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REPLACEMENT ANALYSIS USING PROBABILISTIC LIFE CYCLE COSTING

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ABSTRACT

Life-cycle cost (LCC) is the most frequently used economic model for decision making that considers all costs in the life of a system or equipment. The LCC of repairable equipment highly depends on the reliability and availability of the equipment. Optimum equipment reliability reduces failure which in turn reduces disruption of product that have a direct link to maintenance and production cost. This paper presents a mathematical model to estimate the life cycle cost (LCC) of repairable equipment. Operation and Maintenance cost are calculated using activity based costing. Pump system containing two pumps in a parallel configuration is taken as a case and their LCC is analysed using the developed model. The developed model is used to assess alternative replacement option of the existing pump system. The alternative options are either to continue with the existing system or to replace one of the pumps that have highest downtime or to replace both pumps.

Keywords: life cycle cost, reliability, and repairable equipment.

INTRODUCTION

Life cycle costing (LCC) is one of the tools which is used progressively for supporting decision making. Some of the main reasons for the increased trend of LCC applications are; increasing maintenance cost, increasing cost effectiveness awareness among product users, budget limitations, and costly products and greater ownership costs in comparison to procurement costs [1]. Studies show that the engineering system ownership cost can vary from 10 to 100 times the original acquisition cost [2]. The LCC of repairable equipment depends on its reliability and availability [3]. The reliability and the availability are one of the performance measurements of repairable equipment. Repairable equipment is equipment which, upon failure, is restored to operation by any repair action other than replacing the entire equipment [3]. When a product or system is on its operation phase it will fail and repair to restore to its operating condition, the number of failure, why it fails, when it fails and the time to repair it depends on its reliability and maintainability [4]. Since failure of a system can be occurred unexpectedly when equipment's run under rigorous conditions, which leads to aging, erosion, wear etc. These failures have a directly impact on LCC; the less the number of failure the less the cost of maintenance. Therefore, performance and cost are basis for making optimal decisions in LCC since they depend are dependent on one another [5].

A number of LCC methodologies have been proposed by different researchers. Fabrycky and Blanch's [7] LCC model is a sophisticated one which tries to address detailed cost analysis. It decomposes LCC into four categories: Research and development, production and construction, operation and maintenance, and retirement and disposal costs. Woodward LCC model focuses only with the optimization in ownership cost [8]. A method of modeling uncertainty in cost estimating based on a simple extension of the central limit theorem is proposed in 1997. Aseidu [9] stated that incorporating uncertainty in the objective function helps to obtain a design that has a lower probability of having a high cost. Maintenance cost which is one of the ownership costs of LCC has been addressed through some studies. These studies develop procedures for, which is used to evaluate maintenance of various systems. The maintainability of a system was assessed trough cost of assembly/disassembly by Vujosevic *et al* [10]. Gershenson and Ishii addressed serviceability in design. They divided the drivers of service cost into part cost, labor cost, and failure rate [11]. A research conducted in Finland by Eric and Timo [12] found that 83% of manufacturing industries under study used deterministic nature of LCC analysis, only 17% uses probabilistic model. The deterministic model can't integrate the reliability and availability. Reliability and availability are essentially analytical in nature and characterized a probabilistic process [5]. Thus, in this study, a probabilistic LCC model is developed for repairable item by integrating reliability and maintainability analysis. Pump system containing two pumps in a parallel configuration is taken as a case and their LCC is analysed using the developed model. The developed model is used to assess alternative replacement option of the existing pump system. The alternative options are either to continue with the existing system or to replace one of the pumps that have highest downtime or to replace both pumps. The data required for the analysis is collected for a gas processing plant found in Malaysia and also extracted from [14] [15]

METHODOLOGY

The developed model is presented in Figure 1 and discussed in detail below in the next sub sections.

A. Create an activity hierarchy network, identify and order the entire resource & activity driver

Activity based costing is a method for evaluating the cost and activities by integrating each activity unit cost. The principle of ABC is that, the products or service in the plant requires some activities, and in order to

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perform this activities, resource should be allocated. The allocated resource consumes cost which makes the identified activities to be cost drivers. Pump which is repairable equipment is taken as a case in this paper.

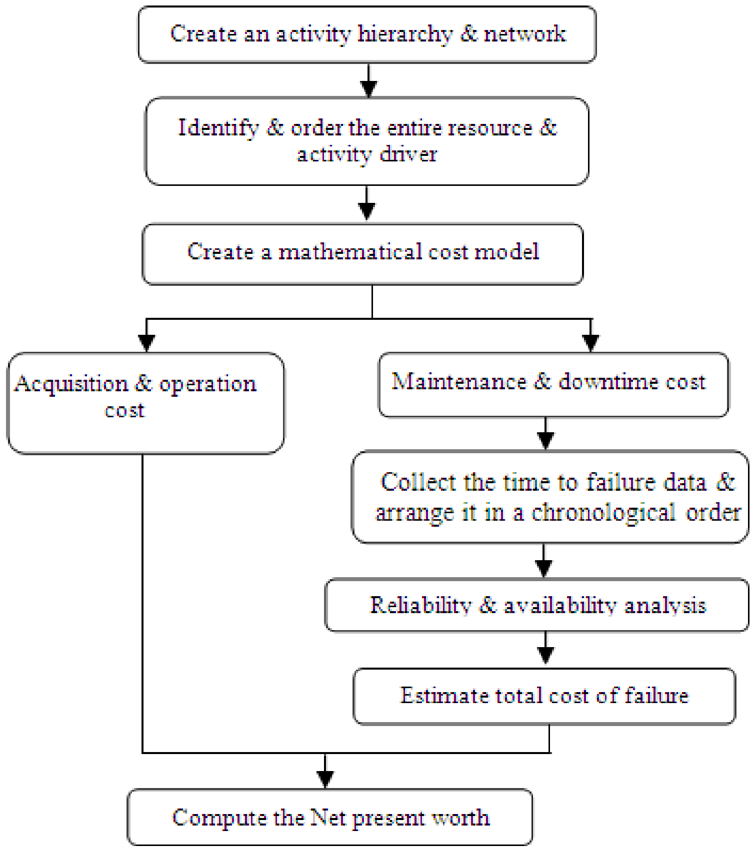

Figure-1. Schematic representation for activity based LCC.

B. Identify and order the entire resource and activity driver

The major cost drivers for the operation phase are operation hour, operating labors, and energy consumption. For maintenance phase the main cost drivers can be time, personnel, tool, test equipment, guideline and so on for activities of inspecting the failure, repairing and verifying it.

C. Mathematical model

In this section, the probabilistic approach LCC model is developed. The general model for the LCC is as shown Equation 1. [2].

$$LCC = C_{aq} + C_i + C_{op} + M_c + P_L \qquad (1)$$

Where C_{aq} is acquisition cost, C_{op}, is operating cost, M_c is maintenance cost and P_L is production loss due to down time. All costs are given in Malaysia Ringgit

a) Acquisition cost

The acquisition cost contains C_1 product planning, C_2 engineering design, C_3 product test and evaluation, C_4 software's used C_5 design documentation and training, C_6 raw materials, and C_7 manufacturing etc. The general expression for the acquisition cost is;

$$C_{aq} = \sum_{j=1}^{j=7} C_j \qquad (2)$$

b) Operation cost

The high impact cost drivers in this phase are number of operation hours, personnel, and cost of energy. Mathematically, cost of operation is therefore going to be estimated by combining the energy and labour cost as shown below.

$$C_{op} = t*(C_e(KW) + C_l) \qquad (3)$$

where t is the service life of the pump (h),C_e is energy cost (*RM/KWH*) and C_l is cost of labour per hour. Energy consumption is calculated by gathering data on the pattern of the system output. Cost of energy for pump can be estimated as shown below [12] [13].

$$C_e = C_{pw}\left[\left(\frac{Q.H}{366.\eta_p.\eta_m}\right)\right] \tag{4}$$

where C_{pw} is cost per input power (*RM/kw*), Q is the pump flow rate (m^3/h), H is the pump head (*m*), η_p is the pump efficiency, η_m is the motor efficiency. These parameters for the existing and the new pump are shown in Table-1.

Table-1. Parameters of the existing and the new pump.

Specifications	Existing pumps	New pump
Initial cost (RM in million)		1.3
Pump head	648m	750
Rate of flow (m^3/h)	1096.92	1136.5
Pump efficiency (%)	83	84
Motor Efficiency (%)	81	89
Power consumed (Input power)	2771	2750
Energy cost/year	RM 0.317/kwh for peak hour RM 0.175/kwh for off-peak hour	RM 0.317/kwh for peak hour RM 0.175/kwh for off-peak hour
Cost of production loss per hour (RM)	500	500
C_l is cost of labour per hour for operation (RM)	100	100

c) Maintenance cost and down time cost

One of the main factors which affect the reliability of the system is proper maintenance. Uncertainties arise from maintenance cost determination, because the failure of the system can happen stochastically. The general equation of maintenance cost is as follows;

$$M_C = C_c N \tag{5}$$

where Mc is the maintenance cost, N is the number of failure,

The corrective maintenance is conducted whenever there is a failure and the cost of repair (Cc) is estimated by the activities it performs

$$Cc = C_{s.p} + C_t + MTTR(l*n) \tag{6}$$

where $C_{s.p}$ is cost of spare part for repairing a failure, if the pump is repaired without replacing any parts $C_{s.p}$ is going to be zero. C_t is cost of tools; MTTR is mean time to repair in hour, l is cost per labor per hour and n is number of labor. Number of failure (N) for repairable item can be expressed

$$N = T / MTBF \tag{7}$$

The failure of the system associates not only with maintenance but also with down time. Due to down time the system is unavailable, which results in the loss of production can be calculated as shown below:

$$P_L = D_t QC \tag{8}$$

Where P_L is the loss of production, D_t is the cumulative down time due to failure, Q is production per hour, C is cost of production per unit. The cumulative down time can be expressed by the unavailability of the system and it is going to be

$$D_t = (1 - \frac{1}{t}\int_0^t A(t)dt) * t \tag{9}$$

Where A(t) is availability

$$A(t) = \left(\frac{MTBF}{MTBF + MTTR}\right) \tag{10}$$

d) Reliability and availability analysis

The existing pump consists of two pumps in a parallel configuration as shown in Figure-2 below.

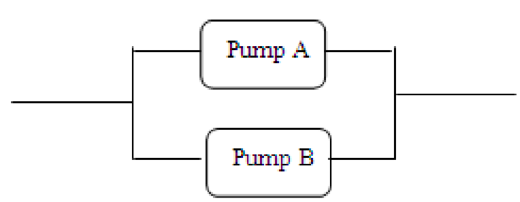

Figure-2. Reliability block diagram for the parallel configuration of the existing system.

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The times to failures for the existing system is collected and arranged in a chronological order as shown in Table-2 below. There is totally 548 and 898 number of failure for pump A and B respectively.

Table-2. Time to failure and cumulative time to failure for the existing system.

Pump A				**Pump B**			
TTF (Days)		**Cumulative TTF (Days)**		**TTF (Days)**		**Cumulative TTF (Days)**	
28	43	28	489	65	47	65	504
28	39	56	528	36	33	101	537
11	20	67	548	35	45	137	582
49		116		30	72	167	654
48		164		34	29	201	683
43		207		30	44	231	727
43		250		47	42	278	769
36		286		33	66	311	835
35		321		45	14	356	849
33		354		43	31	399	881
47		401		41	17	440	898
45		446		17		457	

The Weibull analysis is a widely used technique for statistical data analysis. In this particular case this type of analysis permits to determine the failure behaviour of the pump (early life, random life or wear-out). The Weibull distribution is widely used because it has a great variety of shapes which enables it to fit many kinds of data, especially data relating to product life. The Weibull frequency distribution (or probability density function) has two important parameters: β is called the shape parameter because it defines the shape of this distribution and η is the scale parameter defines the spread of the distribution. The β parameter represents the failure pattern of component under study, for instance if $\beta < 1$ the pump is failing in the early life, if $\beta = 1$ the failure rate is constant and the pump is failing in the section of useful life of the bath curve and if $\beta > 1$ the pump is failing due to wear-out and a scheduled maintenance is justified.

The failure rate and the reliability of the pump can be estimated as

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{11}$$

$$R(t) = e^{\left(\frac{t}{\eta}\right)} \tag{12}$$

Where *R(t)* is reliability, *λ(t) is* Failure rate, *t* is Mission time (hours), β is Shape parameter, η is Scale parameter (hours).

D. Compute the net present worth of the equipment

The final future and annual cost will be discounted to the present by using the interest rate over the appropriate study periods. Aquisation cost is considered as the present cost, operation is the annual cost and maintenance is the future cost.

$$NPW = Caq + C_{op}\left(\frac{1-(1-i)^{-t}}{i}\right) + (M_c + D_t)(1+i)^{-t} \tag{13}$$

where *NPW* is net present worth. *i* effective interest rate. The interest rate is given 3.5% by Malaysian national bank in 2015. *t* represents the time period the analysis is conducted.

RESULTS AND DISCUSSIONS

The shape and scale parameters of the existing system are estimated using the Weibull++10 software. The β for both pumps are greater than one which indicates both the pumps are failing due to wear-out and a scheduled maintenance is justified.

Table-3. The scale and shape parameters of the existing system.

Data	**A**	**B**
η (hr)	323.356	547.413
β	1.29	1.611381

The reliability data for the new pump is extracted from OREDA handbook. The failure and repair data follows exponential distribution with mean value 1.25 (year) and 49.2 (hr) respectively. The mean time to repair (MTTR) of the existing system is fixed as shown in Table 4 for all maintenance activities. The availability of the existing system and the new system for the next 5 years is estimated using Blocksim 10 software. Block sim impliments montecarlo simulation for availability analysis. The analysis is conducted for the next five years result of the analysis is shown in Table-4 below.

Table-4. Reliability and availability parameters.

	Existing system	**New pump**
Mean life (MTBF) days	23	456
Down time (hr)	20727	176.4
Availability	52.68	99.59%
Expected number of failure	94	3.84

The existing system has low availability since the down time is very high and also low reliability since the mean life is very short. The availability of pump A is 51.2% while the availability of pump B is 37.2%. Pump B has the highest down time as shown in Figure-3.

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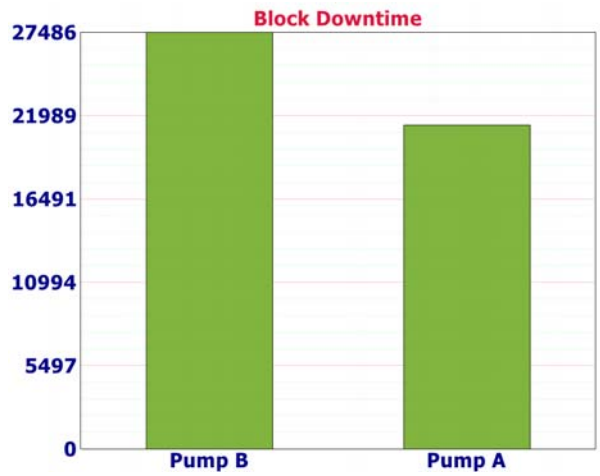

Figure-3. Block down time for the existing system.

The replacement analysis is conducted for three options; option one is to continue with the existing system, option two is replace pump B only, and Option three is replace both pumps. The reliability and availability parameters of the new system after replacement is presented in Table-5.

Table-5. Reliability and availability parameters of the new system after replacement.

	Pump B replaced by the new pump	Both pumps replaced by the new pump
Mean life (MTBF) days	456	684
Down time (hr)	100.6	24.49
Availability	99.7	99.94
Expected number of failure	7.36	2

The existing system reliability become zero at 1657 hr, for the replaced pump system however the reliability become zero at 60000 operating hour. It is obvious that the availability of a system will be improved if a new equipment is being replaced. Is found that the availability does improve by 45.25% when pump B is replaced. The mean life also shows that the reliability of the Pump system is improving.

The main determining factor to continue with the replacement or not is the life cycle cost of the existing and the replaced system

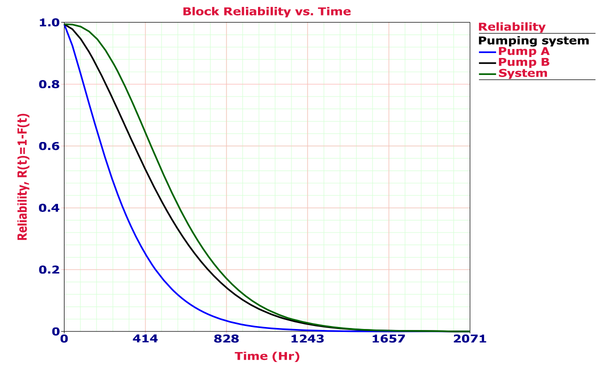

Figure-4. Reliability diagram of the existing system.

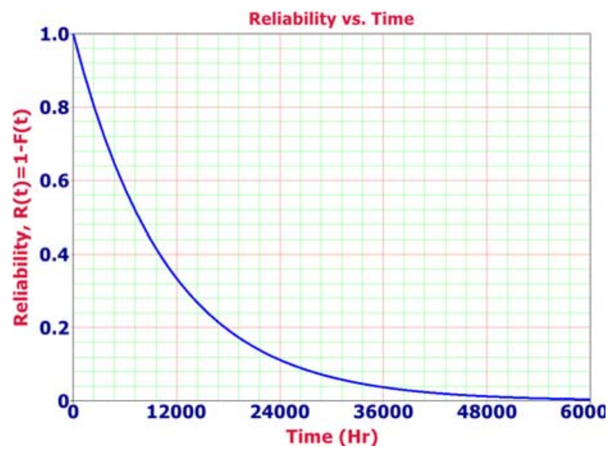

Figure-5. Reliability diagram of the new system.

The acquisition cost of the new pump is 1.3 million RM given in Table-1. The operation cost is estimated using Equation (3), energy cost for pump is a subset of operating cost. The pumps are running 24 hours a day and 365 days a year which is 8760hours. According to Tenaga national Berhad (TNB), which is the largest Electric utility company in Malaysia, high voltage Peak/Off-Peak industrial tariff charges are RM 0.317/kwh and RM 0.175 kwh respectively. Therefore, the power usage by the existing pump during peak and off peak time is estimated using (Equation 4).

$$= \left[\left(\frac{1096\ m^3/hr * 648.1m * 0.94}{366 * 0.83 * 081} \right) \right] = 2715.8 kw/hr$$

Annual energy cost (peak hour)

$$= 2715.8 kw/hr * RM\ 0.317/kwh * 12h * 365\ days$$

$$= RM\ 3{,}770779.67/yr$$

Annual energy cost (non-peak hour)

$$= 2715.8 kw/hr * RM\ 0.175/kwh * 12h * 365\ days$$

$$= RM\ 2{,}081{,}660.70/yr$$

The total annual energy cost for the old pumps is RM 5.85 million/ year. The estimated annual labor cost for operating amine pump is given by the plant (RM100/hr *8760hr/year) =876000RM/year or 0.876 million per year. Therefore, the annual operating cost is the summation of the energy and labor cost which is 6.726 million/ year.

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The power consumption for the new pump is estimated similarly and is found to be 2750. The total annual energy cost for the new pump is RM 5.9.3 million/ year. The labor cost is estimated to be similar with the existing system. The annual operating cost of the new pump is 6.803.

The activity, the resource and cost for the corrective maintenance activity is given in Table-4 below.

Table-6. Resource and cost of maintenance activity.

Activity level	MTTR (Hr)	Resources consumed		Cost		
		Tool	personnel	Tooling cost (RM)	Labour cost (RM)	MTTR (l*n) (RM)
Access to the failed component	1	4	4	200	50	200
Diagnosis	1	4	4	200	50	200
Repair/ replacement	5	4	4	500	50	1000
Verification on & alignment	1	4	4	100	50	200

For the maintenance cost it is found that the tooling cost for all the activities are 1000 RM and the spare part cost for the failure is 4000 RM the labour cost is 1600 RM therefore the cost of repair is (Cc) is equal to 6600 RM/failure.

The expected number of failure for the next five is 94, 7.36 and 2 for the existing system, after the replacement of pump A by the new pump and after the replacement of both pumps respectively. The respective maintenance and down time cost for the three option is estimated using Equation (5) and Equation (8).Table-7 and Table-8 shows all the life cycle costs before and after discount. Equation (13) is used for net present worth (NPW) estimation.

Table-7. Cost element before discount (million RM).

Parameter	Existing system	After replacement of pump B	After replacement of both pumps
Acquisition cost		1.3	2.6
Operation cost	6.72	6.86	6.86
Maintenance cost	0.62	0.049	0.0132
Down time cost	10.36	0.05	0.012
Total LCC	17.7	8.26	9.48

Table-8. Cost element after discount (million RM).

Parameter	Existing system	After replacement of pump B	After replacement of both pumps
Acquisition cost		1.3	2.6
Operation cost	30.34	30.9	30.9
Maintenance & downtime cost	17.96	0.125	0.217
NPW	48.31	32.4	33.8

The LCC of the existing system is higher compared to the new systems. As it is seen from the results changing two of the pumps will incur more cost than changing only Pump A, which is causing the existing to have high unavailability. The Right decision for the pump system availability improvement is to choose the second option; Replace Pump B. There are alternative options for the of the pump system reliability and availability improvement for example, rather than replacing the whole pump, replace the major components that causes the highest failure frequency, or identifying the major failure mode and investigate their improvement or

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develop a schedule preventive maintenance. However due to data limitation this paper only evaluates replacement of the whole pump as an option.

CONCLUSIONS

A generalized Probabilistic LCC model is developed for replacement analysis by integrating the concept of reliability, Availability and Activity based costing. Activity based method is used to identify the activities and cost drivers in operation and maintenance phase. Pump set is taken as a case for this paper. Weibull analysis is used for the reliability analysis. As the replacement analysis shows the existing system the existing system has highest LCC in which the Sixty percent of the LCC comes from maintenance and down time cost. To overcome this, the replacement analysis is done. This analysis is helpful for manager to make the proper decision for the availability improvement and reduced down time of the system.

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