Determining optimal preventive maintenance interval for component of Well Barrier Element in an Oil & Gas Company

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Abstract. An oil and gas company has 2,268 oil and gas wells. Well Barrier Element (WBE) is installed in a well to protect human, prevent asset damage and minimize harm to the environment. The primary WBE component is Surface Controlled Subsurface Safety Valve (SCSSV). The secondary WBE component is Christmas Tree Valves that consist of four valves i.e. Lower Master Valve (LMV), Upper Master Valve (UMV), Swab Valve (SV) and Wing Valve (WV). Current practice on WBE Preventive Maintenance (PM) program is conducted by considering the suggested schedule as stated on manual. Corrective Maintenance (CM) program is conducted when the component fails unexpectedly. Both PM and CM need cost and may cause production loss. This paper attempts to analyze the failure data and reliability based on historical data. Optimal PM interval is determined in order to minimize the total cost of maintenance per unit time. The optimal PM interval for SCSSV is 730 days, LMV is 985 days, UMV is 910 days, SV is 900 days and WV is 780 days. In average of all components, the cost reduction by implementing the suggested interval is 52%, while the reliability is improved by 4% and the availability is increased by 5%.

1. Introduction
An oil and gas company has been established for more than 48 years and operated 2,268 wells. One third of the wells are in production, while two third of the wells are plugged and shut-in due to depleted reservoir, corrosion (leak), and other integrity issues.

Every well has been designed to have well barrier element (WBE) as per company and international standard. WBE consists of primary and secondary elements [1]. The components of WBE directly become a flow path of the hydrocarbon and independent each other Error! Reference source not found..

Every well shall be tested and maintained regularly in order to ensure their integrity for preventing any leak of oil or gas to the surface which can endanger human, environment and asset. Well integrity related to containment and the prevention of the escape of fluids (i.e. liquids or gases) surface [1]. The failure of WBE is mainly related to stuck open or stuck close and leak above the acceptable limit. If there is failure of WBE, the company cannot produce the oil and gas and may cause production loss.
Failure of WBE component can be observed in SCSSV and Christmas Tree Valves following the result of function test, leak test, or gas detection system which leads to the activation of the automatic shutdown system on the well. If there is any unexpected failure during leak test and/or operation, Well Service (WLS) Department will perform Corrective Maintenance (CM), i.e., replacement of the failure component. It requires cost rent of water transportation or slick line unit, spare part material (gate valve for Christmas Tree Valves or retrieved the SCSSV with the new one), and worker. The historical failure and maintenance data are recorded in Well Chronology Database.

The Preventive Maintenance (PM) program is preventive replacement of the component as per schedule stated on the manual, i.e., every 1,095 days. The PM requires rent unit of water transportation or slickline unit, spare part material (seal, seat and API grease for Christmas Tree Valves and retrieved the SCSSV with the new one), and worker. The PM may cause production loss as well.

Currently, there is no systematic evaluation on the current PM program. The historical maintenance data has not been used for any analysis including reliability of WBE. This paper attempts to analyze the failure data and reliability based on historical data. Due to decreasing price of oil and gas between 2015 - 2016, the company need to initiate cost reduction programs. The optimal PM interval will be recommended to the company in order to minimize the total cost of maintenance per unit time.

The WBE is considered as non-repairable item since it has to be replaced with the other equipment. The duration of failure for component of WBE is used to determine Time To Failure (TTF). The Weibull analysis helps to determine the reliability as time function and its parameters [3]. Optimal preventive replacement interval for excavator critical spare part can be determined in order to minimize total cost of maintenance [4].

2. Methods

2.1. Reliability

Reliability is the probability that a system will perform its intended function for a specified period of time under a given set of conditions [5]. Reliability of equipment can be used as key success factor for inspection and maintenance.

In the preventive maintenance, Time To Failure (TTF) is continuous data. In order to calculate the reliability of equipment / component, statistical distribution should be determined. In the reliability analysis, there are some statistical distributions used such as: Weibull, Normal, Lognormal and Exponential distribution. Weibull distribution fits a large number of failure characteristics of equipment. The reliability for three-parameter of Weibull distribution is formulated as follows [6]:

\[
R(t) = \exp \left[ -\left( \frac{t - \gamma}{\eta} \right)^\beta \right],
\]

where:
\( \eta \) = scale parameter; \( \eta > 0 \),
\( \beta \) = shape / slope parameter; \( \beta > 0 \),
\( \gamma \) = location parameter.

Reliability is usually stated as lifetime expectation of the system, noted in \( E[T] \) or Mean Time To Failure (MTTF). MTTF is only used on component or equipment which classified as non-repairable items, once fail, it must be replaced by the new and good one [7]. By applying equation (1), the MTTF for three-parameter Weibull distribution could be written as [6]:

\[
MTTF = \gamma + \eta \Gamma \left( 1 + \frac{1}{\beta} \right),
\]

where \( \Gamma \) is gamma function taken from the function table or by Excel software.
2.2. Maintainability
Maintainability is the probability of component which fails to be repaired and work effectively in the period of time given as per procedure [8]. When TTF data is changed with Time To Repair (TTR) data, the CDF or $F(t)$ will be transformed into maintainability function [9]. Based on equation (1) where CDF is complement of reliability, the maintainability for two-parameter Weibull distribution could be written as follows:

$$M(t) = F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^\beta\right].$$  \hspace{1cm} (3)

Mean Time To Repair (MTTR) is mean time to do maintenance on the component or equipment in order to restore its function into initial state [8]. The MTTF in equation (2) can be transformed as well into MTTR [9]. The MTTR of two-parameter Weibull distribution would be:

$$MTTR = \eta\Gamma\left(1 + \frac{1}{\beta}\right).$$  \hspace{1cm} (4)

2.3. Availability

Availability of component or system in a steady state condition is the comparison between up time ($T_{Up}$) with total operation time ($T_{Up} + T_{Down}$). It is a useful parameter that describes the proportion of time for which an item is not failed. The availability can be modeled with mathematical equation as follows [7]:

$$Availability = \frac{T_{Up}}{T_{Up} + T_{Down}} = \frac{MTTF}{MTTF + MTTR},$$  \hspace{1cm} (5)

where MTTF and MTTR refers to equation (2) and (4).

2.4. Optimal preventive maintenance interval with reliability approach

There are three type of maintenance, i.e., inspection, preventive maintenance and predictive maintenance [7]. Preventive maintenance can be performed if the failure rate becomes higher, where in the bathtub curve is shown with $\beta > 1$ at Weibull distribution. It is called as wear out area. Component of equipment failure can be prevented in this region by performing preventive maintenance [6].

Equipment sometimes called a replaceable unit or part is subject to sudden failure, and when failure occurs, the item has to be replaced. In order to reduce the number of failures, preventive replacement is scheduled to occur at specified intervals [6]. A balance is required between the amount spent on the preventive replacement compared with the failure replacement.

![Figure 1. Preventive maintenance (preventive replacement) and corrective maintenance](image-url)
maintenance (failure replacement) cycles, including replacement duration [6].

As seen in Figure 1, there are two possible cycles of operation, i.e., preventive maintenance and corrective maintenance. The objective is to determine the optimal Preventive Maintenance (PM) interval of the component in order to minimize the total cost per unit time. The optimal interval is determined by utilizing the cost model that solved by analytical method. Based on the two cycles, total cost of maintenance per unit time can be formulated as per below [6]:

\[
C(t_p) = \frac{C_{pm} \times R(t_p) + C_{cm} \times (1-R(t_p))}{(t_p + T_{pm}) \times R(t_p) + \int_0^{t_p} tf(t)dt + T_{cm} \times [1-R(t_p)]}
\]

where:
- \(C(t_p)\) = total cost per unit time,
- \(C_{pm}\) = cost of preventive maintenance / preventive replacement,
- \(C_{cm}\) = cost of corrective maintenance / failure replacement,
- \(R(t_p)\) = Reliability at period of \(t_p\), refers to equation (1),
- \(T_{pm}\) = mean time required to perform a preventive maintenance,
- \(T_{cm}\) = mean time required to perform corrective maintenance, refers to equation (4),
- \(t_p\) = optimal time interval for preventive replacement once the item has reached a specific age,
- \(t\) = Mean Time To Failure (MTTF), refers to equation (2)

3. Result
Data processing is used in order to achieve the research objectives. Time To Failure (TTF) data distribution is tested by Kolmogorov Smirnov (K-S) goodness of fit test. The TTF data distribution fits with the three-parameter Weibull. The reliability parameters on the components can be seen in Table 1. The lowest MTTF is SCSSV i.e. 868.927 days. It means the component has the most frequent failure compared with the other component. SCSSV is the first component in contact with the reservoir oil and gas in order to produce the well.

The shape (\(\beta\)) parameter of WBE components is more than 1 means the components were in the wear out region. The maintenance strategy is preventive maintenance / replacement at fixed intervals.

| No | Component | Distribution | Beta (\(\beta\)) | Eta (\(\eta\)) | Gamma (\(\gamma\)) | MTTF (day) |
|----|-----------|--------------|-----------------|--------------|----------------|------------|
| 1  | SCSSV     | Weibull 3    | 1.5734          | 156.3088     | 728.5600       | 868.927    |
| 2  | LMV       | Weibull 3    | 3.8643          | 967.0521     | 699.4250       | 1574.256   |
| 3  | UMV       | Weibull 3    | 1.6881          | 201.7563     | 907.1350       | 1087.239   |
| 4  | SV        | Weibull 3    | 7.7396          | 1052.3703    | 273.4400       | 1262.896   |
| 5  | WV        | Weibull 3    | 1.9504          | 209.2257     | 767.0800       | 952.601    |

Time To Repair (TTR) history data is tested as well by using K-S goodness of fit test. The TTR data does not fit with three-parameter Weibull but fit with two-parameter Weibull distribution. The maintainability parameters of WBE are provided in Table 2. The longest time for corrective maintenance (\(T_{cm}\)) is LMV i.e. 2.045 days. Because the well need to be plugged in order to have redundant safety barrier (i.e. tubing plug and SCSSV) prior replacing the LMV. The Well Service Supervisor also need to assess the well condition before replacing the component.
Table 2. Maintainability parameters of WBE.

| No | Component | Distribution | Beta (β) | Eta (η) | MTTR |
|----|-----------|--------------|----------|---------|------|
| 1  | SCSSV     | Weibull 2    | 3.3339   | 2.1243  | 1.907|
| 2  | LMV       | Weibull 2    | 3.1701   | 2.2840  | 2.045|
| 3  | UMV       | Weibull 2    | 3.5556   | 1.0313  | 0.929|
| 4  | SV        | Weibull 2    | 2.8779   | 1.0909  | 0.972|
| 5  | WV        | Weibull 2    | 2.9228   | 1.2515  | 1.116|

Following the failure of WBE, the cost for corrective maintenance is available in Table 3. The biggest cost of corrective maintenance ($C_{cm}$) is SCSSV i.e. US$ 129,718.693 since the material cost is much higher compared with the other component. Time to repair ($T_{cm}$) has big impact to production loss thus directly impact on cost corrective maintenance ($C_{cm}$).

Table 3. Cost of corrective maintenance ($C_{cm}$) for every component.

| Equipment       | Cost of Corrective Maintenance (Failure Replacement) | C_{cm} (US$) |
|-----------------|------------------------------------------------------|--------------|
| SCSSV WR-SCSSV  | Rent Unit (US$/d) 13,247 Material / job 40,000 Worker (US$/d) 350 Production Loss (US$/d) 31,793 T_{cm} (day) 1.907 | 126,536.010  |
| LMV Christmas Tree | Rent Unit (US$/d) 13,247 Material / job 21,545 Worker (US$/d) 350 Production Loss (US$/d) 17,200 T_{cm} (day) 2.045 | 84,516.420   |
| UMV            | Rent Unit (US$/d) 1,816 Material / job 31,950 Worker (US$/d) 350 Production Loss (US$/d) 17,200 T_{cm} (day) 0.929 | 49,934.534   |
| SV             | Rent Unit (US$/d) 1,816 Material / job 15,775 Worker (US$/d) 350 Production Loss (US$/d) 17,200 T_{cm} (day) 0.972 | 34,606.788   |
| WV             | Rent Unit (US$/d) 1,816 Material / job 24,856 Worker (US$/d) 350 Production Loss (US$/d) 17,200 T_{cm} (day) 1.116 | 46,473.954   |

The company perform component PM every 3 years (1095 days). In average, the time required for performing preventive maintenance ($T_{pm}$) of WBE component is 0.25 day. Cost for PM is provided in Table 4. The biggest total cost of PM ($C_{pm}$) is SCSSV i.e. US$ 13,912.375 because the material cost is much higher compared with the other component.

Table 4. Cost of preventive maintenance ($C_{pm}$) for every component.

| Equipment       | Cost of Preventive Maintenance (Preventive Replacement) | C_{pm} (US$) |
|-----------------|--------------------------------------------------------|--------------|
| SCSSV WR-SCSSV  | Rent Unit (US$/d) 1,816 Material / job 10,000 Worker (US$/d) 171 Production Loss (US$/d) 13,663 Total Cost (US$/d) 25,650 T_{pm} (day) 0.25 | 13,912.375   |
| LMV Christmas Tree | Rent Unit (US$/d) 13,247 Material / job 2,174 Worker (US$/d) 171 Production Loss (US$/d) 10,735 Total Cost (US$/d) 15,592 T_{pm} (day) 0.25 | 8,212.167    |
| UMV            | Rent Unit (US$/d) 1,816 Material / job 2,174 Worker (US$/d) 171 Production Loss (US$/d) 10,735 Total Cost (US$/d) 15,592 T_{pm} (day) 0.25 | 5,354.375    |
| SV             | Rent Unit (US$/d) 1,816 Material / job 2,174 Worker (US$/d) 171 Production Loss (US$/d) 10,735 Total Cost (US$/d) 3,990 T_{pm} (day) 0.25 | 5,354.375    |
| WV             | Rent Unit (US$/d) 1,816 Material / job 2,174 Worker (US$/d) 171 Production Loss (US$/d) 10,735 Total Cost (US$/d) 3,990 T_{pm} (day) 0.25 | 5,354.375    |

In order to determine optimal PM interval, mathematical model is used to minimize total expected cost per unit time. The total cost consists of PM cost ($C_{pm}$) and corrective maintenance cost ($C_{cm}$) per cycle. The cost consists of rent unit, material/component, worker, and production loss. Based on Table 3 and Table 4 applied into equation (6), the optimal PM interval could be seen in Table 5. The optimal interval ($t_p$) is below the MTTF of each component. Means, the component has to be maintained / replaced prior any unexpected failure. Based on the optimal interval ($t_p$), the reliability and availability can be calculated by using equation (1) and (5).
Table 5. Optimal preventive maintenance interval.

| Equipment   | Type / Component | Optimal PM Interval |          |                |          |
|-------------|------------------|---------------------|----------|----------------|----------|
|             |                  | $t_p$ (day)         | $C(t_p)$ (US$/d) | Reliability | Availability |
| SCSSV       | WR-SCSSV         | 730                 | 99.743   | 0.999          | 0.998     |
| Christmas Tree | LMV             | 985                 | 9.367    | 0.992          | 0.999     |
|             | UMV              | 910                 | 29.489   | 0.999          | 0.999     |
|             | SV               | 900                 | 6.539    | 0.982          | 0.999     |
|             | WV               | 780                 | 27.860   | 0.996          | 0.999     |

Based on MTTF in Table 1 and existing PM schedule, the total cost per unit time could be calculated as well by applying equation (6). The existing total cost for both corrective and preventive maintenance is provided in Table 6. Based on Table 6, the total cost for performing optimal PM on every component is lower than let the component to fail nor performing existing PM. Based on existing PM interval ($T_p$), the reliability and availability on the current PM policy can be calculated as well by using equation (1) and (5). Refer to Table 4 and 5, the optimal and existing PM result is compared. In average, the reliability of every component is improved by 4% compared with the company requirement at 0.95. The availability improvement of every component in average is 5% higher compared with the company requirement.

Table 6. Existing total cost of corrective and preventive maintenance.

| Equipment   | Type / Component | Existing CM |          | Existing PM |
|-------------|------------------|-------------|----------|--------------|
|             |                  | MTTF (day)  | $C(MTTF)$ (US$/d) | $T_p$ (day) | $C(T_p)$ (US$/d)$ |
| SCSSV       | WR-SCSSV         | 868.927     | 351.683  | 1095         | 488.660   |
| Christmas Tree | LMV             | 1574.255    | 31.863   | 1095         | 10.010    |
|             | UMV              | 1087.239    | 99.986   | 1095         | 102.722   |
|             | SV               | 1262.896    | 15.690   | 1095         | 8.648     |
|             | WV               | 952.601     | 83.905   | 1095         | 116.710   |

4. Conclusion
In order to obtain the lowest total cost per unit time, the replacement should be performed at interval $t_p$, i.e. 730 days for SCSSV, 985 days for LMV, 910 days for UMV, 900 days for SV and 780 days for WV. It is sooner than the company’s preventive maintenance policy for replacing the component every 1,095 days. In average for all components, the reduction of total cost per unit time is 52% by implementing the suggested optimal preventive maintenance interval.

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