8	0.4210	0.5826	0.4	0.4678
9	0.4736	0.6242	0.45	0.5159
10	0.5263	0.6658	0.5	0.5640
11	0.5789	0.7490	0.555	0.6276
12	0.6315	0.8322	0.61	0.6912

5.3 The Total Expected Cost Criterion of GRP

Based on the number of GRP equipment (3), degree of importance (0.33), the average of CMC for 12 months (12 x 448 = $5376) and the average of PMC for 12 months (12 x 309 = $3708). TEC aims to specify a maintenance interval at optimal cost for 12 months. Table 7 shows that TEC gradually decreases with increasing in time up to the fifth month at $4715, and then starts in an increase with increasing in time as illustrated in Fig. 1 at point (C). The $4715 represents the optimal value of TEC at the fifth month. This indicates that the optimal time of maintenance once every five months. This also means that the decision-making for GRP maintenance must be done once every five months with the cost of $4715 to avoid any threats associated with unexpected failures that may occur in other items or an increase in maintenance costs.

Table 7. TEC of GRP for 12 months

T (mth)	PoB	PoB^2	∑PoB	$\sum PoB^2$	TEC(T)
1	0.0897	0.0080	0	0	11124
2	0.1794	0.0321	0.0897	0.0080	6285
3	0.2275	0.0517	0.2691	0.040	5155
4	0.2755	0.0759	0.4966	0.0919	4783
5	0.3236	0.1047	0.7721	0.1678	4715
6	0.3717	0.1381	1.0957	0.2726	4799
7	0.4198	0.1762	1.4674	0.4107	4970

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8	0.4678	0.2188	1.8872	0.5869	5195
9	0.5159	0.2661	2.355	0.8058	5456
10	0.564	0.3181	2.8709	1.0719	5743
11	0.6276	0.3938	3.4349	1.3901	6047
12	0.6912	0.4777	4.0625	1.7839	6387

5.4 Total Expected Cost- Variance Criterion (TECV)

Table 8 shows the TECV of GRP for 12 months. The aim of TECV is to select the appropriate month to perform maintenance activities of GRP at the lowest cost. It was found that TECV continuously increased with time. This indicates that the first month of the year, with a cost of $11124, is the optimal time to carry out maintenance events.

Table 8. TECV of GRP for 12 months

T(mth)	CMC/T	$(CMC/T)^2$	PMC/T	$(PMC/T)^2$	TECV(T)
1	5376	28901376	3708	13749264	11124
2	2688	7225344	1854	3437316	579239
3	1792	3211264	1236	1527696	725350
4	1344	1806336	927	859329	722780
5	1075	1156055	742	549970	691784
6	896	802816	618	381924	655278
7	768	589824	530	280597	618788
8	672	451584	463	214832	583693
9	597	356807	412	169744	550210
10	538	289014	371	137493	518229
11	489	238854	337	113630	487554
12	448	200704	309	95481	457271

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6. Analysis of the Results

Based on the results in Table 9, it can be observed that the minimum value of TECV is always greater than the minimum value of TEC. However, the optimal time interval of TECV is always less than the optimal time interval of TEC. Therefore, TEC is more acceptable than TECV in order to schedule maintenance of pumps.

Maintenance activities of pumps in the refinery plant can be scheduled from three to seven months, and planned between the first and third month based on TEC and TECV, respectively, as shown in Table 9.

Table 9.TEC and TECV of pumps used in Brega refinery plant

Rotating M/Cs	Total Expected cost-criterion		Total Expected cost-variance criterion	
	Cost ($)	Optimal interval (mth)	Cost ($)	Optimal time (mth)
(GRP)	4715	5	11124	1
(IP)	6728	4	14976	1
(GCP)	1887	3	5616	3
(MP)	6321	4	35280	1
(WSP)	3130	5	8496	1
(WDP)	2582	4	5856	2
(DWP)	1915	3	3456	2
(CIP)	2107	7	8064	1
(NWDP)	2357	4	4464	1

7. Conclusions

The discussion above shows that maintenance schedules can be streamlined by focusing on a part of critical equipment using some important indicators. This study focused on the pumps as rotating equipment using techniques associated with the expected cost and expected cost-variance to determine the optimal maintenance time, as shown in Table 10.

The maintenance records of critical equipment should be developed to help maintenance management in scheduling maintenance and controlling maintenance costs. The pumps should be made integral to the critical equipment. The study would be useful for maintenance management in any plant similar to a refinery plant due to the complexity of the process and critical equipment. In addition, the planning phase is considered the longest period of maintenance stages. Therefore, the study would also greatly contribute to reducing planning efforts in the future.

Table 10. Maintenance scheduling of grouped pumps in refinery plant

Equipment description	No	Durat (days)	M/P	TEC ($)	Maintenance Interval (Months)											
					1	2	3	4	5	6	7	8	9	10	11	12
Gas recycle pumps (GRP)	3	3	2	4715	5					5					5	
Intermediate pumps (IP)	6	4	3	6728	4				4				4			
Gas condensate pumps (GCP)	2	2	2	1887			3			3			3			3
Main oil line pumps (MP)	10	6	4	6321	4				4				4			
Water supply pumps (WSP)	3	2	2	3130	5					5					5	
Water disposal pumps (WDP)	2	1	2	2582		4				4				4		
Domestic water pumps (DWP)	2	1	2	1915		3			3			3			3	
Chemical injection pumps (CIP)	8	5	4	2107	7							7				
New water disposal pumps (NWDP)	6	3	3	2357	4				4				4			

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