Using statistical models in industrial equipment

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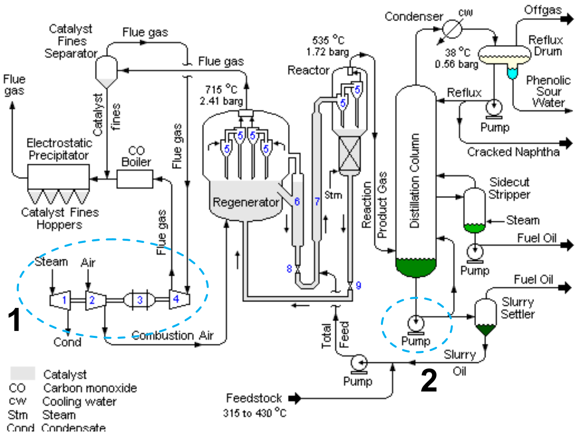
Abstract

Statistical methods are nowadays more and more useful in industrial engineering. From plant design reliability to equipment analysis, there is much to cover with statistical models in order to improve the efficiency of systems. At Sines refinery we used several approaches trying to relate several process variables with the vibration of critical equipment and to model time to failure using parametric and non-parametric models. Critical pumps are also a purpose of the study and we focus on a 2oo3 (two-out-of-three) structure in order to check if maintenance optimization or maintenance cost reduction is possible, and thus, it will be included the study of the operation of some rotary equipment.

1. Introduction

As industries became more competitive, they have to find methods to improve results, reducing costs, improving availability, and mainly, knowing exactly where the problems are. Understanding equipment behaviour helps companies to manage spare parts, man-hours and maintenance issues that will improve reliability and save money. Companies must to find their weakness and find there the opportunity to grow. Reliability Centered Maintenance (RCM) is a methodology that helps organizations to find and focus on the real problem. We know that there will always occur equipment spurious failures, and although efficiency can be achieved with technology, it only can be reliable based on the fact that the system is prepared for failures, managing them the best way. In order to do this, the starting point is to ensure that companies have reliable failure registries data. ISO 14224:2006 (ISO 14224:2006 (2006)) is a petroleum and petrochemical standard that indicates the better way to achieve quality data normalizes equipment boundaries to report failures, statistical parameters, among others. Getting close to the standard will be useful for the Company to compare itself with others in the same industry. At Sines refinery rotary equipment (pumps) justifies our attention. These pumps are the slurry feed pumps of the FCC unit. In this study we meant to study their behaviour and try to relate the failures with maintenance schedules in order to optimize it, if relevant. Sines refinery has been concerned as well with the shut-downs (spurious failures) made by the Turbo-Expander (TE) equipment in the Fluid Catalytic Cracking unit (FCC). As it was having problems due to a vibration failure mode causing FCC unit shut-down since year 2000, it was decided to investigate the origin of the vibration, as it is a big economical issue (Gladys, N., Laura, V. (1999) and Diangu, H. (2011)). TE manufacturers highly recommend investigating efficiency in order to detect scaling deposition in TE rotor blades. It is believed that the composition of some particles resulting from process reaction are the key for scaling, not just erosion. Although the problem has not been revealed in the year 2011, just after the turnaround, it had returned in 2012. However, as previous results in this matter were not definitely conclusive (Madeira, S. et al (2013)), we focus on models that could explain thresholds of vibration as well as times to failure. Cox proportional hazards (Cox D, Oakes D. (1984)), parametric approaches (Rausand, M., Hoyland,



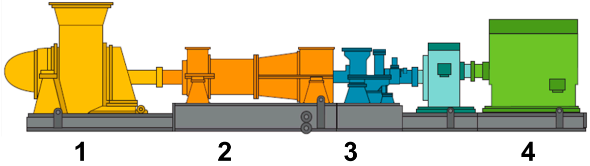
1 – PRU
2 – FCC Feed Pumps

Picture 1 – FCC typical flow diagram

A. (2004)) as well as multinomial and ordinal models (Agresti, A. (2002)) had shown that some variables are, at least, coherent in all tested models and we can conclude that they are related with deposition or vibration (denounce deposition or contribute for it). Following study will be divided in two parts: analysis for Turbo-expander and analysis for the FCC feed (slurry) pumps.

2. *The Power Recover Unit and the TE*

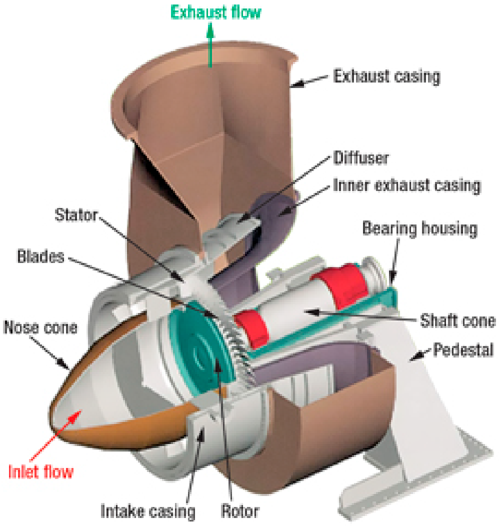
The Power Recover Unit (PRU) is composed of a TE, a main air blower, a turbine, a gear box and a motor/generator which recovers the flue gas from the process to generate energy and steam.



Picture 2 – Power Recover Unit

1 – Turbo-Expander
2 – Main Air Blower
3 – Steam Turbine
4 – Motor Generator

At Sines refinery we can find a particular configuration of the PRU as shown in Picture 2. This configuration brings an additional problem to the system. The fact that the expander is coupled with the other equipment leads to unwanted shut-downs of all FCC units whenever the expander has a shut-down. The vibration failure mode is the main reason for the problems in the expander. This equipment is supposed to have a reliability of 99%, and its only intrinsic failure is vibration. The Turbo-Expander in picture 3 is composed of the nose cone, the rotor blades, the stator ring, the shaft and the casings.



Picture 3 – Turbo-Expander

Process flue gas reaches the expander rotor blades at a pressure of about 2.1 barg and a temperature of 700° Celsius degrees. The flow at this pressure and temperature is here transformed into mechanical energy, making the rotor blades rotate as well as the shaft at approximately 5700 rpm, held by the steam turbine. This mechanical energy is thus transformed in electrical energy through the generator that is coupled with the expander in the same shaft.

2.1 *Variables of interest*

Since the beginning of our study several variables were chosen and tested, but, as long as the models were being accurate, some variables were coming in and out as the events were occurring. We must keep in mind as well the instrumentation that read some process variables and that are crucial for the study but not for the process may be sometimes out of service or damaged, which complicates the analysis. Thus, only variables of interest will be mentioned here, as long as they comply with the model's assumptions and contribute in an explanatory point a view. Vibration, temperatures, size and density of the particles in flue gas are some examples. However, only a few are coherent with all approaches and lead us to the conclusion that despite the randomization of the deposition, they have a contribution for what is happening. Some experiences are currently taking place in order to understand some pattern for scaling, but so far, there is no conclusion.

2.2 *Tested Models*

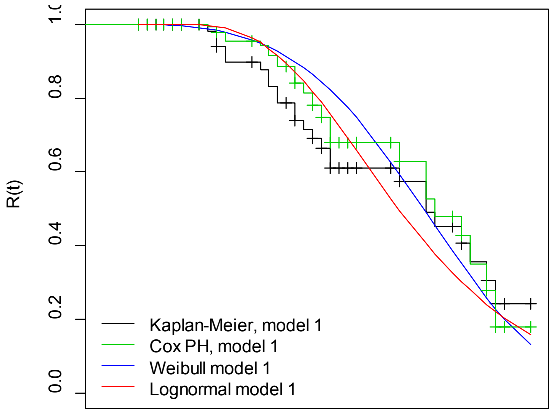
A first approach was to use a non-parametric approach (Kaplan-Meier and Cox Proportional Hazards) to understand the real behaviour of times to failure (vibration above the upper threshold). A pattern for high vibration values can be found for some periods over time, but not exactly for times to failure. This becomes even more complex when we consider that different operation procedures are taken over time, which could bias variables values and not guarantee the "equal process condition". This happens mostly because operation is trying to find an ideal scenario to avoid the spurious failures, once times to failure longer than t_1 are very rare. Thus, considering only times shorter than t_1, we can adjust a new Kaplan-Meier null model and a Cox model as shown in graph 1. The Cox model could be written as:

$$h(t) = h_0(t)\exp\left(\beta_1 x_1 + \cdots + \beta_p x_p\right) \qquad (2)$$

where $h_0(t)$ is the baseline hazard and the relation between the β_i and x_i is as follows:

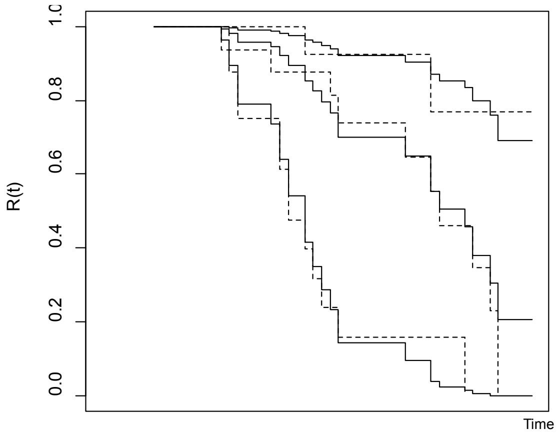
x_i (covariates)	β_i p-value
tpin (inlet temperature)	0.0012
abd (aparent bulk density)	0.0071
sa (surface area)	0.0039
*abd*sa* (interaction 1)	0.0051

Table 1 – Significant covariates, model 1



Graph 1 – Model adjustment's for times until t_1 – approach 1

For times until t_1, in a parametric approach, the same covariates that have been used in the Cox model appear again as the most significant. Weibull model (graph 1) as shown to have the best fit according the AIC criterion (275.49 for Lognormal and 208.98 for Weibull). Although the model overestimates reliability in the beginning, predictions for the Cox quantil intervals for model 1 are satisfactory (graph 2). For the Cox PH assumption was verified trough Shoenfeld residuals and Harrell's test. As all variables are continuous, functional form was verified too.

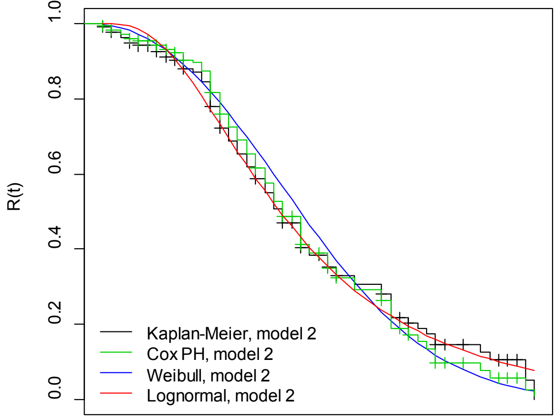


Graph 2 – Prediction of quantil intervals for model 1

Frailty models with different distributions were tested but no significance was revealed for frailty covariates using Gaussian and gamma distributions. A second approach was to use the "high vibration" as a failure mode itself. This means that always the vibration values are upon a certain value considered "high", it counts like an event (that is, a failure). The results are slightly different in this case, with two more covariates than in the previous model (table 2). Again, Weibull distribution seems to have the better approach according to the AIC criterion (777.04 for Lognormal and 764.56 for Weibull), despite that visually, they are very close (graph 3).

x_i (covariates)	β_i p-value
tpin (inlet temperature)	<0.0001
abd (aparent bulk density)	0.0038
sa (surface area)	0.0030
cf (coke factor)	0.0023
gf (gas factor)	0.0033
*abd*sa* (interaction 1)	0.0045
*cf*gf* (interaction 2)	0.0011

Table 2 – Significant covariates, model 2



Graph 3 – Model adjustment's for times until t_1 – approach 2

Frailty models were tried as well for this approach with better results, but yet, not completely adequate. Times above t_1 will be discussed in another opportunity because of its random nature. Probably, a constant hazard rate will be adequate. In order to consolidate the results of these models, it was made a data analysis, which consisted in a simple linear model to analyse vibration values, as well as to check vibration values distribution. Again, we found common covariates with previous models revealing effects directly in vibration values through a multinomial model, with an R^2 of about 20% and acceptable results in the residual analysis.

$$vibration = \beta_0 + \beta_1 na + \beta_2 sa + \beta_3 dt \qquad (3)$$

where

na is the sodium present in the particles, and *dt* is the differential temperature (*tpin-tpout*), which is the inlet temperature minus the exhaust temperature. Here, we have again highly significant, the size of the particles, *sa*.

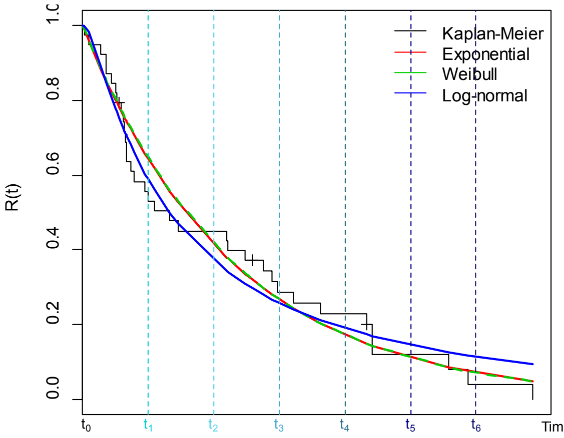
3. FCC feed pumps

FCC feed pumps are those that feed the main column to the reactor, so, if they have low performance, a shut-down can occur to all FCC unit. Due to its relevance, these pumps work on two-out-of-three scheme as they are critical equipment in this plant unit. As a consequence, we decide to evaluate its behaviour, once, in this case, availability it's a crucial issue. Equal pumps are supposed to have the same performance. However, we will see next that it does not occur. Thus, we use two approaches: on the one hand we study the reliability of the three individual pumps and on the other hand we study the reliability of the system of the three pumps.
A system as mentioned will be successful if any 2 out of the 3 components is successful. Data for mechanical failures were collected and analysed. The registry of the working times of the pumps is made in working hours, and all three pumps have similar working hours in its registry, which means that they have worked the same amount of time. Theoretically we are supposed to find the same distribution for the reliability of the three pumps. In graph 4, from all tested models, the exponential distribution have lowest AIC, and seems to be adequate according to real data. In table 3 we can see the reliability for independent times equally distributed. Instead, if we analyse the pumps individually, we found that none of the tested distributions (Exponential, Weibull and Lognormal) fits well the data (graph 5), except for pump 1, which has a reasonable adjustment for all tested distributions. If a distribution for each pump was found, we can write the reliability of the system as following:

$$R(t) = R_1 R_2 (1 - R_3) + R_1 (1 - R_2) R_3 + (1 - R_1) R_2 R_3 + R_1 R_2 R_3 \qquad (4)$$

where

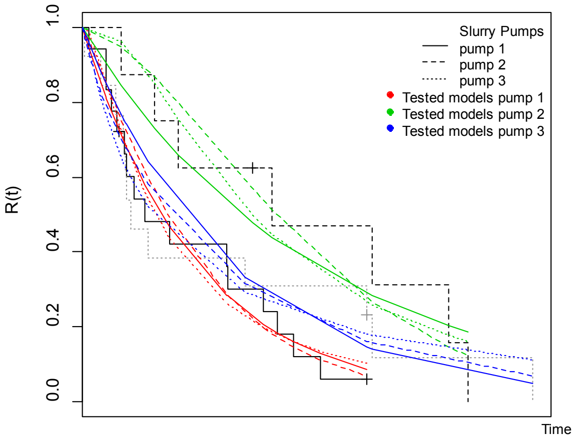
R_i is the reliability of each pump calculated with the corresponding distribution, i=1,2,3



AIC (exponential) = 661.47550817614
AIC (weibull)= 663.46707109021
AIC (lognormal)= 666.490247737104

Graph 4 – Model adjustment for the system

Pump 1 and 3 are responsible for the initial slope of the curve in graph 4. Although similar, these pumps are physically working with a layout that benefits pump 2.



Graph 5 – Kaplan-Meier and model adjustments for each of the 3 pumps

Time	***Reliability for the system (KM)***	***Reliability for the system (Exponential)***
t_0	1	1
t_1	0.528	0.644
t_2	0.432	0.414
t_3	0.282	0.267
t_4	0.240	0.172
t_5	0.099	0.111
t_6	0.035	0.071

Table 3 – Reliability for the 3 pumps for some time instants equally distributed, using exponential distribution and Kaplan-Meier adjustments.

4. Conclusions

With respect to turbo–expander we can conclude that variable *sa* seems to give an important contribution for scaling. Thus, monitoring the particles analysis related with the mentioned variables (*sa* and temperatures) seems to be a good start to predict scaling. However, it cannot prevent high vibrations or shut-downs. In order to prevent scaling, a maintenance procedure has been carried on since December 2013, that is, to do a scheduled thermal chock, to check whether or not it reduce deposits. Future work will relay on that results.

For the FCC feed pumps we can say that reliability can be improved if pump 1 and 3 have the same reliability values than pump 2. An RCM policy started to be implemented with the study of a small unit at Sines refinery and that could be a plus for the management for several situations, including this one. ISO 14224:2006 is now being studied in order to apply and comply with its assumptions and recommendations. These studies are being enlarged and we expect to cover all critical pumps of the FCC unit and other important pumps or compressors until the end of the year, as well as the adaptation of the best practices from ISO 14224:206.

Acknowledgements

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