"The New Optimum Replacement time Methodology for Aged Equipment: The UFCC compressor case study"

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Abstract: The New Optimum Replacement Time Methodology for aged equipment, supports the best replacement time decision related to aging asset where the preventive maintenance is not able to recover the reliability to a state economically feasible. Such proposed methodology encompasses different methods through the implementation steps such as RAM analysis, Lifetime data analysis, Reliability Growth Analysis and Equipment Operation Cost Analysis. The main different of the previous methodology is that the expected operational cost proposed is based on Crow AMSSA model. In order to demonstrate such methodology a case study about critical compressor of the UFCC refinery plant will be assessed.

Key Words: RAM analysis, Lifetime Data Analysis, Reliability Growth Analysis, Operational Cost Analysis, Best Replacement time.

1 - FAILURE AND REPAIR DATA ANALYSIS

The FCC (fluid catalytic cracking) plants convert the high-boiling, high-molecular weight hydrocarbon fractions of petroleum crude oils to more valuable gasoline, olefinic gases, and other products. In order to predict future performance and define the FCC critical equipment the RAM analysis was performed for this plant.

Once defined the RAM analysis scope, the Lifetime Data Analysis (LDA) is the further step. The Lifetime Data Analysis based on historical failure data of FCC plants in operation was the main input for the RAM analysis. Thus, by collecting the failure and repair data from equipment files, it was possible to obtain the proper data and perform the life time data analysis by using statistic software (Weibull ++ 7 Reliasoft) to define PDF parameters for each equipment that is part of this study.

To ensure the accurate representation of such data, maintenance professionals with knowledge of each piece of equipment took part into this stage.

The figure 1 shows an example of the compressor PDF parameters for failure and repair as result of the Life Time Data analysis as part of the RAM analysis.

TAG	Failurre Mode	Failure Time (Years)					Repair Time (hour)				
		PDF	Parameters				PDF	Parameters			
EC-301 A	Turbine Bearing	Gumbel		μ	∂		Lognormal	μ	∂		
				4,5	2,04			3,08	0,64		
	Gas Valve 1	Exponencial		λ	γ		Normal	μ	∂		
				0,5426	0,0946			47,6	40,8		
	Gas valve 2	Weibull	β	η	γ		Normal	μ	∂		
			0,5418	1,2061	0,6185			36,4	20,94		
	Seal leakage	Gumbel		μ	∂		Weibull	β	η	γ	
				4,97	0,24			0,77	4,23	2,36	
EC-301 B	Gas valve 1	Weibull	β	η	γ		Lognormal	μ	∂		
			0,51	2,85	0,298			3,21	1,73		
	Gas valve 2	Weibull	β	η	γ		Loglogistic	μ	∂		
			0,418	0,64	0,6049			3,3	0,75		
	Turbine Bearing	Normal	μ	∂			Normal	μ	∂		
			3,56	0,1				24	1		
EC-301 C	Turbine Bearing	Gumbel		μ	∂		Lognormal	μ	∂		
				4,09	1,61			2,93	0,92		
	Gas valve 1	Gumbel		μ	∂		Lognormal	μ	∂		
				4,3	1,77			3,05	1,09		
	PSV valve and others	Normal	μ	∂			Lognormal	μ	∂		
			2,07	1,21				2,72	1,52		

Figure 1 - Furnace failure and repair PDF parameters. Source: Calixto, E, et al 2012

2 – Reliability Diagram Block Modeling

Before performing Monte Carlo simulation, it is necessary to create a reliability diagram block. In this way, it is important to be familiar with the production flowchart details that influence losses in production. Consequently, some statements and definitions about the equipment failure impact on the FCC process were applied to the RBD modeling. At top level configuration, whenever any of critical subsystems is unavailable such as warming, conversion, cold area, diethylamine (DEA), and cleaning, the FCC system is also unavailable. The main FCC profile information are:

- The availability target is 98% in 5 years.
- The facility supply had 100% availability in 5 years.

- The total production per day was 55 m3.

The Figure 2 shows the FCC system RBD model.

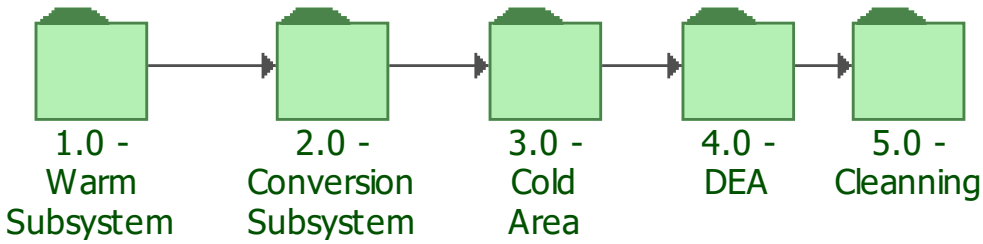

Figure 2 - Fluid Cracking Catalytic System RBD. Source: Calixto, E, et al 2012

3 - Simulation

RAM analysis simulation was performed by using the BlockSim software. The Monte Carlo simulation allows the creation of typical life cycle scenarios for the system by considering the RBD models and reliability and maintainability PDFs input data. The entire UFCC plant unit was modeled through RBDs, considering the redundancies and the possibilities for bypass in each equipment or system configuration as demonstrate in item 2. The Monte Carlo simulation allows assessment the operational availability prediction to verify if the operational availability target of 98% in 3 years will be achieved. If the operational availability target is not achieved, it becomes necessary to improve critical equipment operational performance.
The simulation was performed concerning 5 years life time and 1000 simulation were run to converge the results. The RAM analysis simulation results show the UFCC operational availability achieves 99.81% in 5 years and is expected five equipment failures during this period.

4 - Critical analysis

The critical analysis defines which are the most critical subsystems and equipment which has the most influence on operational availability and consequently in the production losses. There are two indicators applied to demonstrate the criticality such as the Reliability Importance (RI) and Down Event Critical Index (DECI).
The first one shows how much influence one subsystem or equipment has on system reliability. Thus, using partial derivation, it is possible to demonstrate how much it is necessary to increase subsystem or equipment reliability to improve the whole system reliability.
The following equation shows the mathematical relation:

$$\frac{\partial R(System)}{\partial R(Sub-system)} = RI$$

Despite this relation, some equipment or subsystems may be prioritized due to repair time having an expressive impact on system operational availability. This means that the operational availability impact is the most important parameter, despite reliability being highly influential in the system performance. However, the RI is the best index for the equipment reliability target achievement. In this case the RI is the best index to show how much improvement, reliability the system can accommodate. But as discussed, it is necessary to consider availability. In the FCC system the most critical subsystems are the cold area and conversion subsystems based on the RI and DECI assessment. The figure 8 shows the RI assessment results.

The DECI was also used to assess which equipment cause more shutdowns in the FCC system, and despite the low number of shutdowns and k/n configuration, compressors EC-01 A–C are responsible for most of them, as shown in Figure 9.

Despite of being the compressor the most critical equipment, the fluid catalytic cracking system achieved the availability target (99.91% in 5 years) and by target achievement point of view, no improvements are required by this system. However, this compressor operates for over 20 years, and despite increasing corrective and preventive maintenance costs, requires optimum replacement time analysis to decide when such compressors must be replaced.

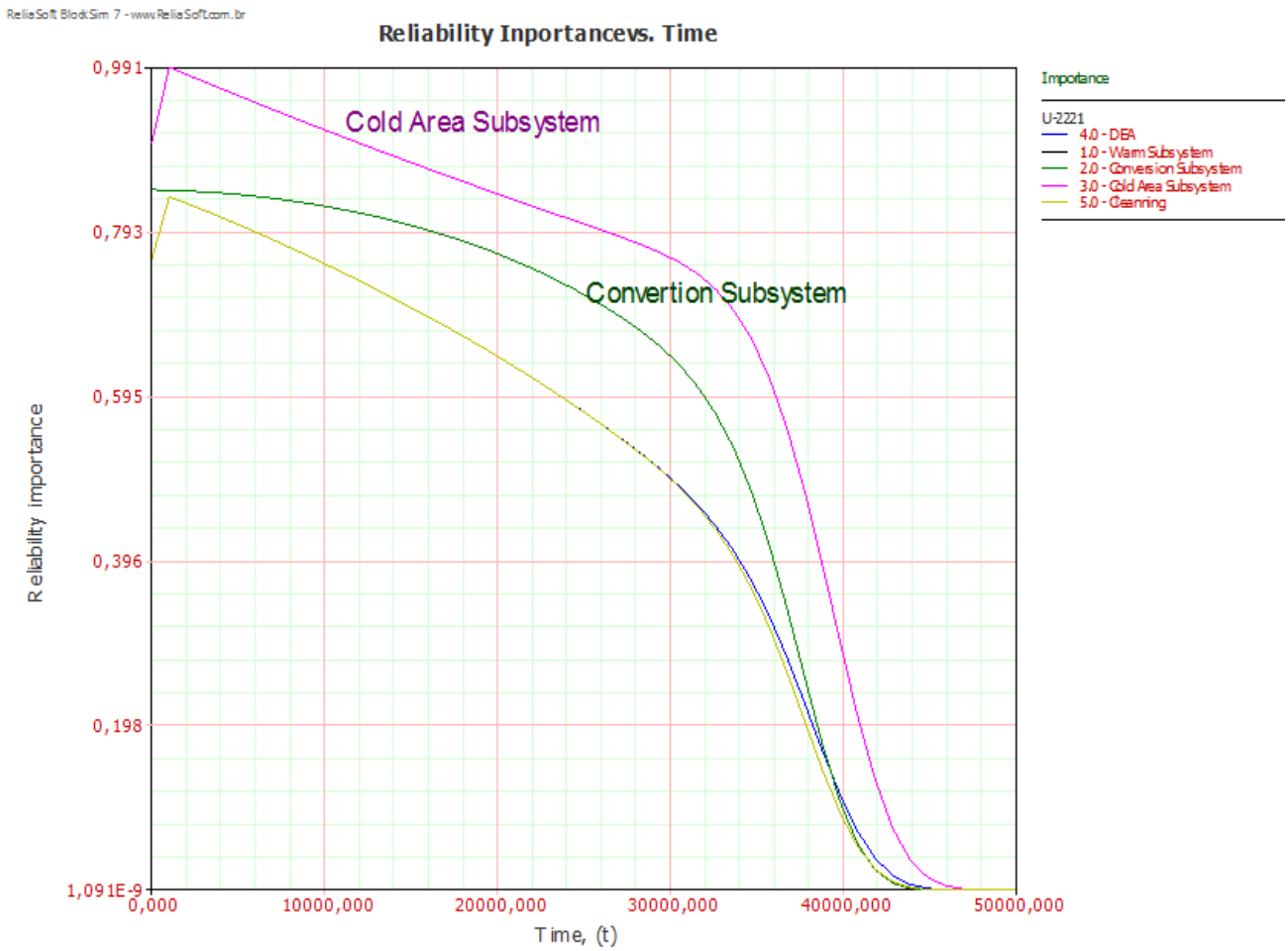

Figure 8 - IR (Reliability Index). Source: Calixto, E, et al 2012

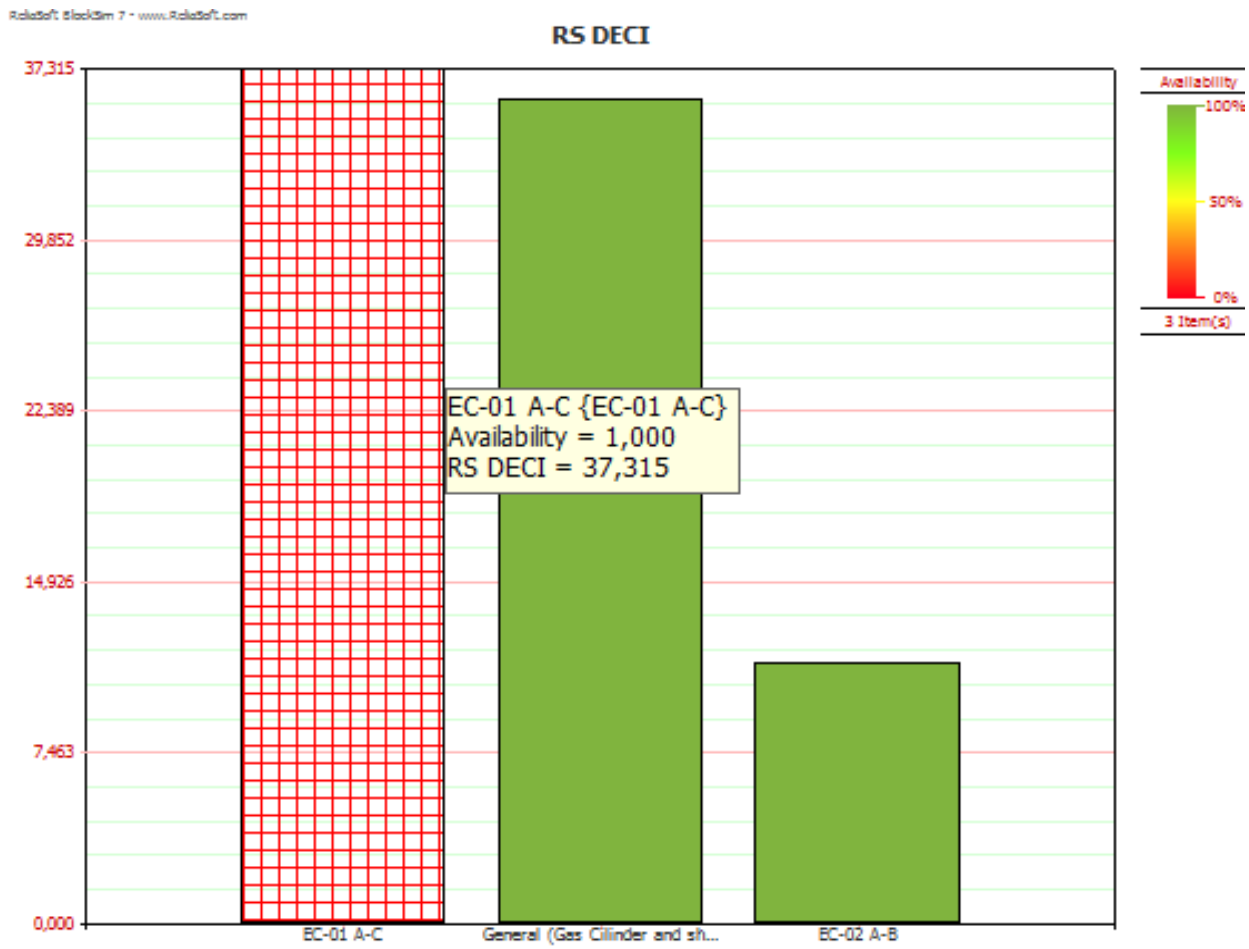

Figure 9 - DECI (Down Event Critical Index). Source: Calixto, E, et al 2012

5 - Sensibility Analysis: The Optimum Replacement Time

After critical analysis, it becomes clear that no improvement actions are required in the FCC system concerning the system operational availability target achievement. However, optimum replacement time assessment is required to decide when the compressors need to be replaced to reduce the operational cost and FCC shutdown risk. Therefore, the following assessment will be considered in the sensitivity analysis:

- Optimum replacement time;
- Phase block diagram analysis.

In the first case, it is necessary to assess each compressor and define the future optimum replacement time considering operational costs of the each equipment, which includes maintenance, purchases, and costs related to the loss of production. Despite k/n configuration, such compressors do not impact on FCC operational availability, but have increasing operational costs over time. Figure 10 shows the optimum replacement time philosophy based on cost point of view.

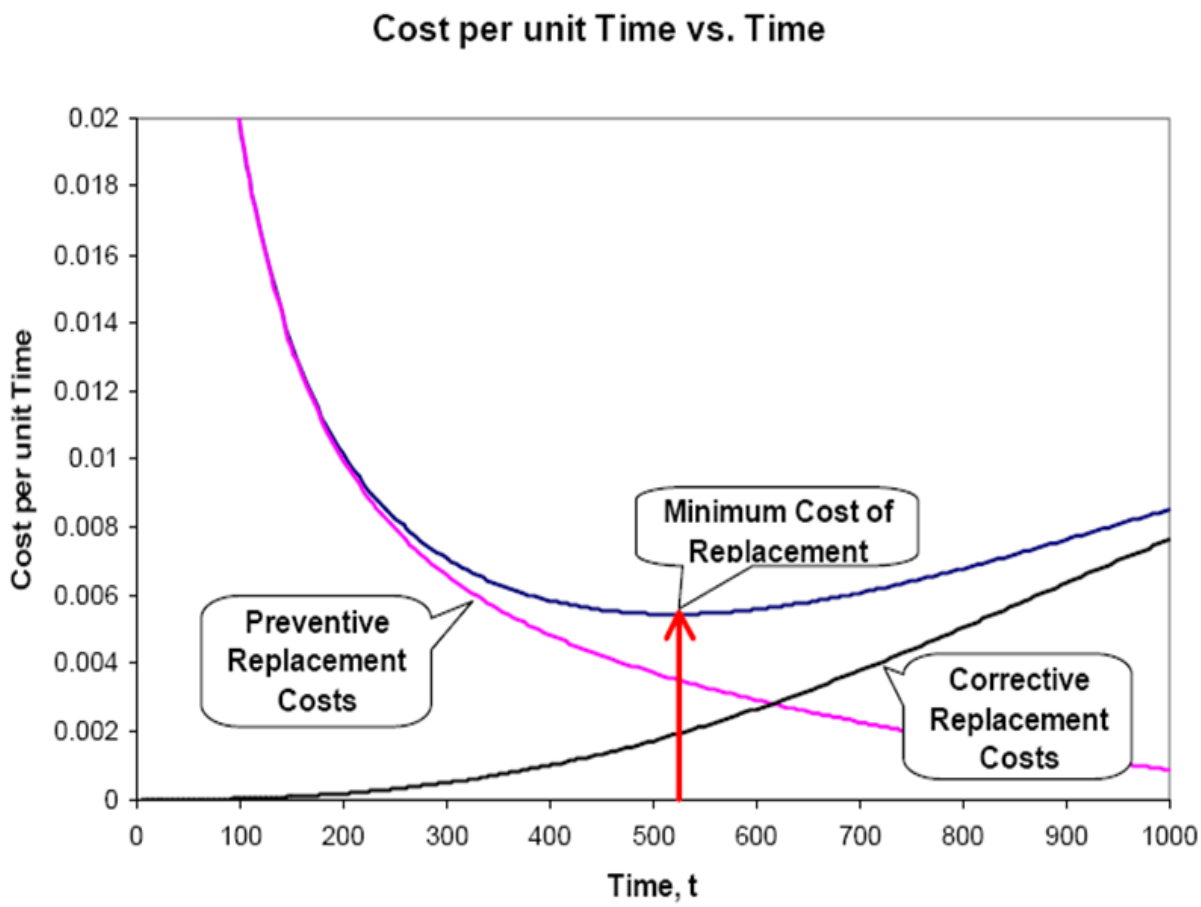

Figure 10 - Optimum Replacement Time. Source: Calixto, E, et al 2012

Indeed, the cost is not the only driver to be considered to replace and equipment. In addition to cost, it´s also necessary to access additional aspects such as future expected number of failures based on the proposed Crow AMSAA reliability growth analysis (RGA) model prediction. The complete approach to assess the best time to replace the equipment is described in figure 11.

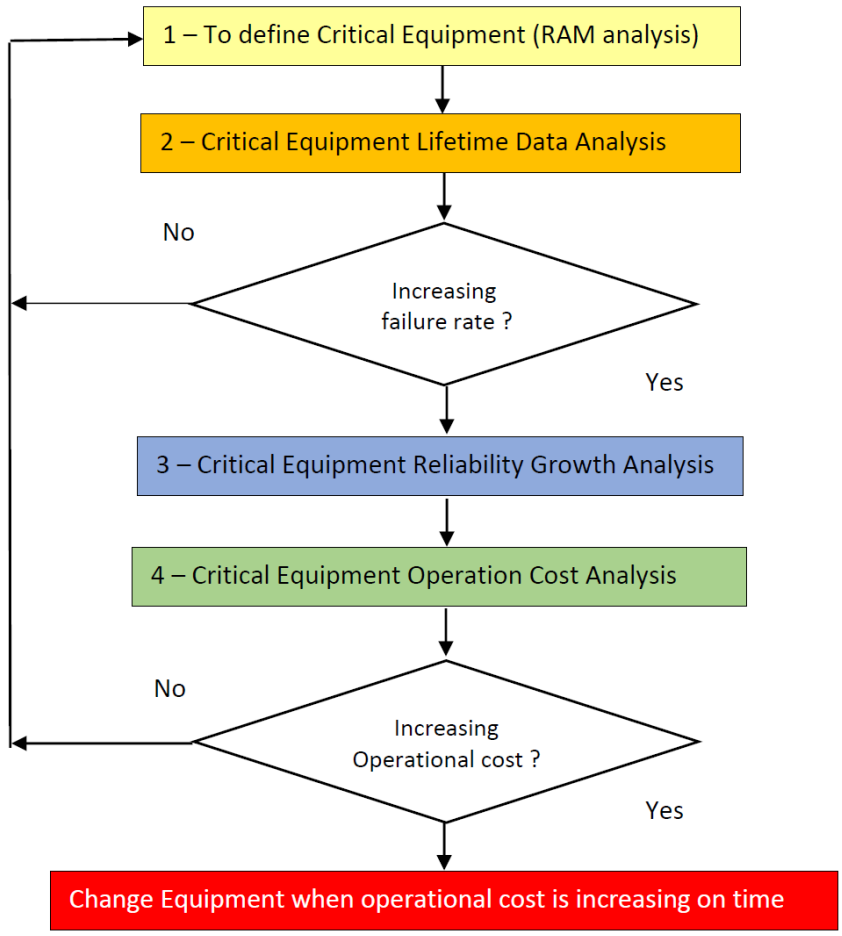

Figure 11 - Optimum Replacement time methodology. Source: Calixto, E, et al 2012

Therefore, by considering the compressor A, for example, the lifetime data analysis after overhauling revealed increasing failure rates for most of the components, as shown in Figure 12. However, the lifetime data analysis is not enough to decide if equipment must be replaced. The further step is to perform the Reliability Growth analysis and depends on the result, go to the step four and access the operational cost for the critical equipment.

The Compressor A reveals, based on the life cycle analysis, that after overhauling, there´s an increasing failure rates for the most of components as shows Figure 12.

The next step based on figure 11 methodology is to apply the Crow AMSSA Model. This model was introduced by Dr. Larry H. Crow in 1974, is a statistical model that uses the Weibull distribution parameter to describe the relationship between accumulated time between failure and test time. This approach is applied in reliability growth analysis to show the effect of corrective actions on reliability when a product is being developed or even in repairable systems during the operation phase. Thus, whenever improvements are implemented during testing (test-fix-test), the

Crow AMSAA model is used to predict reliability growth and the expected cumulative number of failures. The expected cumulative number of failures is represented mathematically by:

$$E(N_i) = \int_o^T \rho(t)dt$$

The Crow AMSAA model assumes that intensity failure is approximately the Weibull failure rate, thus intensity of failure on time is:

$$\rho(t) = \frac{\beta}{\eta^\beta} T^{\beta-1}$$

Using the initial failure rate as:

$$\lambda_i = \frac{1}{\eta^\beta}$$

if the cumulative failure rate is approximately the failure intensity we have:

$$\lambda_c = \beta \lambda_i T^{\beta-1}$$

The Time to failure is defined by the equation:

$$T_i = \left(\frac{E(N_i)}{\lambda_i}\right)^{\frac{1}{\beta}}$$

The preceding equation describes failure intensity during testing and depends on the β value its increase/decrease or remain constant over time. In fact, β is a shape parameter of the intensity failure function in the Crow AMSAA model. Thus, in this model when β > 1, the reliability is decreasing over time because failure intensity is increasing, or in other words, the corrective product actions are not improving the product. When β < 1, the intensity of failure is decreasing over time, or in other words, the corrective product actions are improving product reliability. When β=1, the product behaves as if no corrective action has taken place and intensity failure is constant over time. It is important to keep in mind that the b in the Crow-AMSAA model describes intensity failure behavior and has no relation to the Weibull distribution shape parameter. The growth rate in the Crow-AMSAA model is 1-β. The Crow AMSSA model assessment was applied for the compressor A as defined in figure 11 as step 3 of the Optimum Replacement Time methodology.

In case of equipment in operation the model considers the effect of preventive maintenance and replacement as well as all other operational effect on equipment performance.

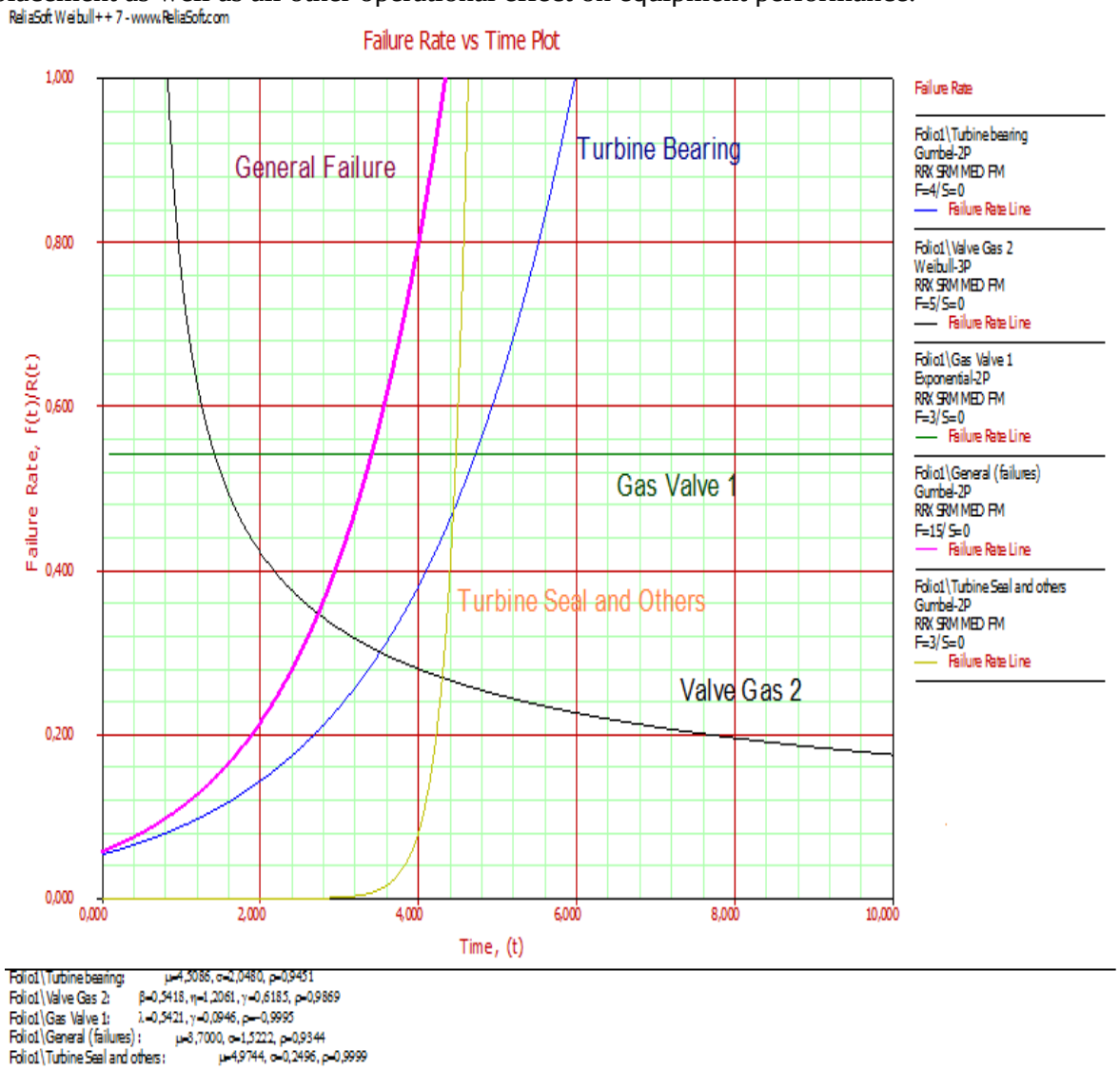

Figure 12 - Compressor A LDA failure rate functions. Source: Calixto, E, et al 2012

When β > 1, the failure intensity is increasing and MTBF decreases, or in other words, the preventive maintenance actions and replacement are not improving or recovering (as good as new) the equipment performance. When β < 1, the intensity of failure is decreasing over time and the MTBF is increasing, or in other words, the preventive maintenance or replacement actions are improving equipment reliability. That happens only if the equipment of some component is replaced for another one with higher reliability or in case of equipment re-design. When β=1, the equipment recovers the reliability to the state "as good as new" due to the preventive maintenance and replacement effect on the equipment. The intensity failure and the MTBF are constant over

time. The figure 13 shows the cumulative number of the failures. The figure 14 shows the MTBF rends.

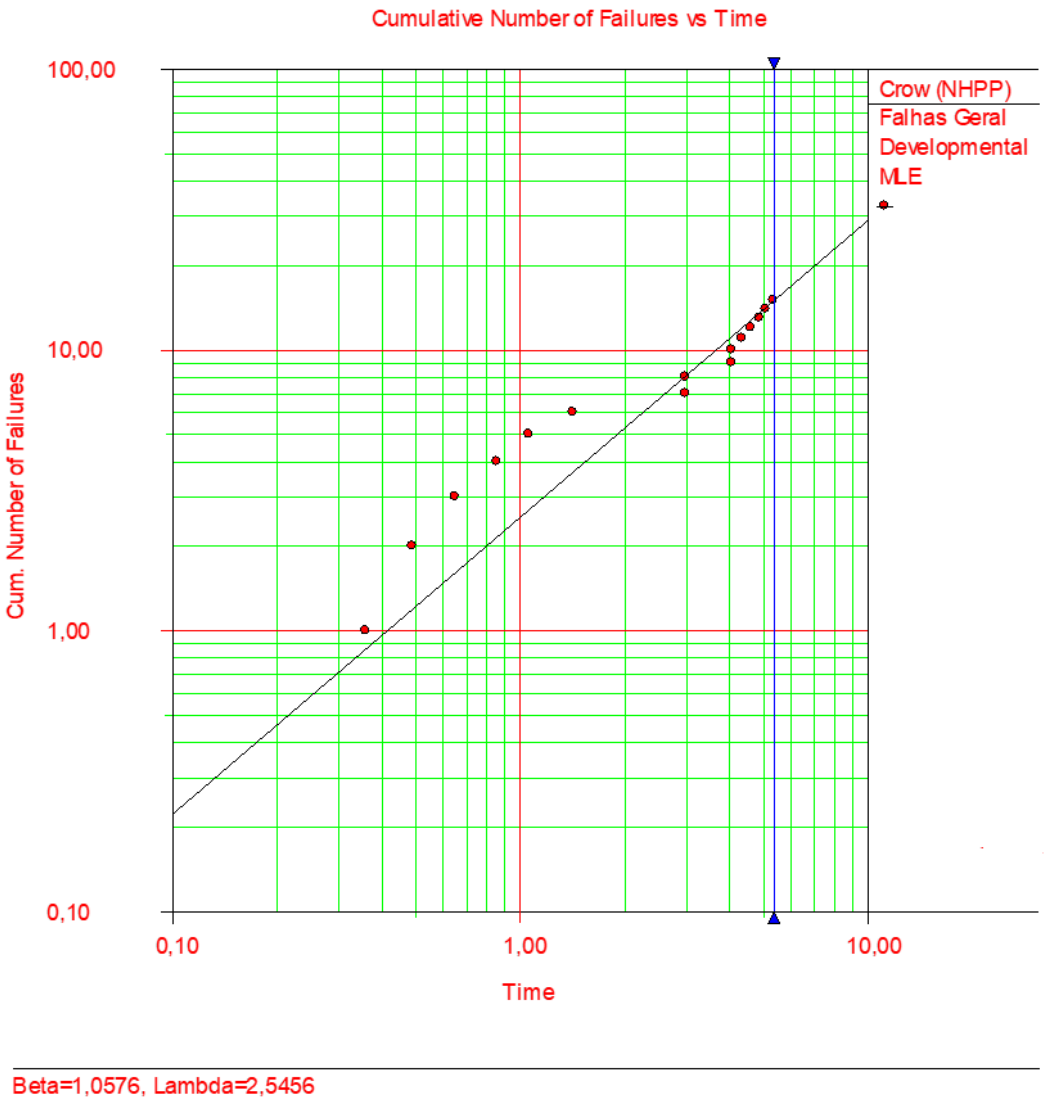

Figure 13 - Cumulative Number of failure vs time. Source: Calixto, E, et al 2012

Based on figures 13 and 14, the equipment performance decrease on time even with the preventive maintenance implementation. Therefore, it´s necessary to access the operational cost as defined in the figure 11 as the step 4 of the Optimum Replacement Time Methodology approach.
Therefore, the CROW AMSAA Model is applied to predict the future expected failure. By doing so, the total cost in a specific period of time will be described as:

$$C(t_r) = C(Ac) + E(N_t) \times C(M_t)$$

$C(Ac) = Acquisition\ Cost,$

$E(N_t) = Expected\ \ Number\ of\ Failure$

$C(M_t) = Maintenance\ cost\ per\ failure$

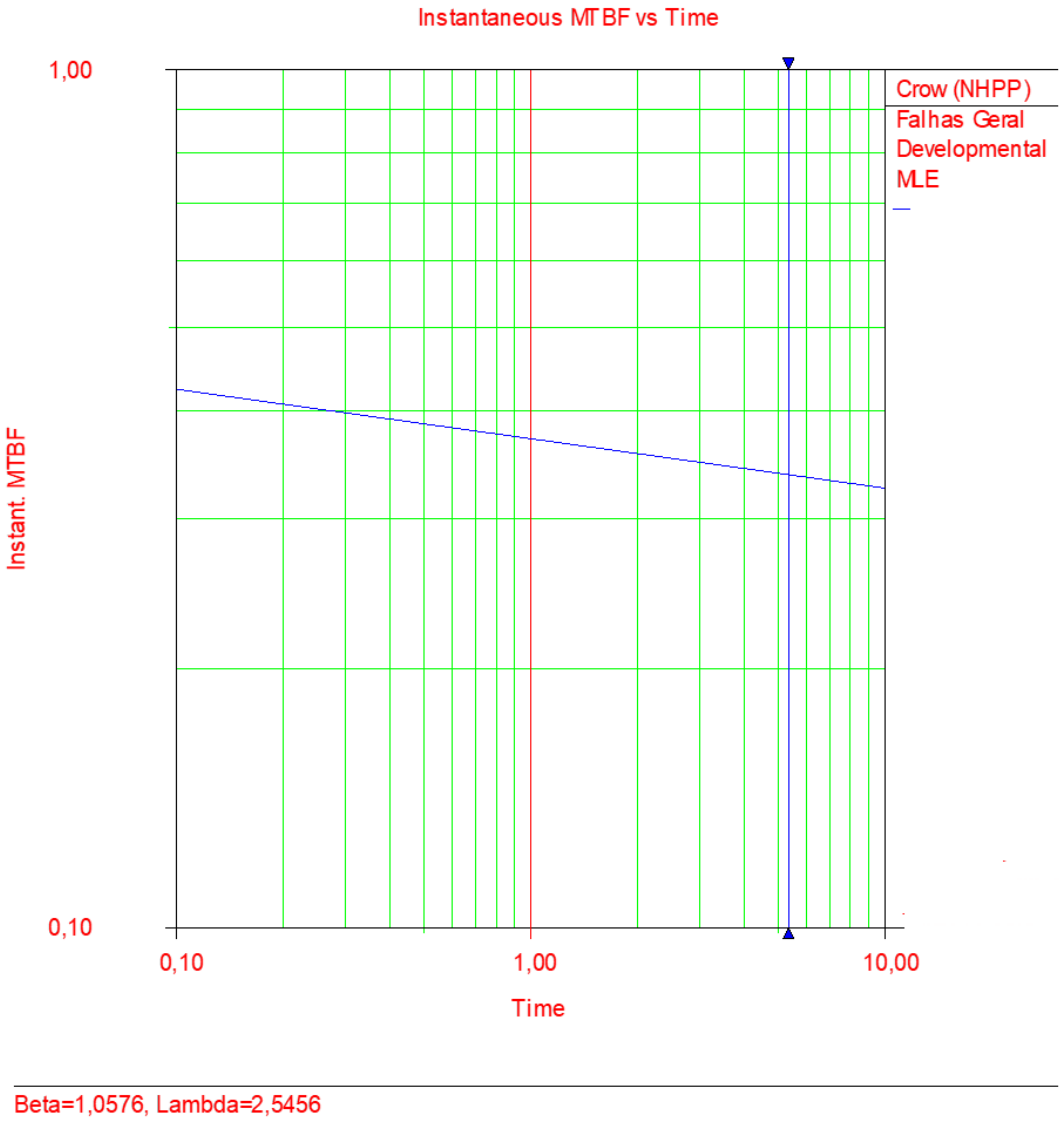

Figure 14 - Instantaneous MTBF vs time. Source: Calixto, E, et al 2012

Since the Optimum Time to replace needs to define the operational cost along time, the predictions of cumulative number of failures need to be brake down in interval of time that can be done based on graphic observation like demonstrated in figure 13 or defining the time to expected failure based on the equation.

$$T_i = \left(\frac{E(N_i)}{\lambda_i}\right)^{\frac{1}{\beta}}$$

Where,

$T_i = Time\ to\ failure$

$E(N_t) = Expected\ \ Number\ of\ Failure$ in time i

$\lambda_i = initial\ failure\ rate$

By applying this equation, the current cumulative number of failures plus one need to be the used as $E(N_t)$ value. Based on such definition and using the other equation parameter's values, it will be possible to predict when the next failure will occur (T_i).
Since the study case intend to predict the next five years of operational cost, the prediction will be based on five years interval of time.

$C(t_i) = C(Ac) + F(t_i)\ \times C(M_i)$
where

$C(t_i) =\ \ Operation\ cost\ in\ time\ i$

$C(Ac) = Acquisition\ Cost,$

$F(t_i) = failure\ in\ time\ i$

$C(M_t) = Maintenance\ cost\ per\ failure$

And

$F(T_i) = 1$

For each unit of time, the Marginal Operational cost is defined by the equation.

$$C(Mt_i) = \frac{C(t_r)}{t_i}$$

Where,

$C(Mt_i) = Marginal\ cost\ in\ time\ i$

$C(t_r) = Cumulative\ Operational\ cost\ in\ time\ i$

$C(t_r) = C(t_i) - C(t_{i-1})$

$t_i = Time\ of\ failure$

By plotting each marginal cost in a graph cost versus time, the optimum replacement time is defined by the operating costs increase point that is 4.5 years, as shown in Figure 15.

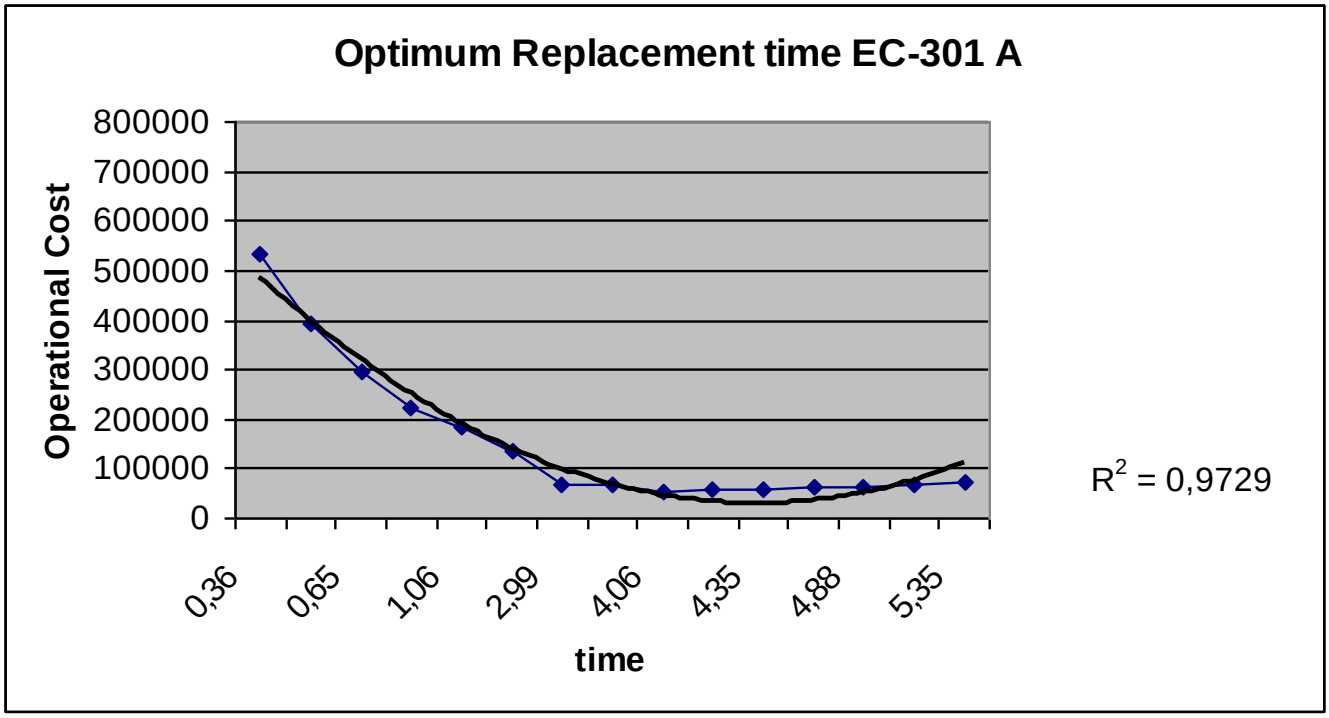

Figure 15 - Compressor A Life Cycle Analysis Source: Calixto, E et al 2012

The optimum replacement time was performed for other compressors and all of them presented increasing costs over 4 years and must be replaced.

The second and final sensitivity analysis uses phase block diagram analysis to assess the impact on system operational availability related to not replacing such compressors. The phase diagram methodology's main propose is to simulate the system in which configuration changes over time (simulation time). Thus, for the FCC system case, it was possible to simulate three scenarios, as shown in Figure 16.

The phase diagrams are simulating in three phases scenarios. The first one shows the system operating for the first 6 months without one compressor and the other 2.5 years with three compressors.

The second scenario shows the system operating with two compressors from 1.5 years over 6 months, and the third scenario shows the system operating without one compressor in the last 6 months of 3 years operation.

In the first case the system achieved 97.7% availability in 3 years, in the second case the system achieved 97.34% availability in 3 years, and in the third case the system achieved 98.49%

availability in 3 years. In these scenarios, 3 years of operation time were used because in the near future, such systems (FCC) will operate and supply other systems that operate for 3 years.

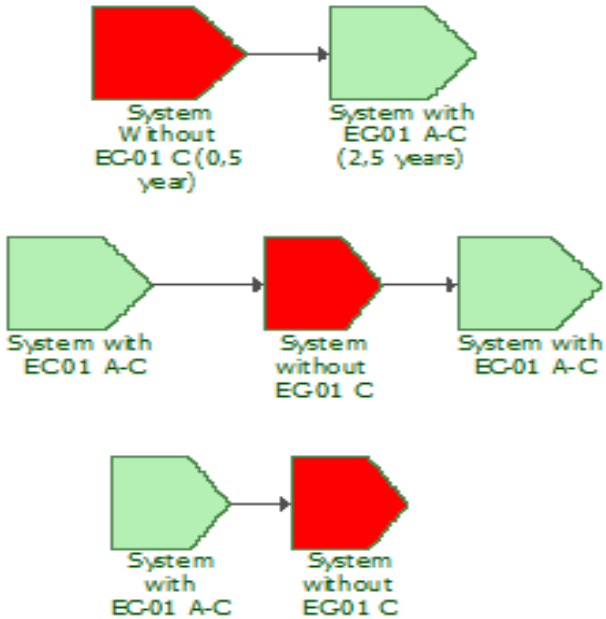

Figure 16 - System phase diagram for three scenarios. Source: Calixto, E, et al 2012

6 – Conclusion

The study achieved the main objective that was to identify if it´s necessary to replace any critical equipment, such as the compressor and support the decision of the best time to replace it if it´s necessary.

In order to carry out such assessment the Optimum replacement methodology was proposed as described in figure 11, which consider the definition of the critical equipment quantitatively based on RAM analysis methodology, lifetime data analysis implementation, reliability growth analysis implementation and operational cost analysis.

RAM analysis performed in the fluid catalytic cracking plant has shown that even when a system achieves its target it is possible to improve system performance from an economical perspective by performing optimum replacement time analysis for equipment with increasing operational costs. In addition, the phase block diagram methodology was applied to assess different system compressor shutdown scenario over time. It is a powerful tool for modeling systems that change their configurations over time.

Such methodology implementation requires a historical failure data of the critical equipment as well as detailed information considering operational cost.

The prediction of operational cost can be complex if the prediction of future expected failure based on CROW AMSSA Model is performed based on different equipment component and its failure

modes. By the other hand, such detailed approach may be well applied for the cases where only some components need to be replaced.
The prediction of operational cost can be based on the preventive maintenance, corrective maintenance or both. This case study considers a worse case scenario where the preventive maintenance does not avoid the failures in the equipment. Its also need to be considered that since the events are considered in equipment level, its not possible to have a details information about the effectiveness of the preventive maintenance for each component. However, it can be done for a more detailed study.
The proposed methodology will be applied to other aged critical equipment to define the best replacement time.
The replacement of age asset is a big challenge which Oil and Gas industries as well as other industries are facing nowadays. The decision of replacing or let such aged equipment in operation may affect not only the asset performance, but also the economic performance as well as safety. Therefore, a structure, methodology is necessary to be implemented.
In order to have a consistent decision, it´s necessary to have reliable historical failure data base which enable to collect the necessary information to perform the reliability engineering methods described in this paper.

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