

Considerations regarding determination of optimal preventive maintenance periodicity for subsurface sucker rod pumps

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Abstract. The subsurface sucker rod pumps are important equipment used for the secondary oil recovery. In their structure, there are friction couples, which are strongly subjected at wear like barrel-plunger, traveling valve and standing valve. The operating durability of subsurface sucker rod pumps is practically determined by the reliability of these couples depending on the work conditions.

The paper presents a case study on the optimization of preventive maintenance of the subsurface sucker rod pumps. The optimal periodicity, of the preventive maintenance of the above mentioned friction couples, is determined on the basis of their operating reliability. There were analyzed two types of preventive maintenance, at fixed time, and at fixed age respectively. The paper results are embodied in practical charts which can be used for choosing optimal preventive maintenance period of the subsurface sucker rod pumps.

1. Introduction

The deep-well pumping system is used for the oil wells exploitation. In our country, this system is used at least for 75 % of the oil wells. The deep-well pumping exploitation is applied in a finally phase, when the natural energy of the stratum decreased and its value is insufficiently for surface oil ascending, or in the case when the artificial lifting can't be done). The efficiency of the deep-well pumping system is influenced by the operating life of the pumps, and in the case of subsurface sucker rod pumps, by the consumption of the high wear repair parts (barrels, plungers and valves [1, 2].

Subsurface sucker rod pumps operating life depends on: the service conditions (the depth of the hole, the aggressiveness of the pumped fluids, the pumping parameters); the subsurface sucker rod pumps construction (the type of the pump, the materials used at pumps construction, the quality of the manufacture etc.); the maintenance activities. Regarding the subsurface sucker rod pumps operating life, it can be done the remark that this is determined mainly by the high wear couples which are: barrel-plunger, standing valve and traveling valve. The failure of these couples implies the subsurface sucker rod pump replacement [3, 4, 5].

Taking into account of the above statements, it can be concluded that it is necessary to establish a subsurface sucker rod pump optimum maintenance program that can reduces at maximum the operating expenses. One of the maintenance strategies that achieve this goal is preventive maintenance based on operational reliability [6].

The paper aim is to present a general methodology to determine the optimal duration of preventive maintenance as a function of the component replacing cost. This methodology is exemplified for the

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high wear couples above mentioned that are the most often replaced components. The paper results are embodied in practical charts which can be used for choosing optimal preventive maintenance period of the subsurface sucker rod pump.

2. Construction and operation of the sucker rod pumps

The considered subsurface sucker rod pump in this study is 25-175-RHAC 20-8-2 type and it equips the oil-wells of the Ciuresti oil field. According API Specification 11 Ax standard [7], the 25-175-RHAC 20-8-2 subsurface sucker rod pump main characteristics are the following:

- nominal tubing size 73.0 mm ($2\frac{7}{8}$ in);
- basic bore diameter 44.5 mm ($1\frac{3}{4}$ in);
- type of the pump: rod, stationary heavy wall barrel, top anchor, introduced in oil well with the sucker rods;
- barrel length 6.096 m (20 ft);
- plunger length 2.438 m (8 ft);
- total length of extensions 0.610 m (2 ft);
- standing and traveling valves - globe valve type;
- component parts of the valves (the valve seat and the ball) made from anticorrosive stainless steel AISI 410-440, steel type X40Cr14 (UNI 6901) respectively X38Cr13 (DIN 17440) that have the chemical composition (wt.%): C - (0.35 .. 0.44), Si - max 0.6, Mn - max 0.6, Cr - (12.0 ... 14.0) [3];
- hardness of the valve components, ball – Rc 58-65, respectively seat – Rc 52-56;
- pump barrel made from steel chrome plated, thickness of coating 0.076 mm, hardness of coating Rc 67-71, base material 10XX steel, base core hardness Rb 90-Rc 23;
- pump plunger coated with spray metal, thickness of the coating 0.254 mm, hardness of the coating Rc 58, base material 1018-1045 steel, base core hardness Rb 70-Rc 23.

The construction and working principle of the subsurface sucker rod pump is presented in figure 1. In this figure, it can be observed the high wear couples of the pump: barrel-plunger, standing valve and traveling valve.

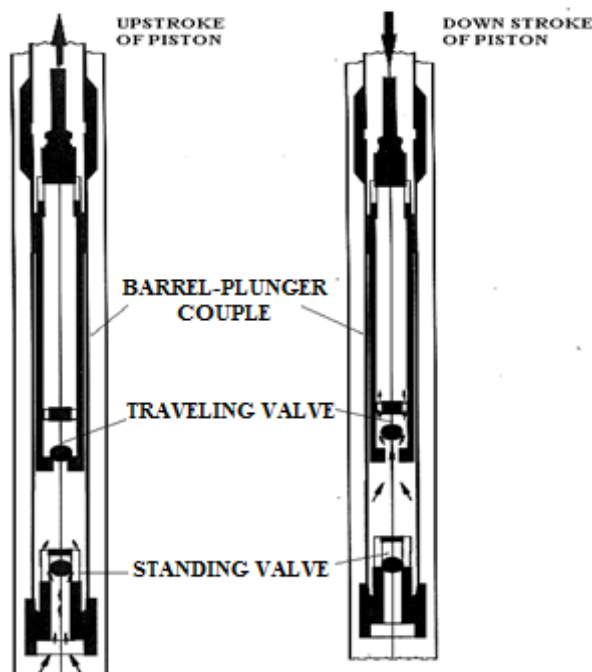


Figure 1. The construction and the working principle of the subsurface sucker rod pump.



Figure 2. Some examples concerning the working damage of valves.

The pump working is characterized by two strokes: one for the upward of the plunger and the other for the downward of the plunger. At the upstroke of the plunger, the standing valve is opened and the traveling valve is closed. Thus, the fluid enters in pump and the fluid, which is situated inside of the plunger, is pushed up. At the down stroke of the plunger, the standing valve is closed and the traveling valve is opened. Thus, the fluid enters in piston chamber because of the pressure, which appears in the pump chamber.

The subsurface sucker rod pumps work in different agents who are characterized by the fluid properties (the content of impurities, the corrosiveness etc.) [2, 3, 4]. In figure 2 there are represented some examples concerning the damage of the valves. From this figure, it can be observed that valves can be damaged by erosion and abrasion. Also, the wear of barrel-plunger couple is produced because of erosion and abrasion [3, 4]. The wear of barrel-plunger and valves has like effect the decrease of the flow and implicitly replacement of these [6].

3. Reliability modeling of barrel-plunger and valves of the subsurface sucker rod pump

The reliability modeling of the high wear couples of the subsurface sucker rod pumps was done using the data concerning the operating durability of these. So, there were taken into consideration the data, which were obtained, from 7 subsurface sucker rod pumps used in the oil field Ciuresti. These pumps are characterized by the following characteristics concerning the construction and the operating:

- type of the pumps 25-175-RHAC 20-8-2;
- anchorage depth between 1900 and 2600 m;
- flow rate in the range of 5 ... 30 m³/24 hours;
- double strokes number in the range of 8 ... 10 double strokes/minute;
- operating durability between replacements of considered friction couples in the range of 36 ... 213 days;
- type of the agent – hybrid (mixed).

The operating durability registered for the considered couples are presented in table 1.

Table 1. Working durability of high wear couples of subsurface sucker rod pumps.

Couple	Durability (days)									
Barrel-Plunger	36	44	48	81	86	111	123	125	190	213
Standing valve	36	48	106	107	111	123	167	169	190	
Traveling valve	36	44	50	54	75	88	113	123	125	159 190

For modeling the survival processes which characterize subsurface sucker rod pumps couples, it was used the Weibull partition law with two parameters [8, 9]. The expression of the Weibull law indicators are:

- the probability density:

$$f(t, \eta, \beta) = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta-1} \exp \left[- \left(\frac{t}{\eta} \right)^\beta \right] \quad (1)$$

- the reliability:

$$R(t) = \exp \left[- \left(\frac{t}{\eta} \right)^\beta \right] \quad (2)$$

- partition function

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

- failure rate

$$z(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta} \right)^{\beta-1} \quad (4)$$

- mean time between failures

$$MTBF = \eta \cdot \Gamma \left(\frac{1}{\beta} + 1 \right) \quad (5)$$

where $\Gamma \left(\frac{1}{\beta} + 1 \right)$ is first species Euler function

Analytical determination of β and η parameters was done using the method of least square fit. In table 2 there are presented the values of Weibull parameters.

Table 2. Parameter values of Weibull law for subsurface sucker rod pumps couples.

Couple	Weibull law parameter values		Determination coefficient r^2	MTBF (days)
	β	η		
Barrel-Plunger	1.8	123	0.968	109
Standing valve	1.75	154	0.988	137
Traveling valve	2.0	108	0.976	204

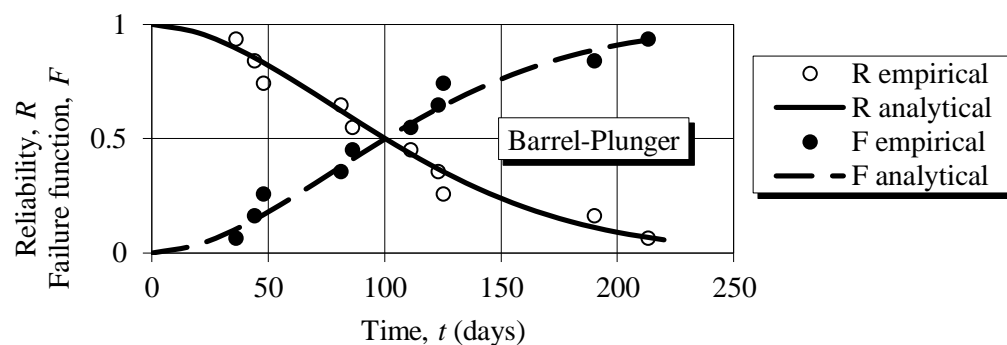


Figure 3. Empirical and analytical reliability and failure function for barrel-plunger couple.

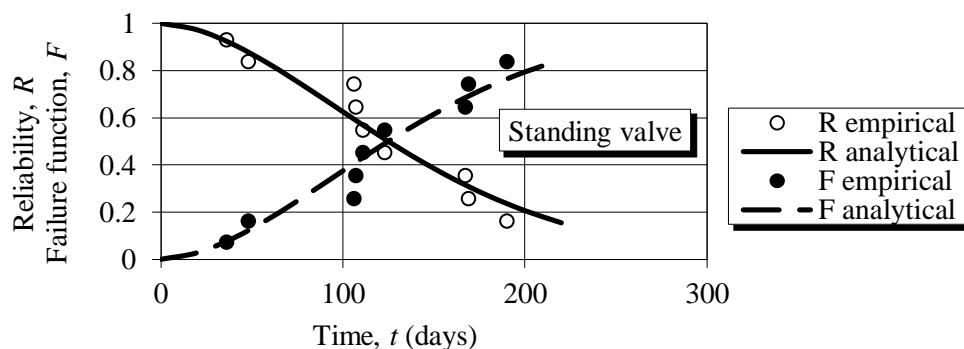


Figure 4. Empirical and analytical reliability and failure function for standing valve couple.

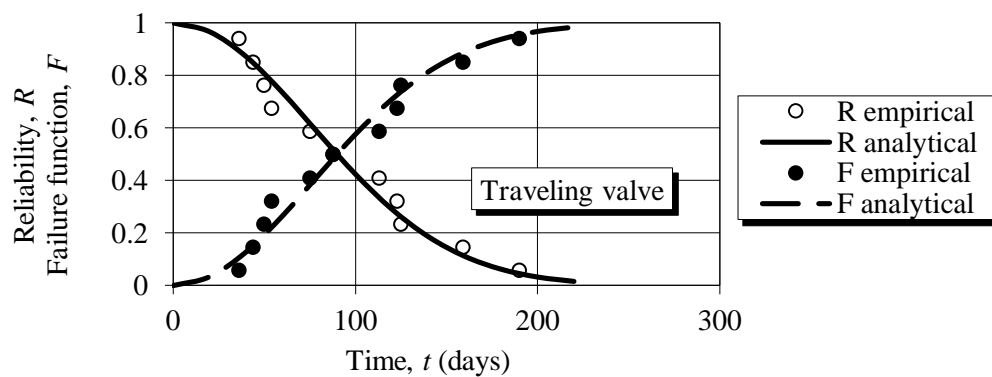


Figure 5. Empirical and analytical reliability and failure function for traveling valve couple.

Using calculated values of η and β parameters there were plotted the diagrams for reliability and failure function (figure 3, figure 4 and figure 5), failure rate (figure 6) and probability density (figure 7). The obtained results concerning the Weibull law parameters and the presented diagrams from above mentioned figures will be used for determination of preventive maintenance periodicity.

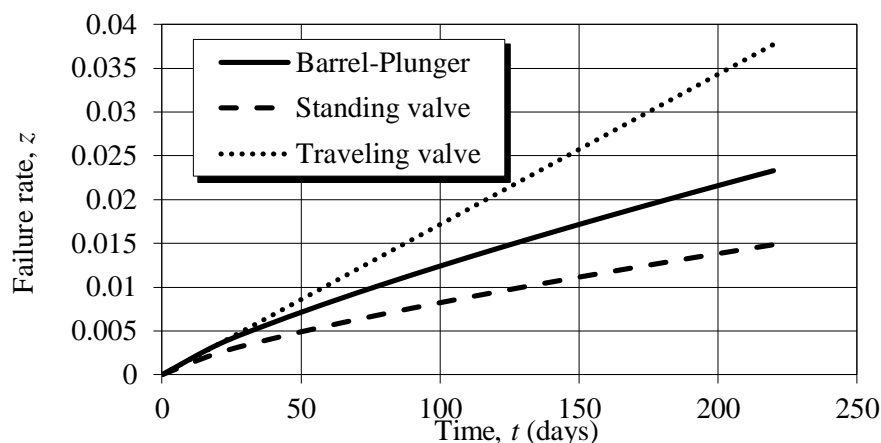


Figure 6. Weibull law failure rate for high wear couples of subsurface sucker rod pumps.

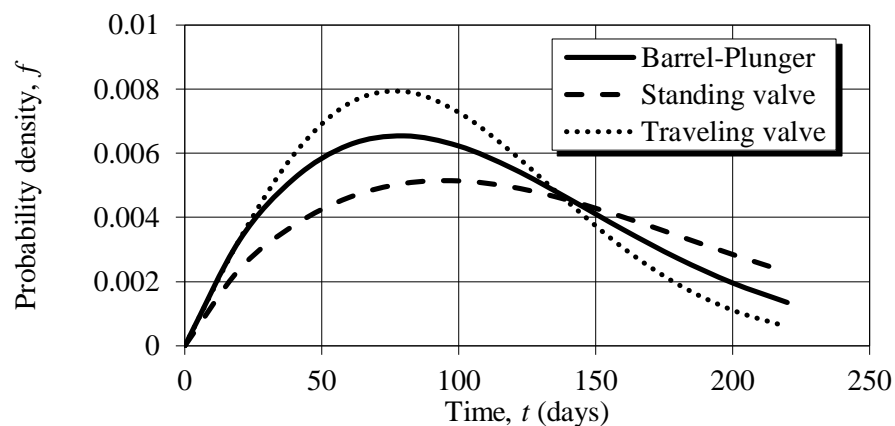


Figure 7. Weibull law probability density for high wear couples of subsurface sucker rod pumps.

4. Optimal preventive maintenance periodicity determination

One of economic problems that can be solved by knowing of operating reliability is the determination of the optimal preventive maintenance periodicity. This is justified from economic considerations when the following two conditions are met:

- the preventive and planned replacement of a device at fixed date has to cost less than the random replacement made when the device fails;
- the failure rate of the programmed preventive maintenance device has to be increasing.

Further will be used the following notations: c_1 – replacement cost for a good condition device; c_2 – cost of an unexpected failure ($c_2 > c_1$); T – the period when the device attains T age and it is replaced with a new one; $f(t)$ – the probability density; $R(t)$ – the reliability function.

There are two possible maintenance policies, which will be further presented. These policies have to be considered since the product design, and the technical documentation has to contain the maintenance indicators and their determination procedure in addition to reliability indicators [5].

4.1. Maintenance at fixed time

In this case all devices are replaced with a periodicity T , whatever their age. In other words, even if at $(T - \varepsilon)$ moment a device was individually replaced, at the fixed time will be replaced all devices again.

It presumes being replaced, then new, all devices at the 0 moment and it is calculated mathematical expectation (average) of the device replacement cost at the T moment and for a cost c_1 . Then, the probability for having one failure in time T , with $c_1 + c_2$ cost is:

$$\int_0^T F(t_1)R(T-t_1)dt_1 \quad (6)$$

Probability for two failures with $c_1 + 2c_2$ cost is:

$$\int_0^T F(t_1)dt_1 \int_{t_1}^T F(t_2-t_1)R(T-t_2)dt_2 \quad (7)$$

Continuing the reasoning, the cost replacement average for a device is:

$$M(c) = c_1 + c_2 \left\{ \int_0^T F(t_1)R(T-t_1)dt_1 + 2 \int_0^T F(t_1)dt_1 \int_{t_1}^T F(t_2-t_1)R(T-t_2)dt_2 + \dots \right\} \quad (8)$$

An optimistic account, which presumes that the global replacements frequency is well chosen, so that never exist more than two consecutive replacements, give a unitary cost equal with:

$$K = c_1 + [1 - R(T)] c_2 \quad (9)$$

This corresponds at a price for unit time and device:

$$c = \frac{c_1 + [1 - R(t)] c_2}{T} \quad (10)$$

Deriving relation (10) and equalizing with zero it can be determined the minimum cost which corresponds for an optimum replacement time T^* , then:

$$R(T^*) + Tf(T^*) = \frac{c_1 + c_2}{c_2} \quad (11)$$

The T^* value can be obtained using a graphic method (figure 8) which consists in searching minimum value applying relation (11).

For drawing the curves presented in figure 8 there are used the reliability expressions previous determined. The curves were plotted for a time range of 0 – 80 days, and they can be used for determining of ratio $(c_1 + c_2)/c_2$. Has to be mentioned that the maximum value of this ratio is 2 that corresponding to situation when $c_1 = c_2$, and the minimum value (theoretical) is 1.

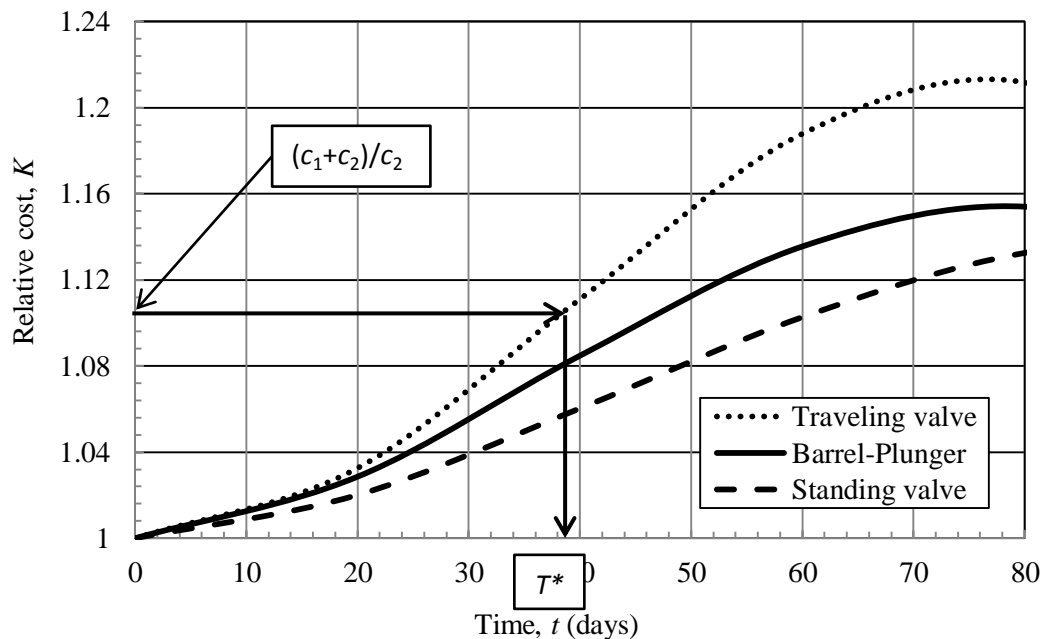


Figure 8. Maintenance at fixed time for considered couples of the subsurface sucker rod pump.

4.2. Maintenance at fixed age

The second case of maintenance is characterized by a continuous surveillance of the each element (device) age, so this is replaced when attains the age T . From economic reasons, in comparison with the previous case, the differences are the following [5]:

- the number of elements replaced (devices) is reducing, because if one is replaced like being defect, it will not be replaced automatically in a preventive way at a fixed time (that could be immediately after - the remedial of defect), just in the moment when attains the age T ;
- the device's age has to be known, this implies the existence of a special monitoring;
- replacements at a fixed age are more expensive because they are done only for a single device at a time.

The calculus can be made in a manner that put in evidence the difference between the two types of maintenance. Whether:

$$\frac{1}{M(t)} = \frac{1}{\int_0^T R(t)dt} = \frac{1}{MTBC} + \frac{1}{MTBP} \quad (12)$$

where:

$$MTBC = \frac{\int_0^T R(t)dt}{1 - R(t)} \quad (13)$$

is the average interval between corrective maintenances and

$$MTBP = \frac{\int_0^T R(t) dt}{R(t)} \quad (14)$$

is the average interval between preventive maintenances.

The cost per unit time is:

$$K_u = \frac{c_1}{MTBP} + \frac{c_2}{MTBC} \quad (15)$$

so:

$$K_u = \frac{c_1 R(T)}{\int_0^T R(t) dt} + \frac{c_2 F(T)}{\int_0^T R(t) dt} \quad (16)$$

with $F(T) = 1 - R(T)$.

The determination of K_u value is done, also, in a graphic manner.

In figure 9, figure 10 and figure 11 are plotted the curves corresponding on concrete operating conditions of the barrel-plunger, standing valve and traveling valve respectively. Has to be mentioned that in above mentioned figures are plotted many curves that corresponding to different values of ratio c_1/c_2 , because, as been stated, generally is difficult to establish a unique value of this ratio.

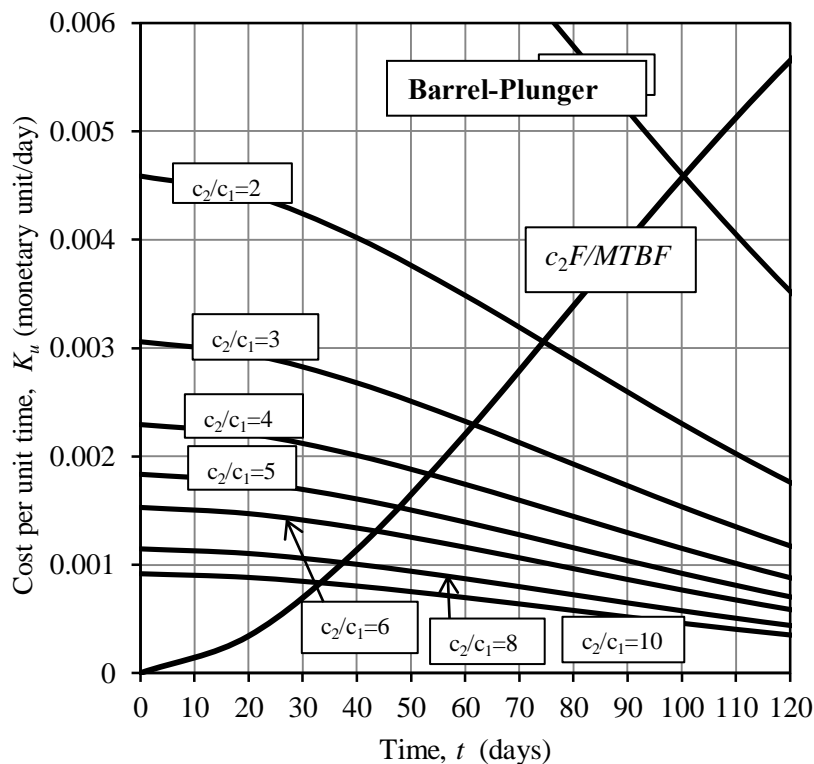


Figure 9. Graphical determination of minimum cost for maintenance at fixed age for barrel-plunger and for different values of ratio c_2/c_1 .

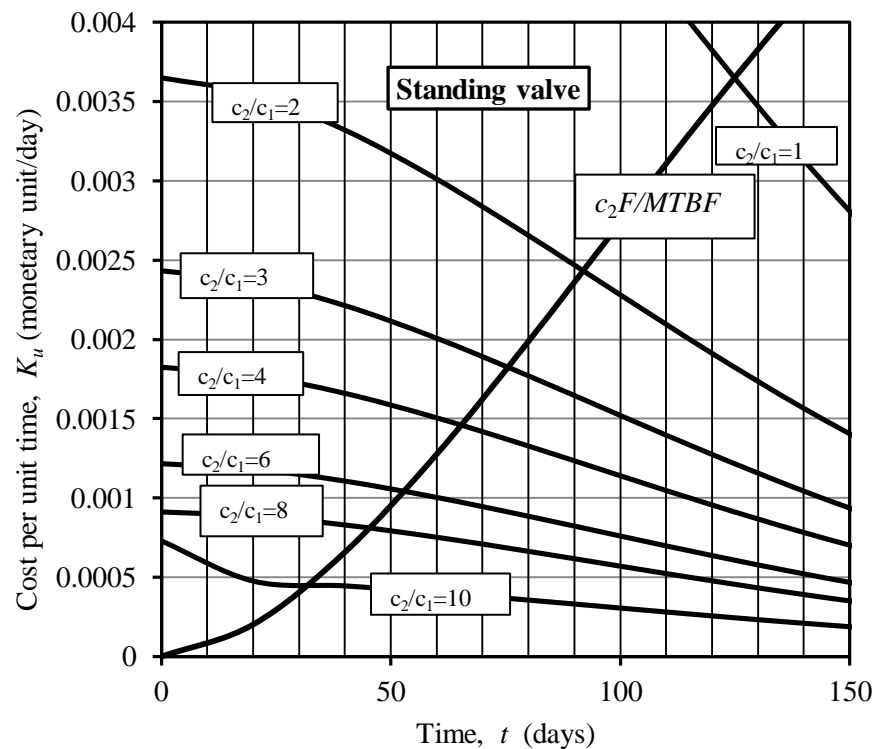


Figure 10. Graphical determination of minimum cost for maintenance at fixed age for standing valve and for different values of ratio c_2/c_1 .

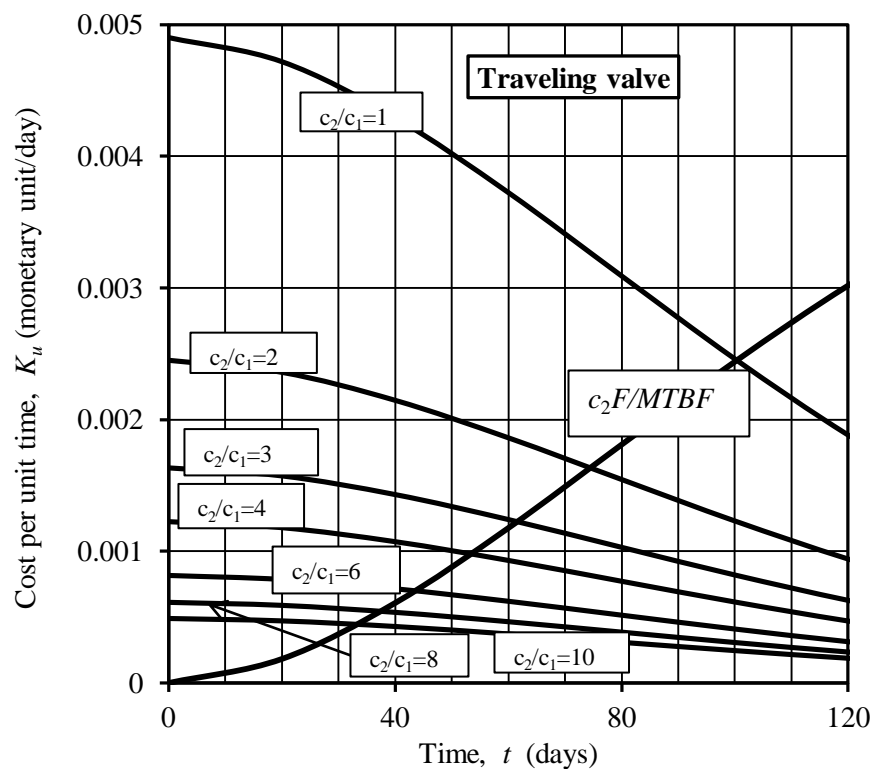


Figure 11. Graphical determination of minimum cost for maintenance at fixed age for traveling valve and for different values of ratio c_2/c_1 .

5. Discussions

For comparing the two preventive maintenance variants, at fixed time and fixed age, from the point of view of costs and durations, in figure 12, figure 13 and figure 14, there were represented the dependence curves between cost ratio c_2/c_1 and maintenance time.

From above mentioned figures it can be observed that for the considered couples when the cost ratio c_2/c_1 has values higher than 10, maintenance at fixed time is recommended while for $c_2/c_1 < 10$ the maintenance at fixed age is more economical.

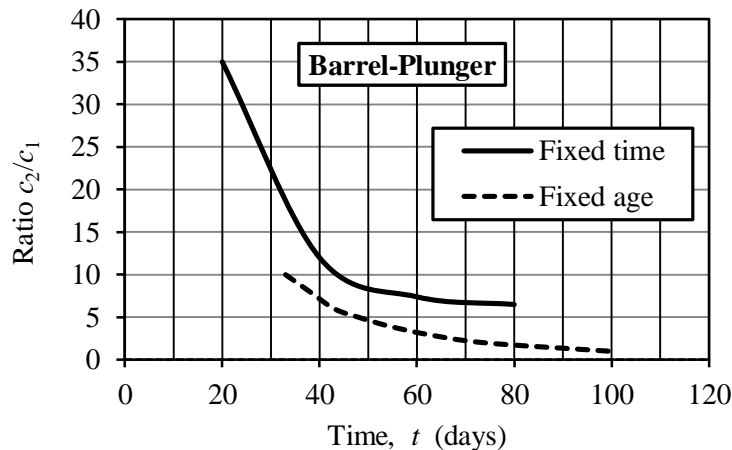


Figure 12. Comparison between maintenance at fixed time and at fixed age for barrel-plunger couple.

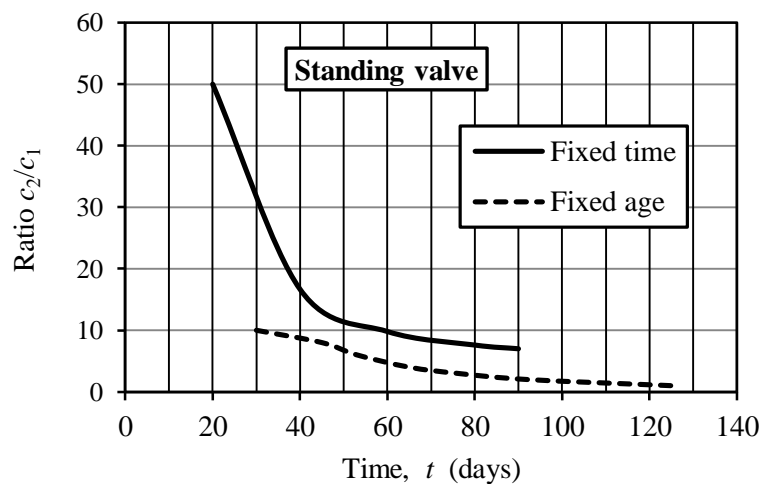


Figure 13. Comparison between maintenance at fixed time and at fixed age for standing valve couple.

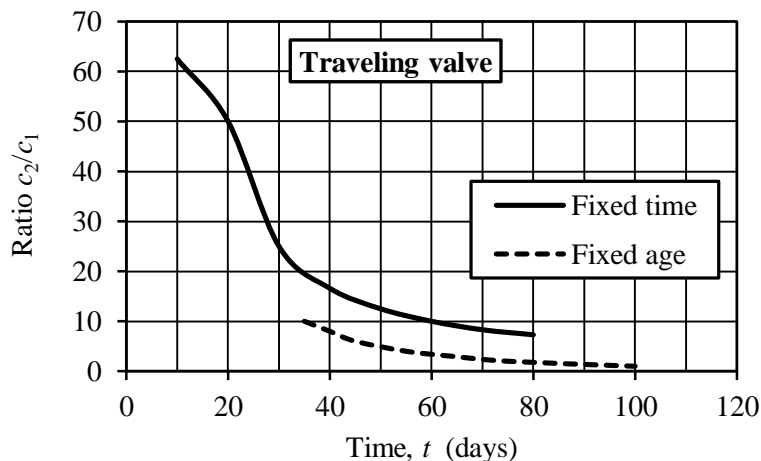


Figure 14. Comparison between maintenance at fixed time and at fixed age for traveling valve couple.

For considered couples (figure 12, figure 13 and figure 14) in the time range of 40 ... 80 days the economic value of the ratio c_2/c_1 is higher than 8 for the fixed time maintenance and smaller than 5 for the maintenance at fixed age.

In figure 12 and figure 14 it can be observed that for the same ratio c_2/c_1 the smallest replacement periods at fixed time are registered for barrel-plunger and traveling valve, while for standing valve they are the biggest (figure 13). These results are in accordance with their values of operating reliability.

Regarding the maintenance at fixed age the biggest replacement periods are registered for the same c_2/c_1 ratio in the case of standing valve (figure 13). Anyway, the minimum values of each curve indicate optimum values of ratios c_2/c_1 for each component.

6. Conclusions

The main conclusions, which can be detached from this paper, are following:

- paper presents an original approach of preventive maintenance periodicity determination, applied for subsurface sucker rod pumps used for oil secondary exploitation;
- because the preventive maintenance is a component of reliability centered maintenance process, the paper results can be used firstly in design activity of subsurface sucker rod pumps;
- paper presents a case study which is imposed to be done for every subsurface sucker rod pump type, because of the operating conditions which are different from one oil field to another;
- calculus manner of reliability which was presented in this paper can be used for each type of subsurface sucker rod pump, and generally for any element (device);
- paper results can be used for optimum programing of maintenance activity of subsurface sucker rod pumps, in order to obtain the highest operating durability and lowest costs.

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