Contributions to the implementation of a RAM methodology in AdP Group infrastructure

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Abstract

A good strategy in Asset Management has a big importance because it is indispensable to guarantee the useful life and the availability of the equipment and infrastructures to be managed. Thus, it is necessary to value the question of maintenance being one of the areas with high importance in the strategy of competitiveness of a company, since the actions carried out have direct impact on costs and quality of the services provided. In fact, good management of physical assets will only be possible through active and persistent but careful and thoughtful maintenance management, to ensure the availability and speed of response of the necessary means to the maintenance operations, ensuring an adequate cost management.

In the scope of maintenance management, this dissertation intends to promote an improvement in the management of corrective maintenance actions in the equipment present on Grupo Águas de Portugal infrastructures. Due to the importance that these equipments have for the operational activity of the infrastructures, and in response to the large investments made in the acquisition phase, it is in the best interest to guarantee the best possible availability in order to ensure the operability of the infrastructures as well as an optimization of the investments, question increasingly pressing.

This dissertation focusses on the definition of solutions that allow a better monitoring and analysis of corrective maintenance performance in the equipment of infrastructures type lift stations at Grupo Águas de Portugal, namely in the development of methodologies for the calculus of the availability and reliability as measures of its operational performance.

In the case study performed a methodology of equipment's failure criticality classification is developed, taking account on factors such as the frequency and severity that will allow a critical analysis to assets failure and respective prioritization. A model was also created through a block diagram, where it was possible to obtain the availability and reliability of the infrastructure. Finally, corrective actions will be proposed to act on infrastructure and equipment's reliability and availability restitution

Keywords: Maintenance, physical assets management, Availability, Reliability, failure criticality, severity, frequency

1. Introduction

The Grupo Águas de Portugal is composed by twelve companies. Their activities includes project, conservation and exploration of infrastructures inserted in all the extension of the urban water cycle, since its catchment, treatment, distribution until the exhaust on the receptor environment. The two principal business areas, water supply and sanitation of residual waters, differ from each other on the functioning and type of infrastructures existing on the process.

There are 1155 catchment units, 157 water treatment plants, 992 waste water treatment plants, 2719 lift stations scattered throughout Portugal. The latter are responsible for the elevation of the fluid on the process, which is developed taking advantage of gravity, or when water is needed at a higher height [1].

This paper deals with maintenance management of equipment's and infrastructures of the Group. This area assumes a critical relevance, being the main source of income for the companies, reason why is so important the maximization of the availability level as a payback on the large investments made during their acquisition phase.

To guarantee this operational availability, certain operating conditions need to be assured, such as water discharges minimization on lakes, bays or rivers, and ideal conditions for equipment's operation. This is only possible due to an efficient maintenance level on the equipment's by monitoring reliability and availability indicators and allocate certain mitigation actions as a response to the values obtained.

The main goals for this paper emerge from the previous scenario described and consist on the definition of a methodology and solutions, which ensure an efficient equipment's management in order to guarantee the best commitment possible between the network operationality and operational availability. These objectives can be achieved through the concretization of certain assumptions:

- Acquisition of equipment and component's maintenance historic enabling reliability analysis.
- Development of a failure criticality classification model on components taking account aspects as failure's frequency and severity (which regards functional, economical and operational standpoints).
- Development of a reliability block diagram capable of stablishing the functioning of the complex system as a connection of several less complex subsistems allowing a reliability and availability analysis as well as identification of replacement needs.
- Capability of monitoring reliability levels on equipments aiming mitigation actions for reliability and operating conditions restitution.

These objectives contribute to the ultimate purpose, which is improving and monitoring the equipment's availability and reliability, and consequently a better maintenance management in Group.

2. Methods

The methodology explicit in this paper consists on a Reliability, Availability and Maintenance - RAM Analysis (figure 1) applied at the Jamor Lift Station (inaugurated on April 1998). Due to the lack of appropriate data regarding other infrastructures, it was chosen this one.

As an input, all the data regarding maintenance interventions on the infrastructure was analysed and the operating time of the equipment's was recorded.

Although the study was based on this infrastructure, the developed methodologies can also be applied to the remaining ones, with the respective changes, due to the differences on the process (functioning lines), and consequently on the equipments installed.

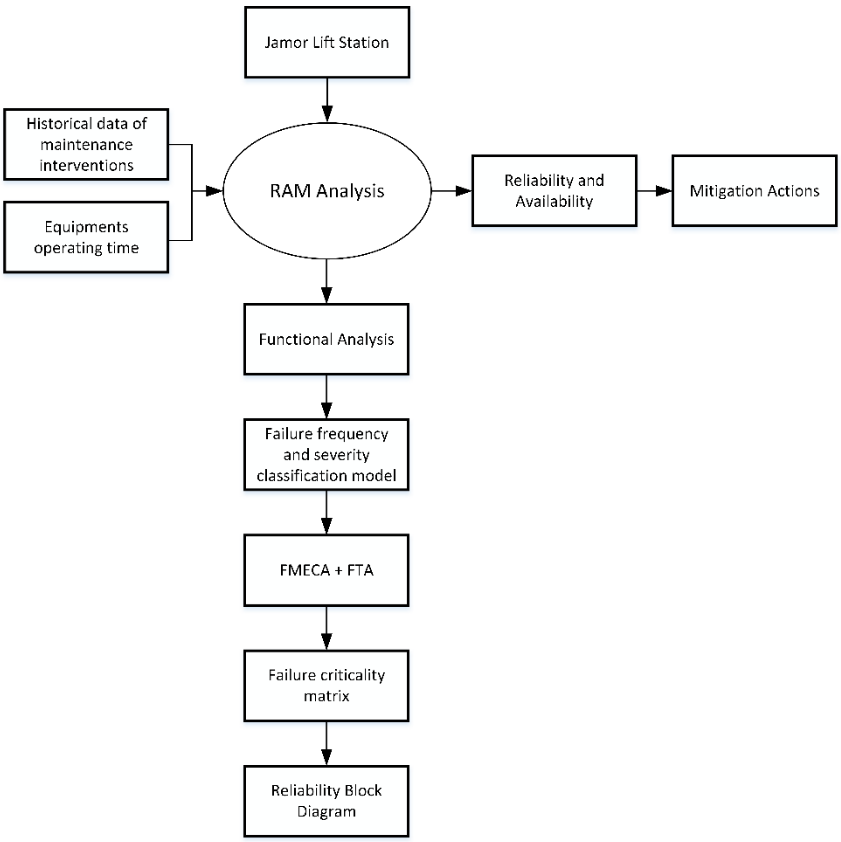

Figure 1 - Methodological scheme

The methodology was developed in five different phases [2]. First, a functional analysis of the infrastructure was made identifying the main function as well as all the twelve subfunctions responsible for the concretization of the main one. This is a very important step because every subfunction corresponds to a certain phase of the process in which certain equipment's are required. In the future, when applying the method to the different typology of infrastructures, new subfunctions will have to be added or deleted (depending on the equipment's installed), avoiding major changes.

The second phase allows the criticality classification failure regarding aspects as frequency (in terms of time between failures) and severity (considering three relevant aspects – economical, maintenance efficiency and risk of failure in an operational point of view).

In the third phase, it´s performed a Failure Modes, Effects and Criticality Analysis – FMECA, which consists on the identification of the several failure modes and respective effects (on the infrastructure) associated to the subfunctions highlighted previously on the functional analysis. For reliability and availability analysis the infrastructure failure must be defined, however, this failure doesn't occur with just a failure of a certain equipment but with the reunion of several simultaneous failures, reason why it is needed a Fault Tree Analysis – FTA, exposing these events.

With the failures rated in terms of criticality it's possible to plot a "frequency vs severity" chart in order to rank them as less critical, critical, and high critical for the mitigation actions afterwards.

The fifth phase is the construction of a Reliability Block Diagram – RBD – with all the equipment's which failure was ranked as critical or high critical.

With the RBD defined it's possible to get the Availability and Reliability for the system. For this analysis was resorted exponential probability distribution as the statistical analysis model. The choose of this model was based on its simplicity of calculus assuming that the infrastructure stands in useful life on the bathtub curve.

Then the reliability of the system was plotted through time, in this case, considered 20 years. With this result it was possible the allocation of mitigation actions in order to restore infrastructure's reliability.

3. Data for Analysis

The data basis provided regarding corrective maintenance in Jamor Lift Station counts with 350 registrations from an interval of 114 months (since January 2010 to June 2018). As each infrastructure is composed by different equipment´s classes, it's necessary the registration of the corrective order (on the maintenance management software) at the level 8 (at least) from a total of 9 levels of localization codes. In fact, regarding to localization codes, level 6 stands for infrastructure, level 8 refers to the equipment's and level 9 stands for components of the equipment's identification.

Contrary to the previous scenario, all these records were made until level 8 of localization code, allowing the allocation of a maintenance order to a specific equipment. Thus, a separation of incidences between equipment classes was possible in order to diagnose which type of equipment fail more often. In this case, the classes bomb and sieves, revealed to be the most critical in terms of failure with 20 and 16 percent of the total occurrences, respectively. As none of the regists were made until level 9, a component identification became impossible, having to analyse description fields as "Order Description" and "Localization Description" to identify which components were intervened and to be able to construct the block system to get the fiabilistic indicators.

The next step consisted on the calculus of the Mean time Between Failures (MTBF) and the Mean Time to Repair (MTTR) associated to each intervention. For each equipment (and component) it was obtained several MTBF and MTTR (corresponding to the intervals between failures, i.e., a "number of failures -1" different values were obtained, having to consider an average value for these two parameters.

Regarding the equipment's operating time, most of them were obtained through an hour counter installed on the respective electrical boards. However, for some equipments whose operation is discontinuous, by actuation, an operating time needed to be estimated. For this reason, the number of actuations was calculated (based on the number of exhausts occurred within the period of time considered) and multiplied for the duration of this interventions (validated by the Maintenance Department).

4. RAM Process

To analyse the Jamor Lift Station reliability it was used an exponential probability distribution as statistical model of analysis. It was chosen this type of distribution given its ease of calculation becoming a power tool to the methodology implementation.

4.1. Functional Analysis

The first step of a RAM analysis consists on the creation of a functional breakdown from the main function to the subfunctions that articulated together ensuring the concretization of the main one. The main objective of this tool is to identify all the functions that the system must perform to meet the requirements as well as the critical components associated with these basic functions. Among others it was possible the identification of 5 critical functions with the correspondent equipments (also considered critical).

- **Control caudal inlet at the lift station**
    - Wall Valve entrance
    - Pneumatic actuator for Wall Valve
    - Control Valve frame for the pneumatic actuator.
- **Solid Removal**
    - Sieving grill
    - Lifting screw
    - Electric motor
    - Level probe
- **Electrical energy delivery**
    - Alternator
    - Diesel Motor
    - Transformation Substation
    - General Electric board
- **Pneumatic energy delivery**
    - Hydraulic piping circuit
    - Compressed air reservoir
    - Safety Compressors
- **Water Lift from the pumping well**
    - Aspiration zone
    - Pumping bomb
    - Compression conduit
    - Frequency variator
    - Partial electric board

4.2. Failure frequency and severity classification model

The criticality level of each Failure Mode (FM) is calculated according to the expression (1) and consists on the classification used in the railway norm.

$$criticality = Frequency * Severity \tag{1}$$

The first indicator consists on the frequency of failure measured in terms of MTBF of the equipments and the second one, severity, is measured as a combination of three different factors (MTTR, reparation cost and risk of failure) reflecting maintenance efficiency, economical and influence of the processes concerns.

Both indicators have a scale range from 1 to 5, defined internally at Group, causing a criticality range from 1 to 25. According to its level, failure criticality is divided by zones representing low, medium and high criticality's failure.

A criticality under 5 is considered low critical, and mitigation actions are optional. In another way, a criticality situated between 5 and 13 is considered medium critical, and mitigation options are considered recommended. A criticality over 13, reflecting high critical failures, mitigation actions are considered mandatory.

4.3. Failure modes, effects and criticality analysis

The FMECA uses the results of the functional analysis as input, and it consists in four main phases [3]:

- Identification of all the FM associated with the basic functions described before.
- Recognition of causes and effects of the FM on the overall function of the infrastructure.
- Qualitative assessment of the occurrence of causes and severity of effects.

As a next step there is a prioritization of risks as a function of criticality of the FM, that will be defined further in this paper, in a criticality matrix.

This study began with a list of all the basic functions and respective FM associated listed below:

- **Control caudal inlet at the lift station**
    - Caudal is retained at the entrance
- **Solid Removal**
    - Do not remove solids
    - Remove solids partially
- **Electrical energy delivery**
    - Total loss of electrical energy
    - Partial loss of electrical energy
    - Voltage drops
- **Pneumatic energy delivery**
    - Pneumatic energy doesn’t arrive to equipment’s
    - Pneumatic energy with production problems
    - Problems in pneumatic-mechanic energy conversion
- **Water Lift from the pumping well**
    - Presence of debris at the fluid
    - Do not lift
    - Do not lift the desired caudal.

The next stage was to identify which were the causes (which equipment failures are responsible for the functionality loss) and effects (consequences of the functionality loss) related to the FM described before.

The causes of failure were already described on chapter 4.1, knowing that every component failure could cause loss of functionality of the correspondent basic function. Regarding failure effects, they were more diverse, however, for the study made only “Exhaust on the receptor environment” was considered as ultimate failure.

Recognizing that an isolate failure of a certain equipment doesn’t compromise the function of the lift station, a Fault Tree Analysis – FTA development was needed in order to expose the cumulative equipment’s failure needed to this system failure occur. The results of this tool will be reflected on the Reliability Block Diagram.

4.4. Failure criticality matrix

Figure 2 represents criticality matrix, considering failure impact on Jamor Lift Station operation. Approximately half of the system failures occur on the yellow area (58.7% corresponding to 37 incidences) indicting a more careful approach (all the equipment’s described at chapter 4.1 correspond to this area). There isn’t any component at the red area (corresponding to a combination on high severity and frequency). In fact, its perceptible that severity is more pronounced then frequency - 67% of the data presented has a severity classification greater or equal to 3, while, for the frequency, only 3% of the data correspond to this criterion.

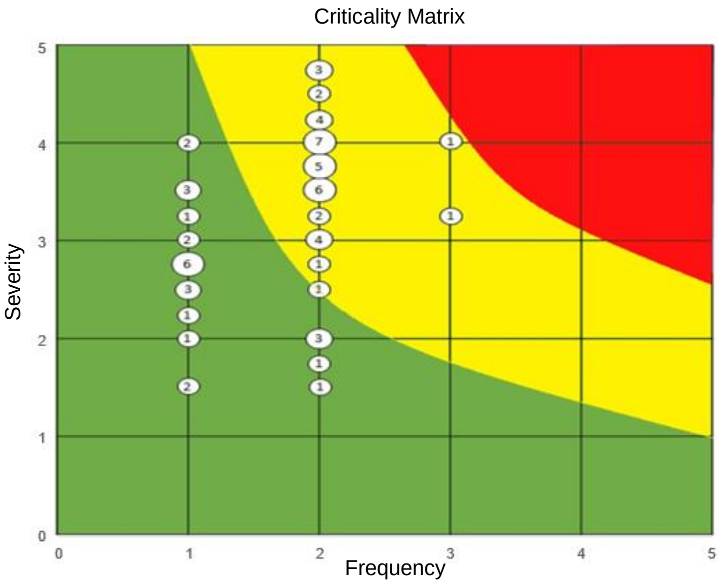

Figure 2 - Failure criticality matrix

4.5. Reliability Block Diagram and Exponential Distribution

After have set the failures considered medium critical, it was possible the construction of an RBD, to compute the reliability (and availability) of the infrastructure from its component’s reliabilities (and availabilities) [4].

The RBD of the infrastructure can be described in a simple way by a series system of all the 5 functional breakdowns described at the FTA (figure 3) which consist on the failure at the wall valves (preventing the entrance of the fluid on the Lift Station making it impossible to raise it until the general interceptor), a failure on the pumping well (with the pumps installed) and at the pre-treatment (with a failure with the equipment's responsible for the solids removal). Finally, also failures regarding to energy in both forms (electrical and pneumatic) can cause failure of the lift station due to a lack of electrical energy that would ensure equipment's functioning or a lack of pressure at the hydraulic system that would ensure actuator motion.

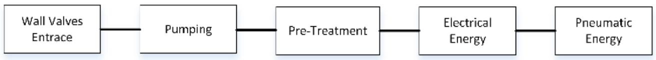

Figure 3 - Jamor Lift Station RBD

The next step was the construction of the system design according to the possibilities of failure mentioned before (figure 4).

At the entrance of the lift station there are two wall valves arranged in parallel, which failure of both equipment's will make its closure and consequently the opening of the by-pass valve causing water exhaust and failure of the lift station. The wall valve is considered the system of the iron structure plus the pneumatic actuator and the control valve frame which commands the functioning of the pneumatic actuator through the air inlet valves.

For each wall valve, immediately after, there is a pre-treatment equipment consisting on a sieving grill responsible for the solid's blockage. To separate these solids from the fluid and to unclog the flow passage there is a lifting screw type Arquimedes which motion is guaranteed by an electric motor that converts electrical energy into mechanical. For this equipment there are two work modes, automatic and by actuation. The second one occurs whenever the level of fluid at the canal is too high, causing the start of the equipment, in order to decrease this level. For this reason, a failure of this trigger is also considered critical since the automatic mode (every 15 minutes) can reveal to be insufficient to the functional requirements.

The main structure of the lift station is the pumping well composed by 3 electric pump groups in parallel because it is responsible by the main function which is the fluid elevation through the general interceptor. Each electric pump group is composed by a series association of 5 components. The aspiration zone is the entry of the pump where the fluid is sucked (the main failures associated with this part it's the obstruction with solids as rags), after, there is the impeller covered by the volute that consists the pump (while registering maintenance interventions workers doesn't make any distinction between these two components) that conducts the fluid until the compression conduit at the exit (there the failure occurs especially because of leaks at the non-return valve). There's also a frequency variator responsible for changing the pump's speed in order to respond to higher elevation requirements and a partial electric board which ensures the energy to the pump functioning.

Finally, there's also the electrical and pneumatic energy failure as responsible for the cessation of the main function of the infrastructure for stopping the equipments. When the transformation substation fails, causing electrical energy loss, an emergency generator is triggered to provide electrical energy within a period of time. However, if this equipment also fails, the equipments won't work causing the system failure. Also, a loss of pressure on the hydraulic piping circuit, or at the compressed air reservoir with the safety compressors simultaneously make impossible actuators to move, causing wall valves closure and exhaust.

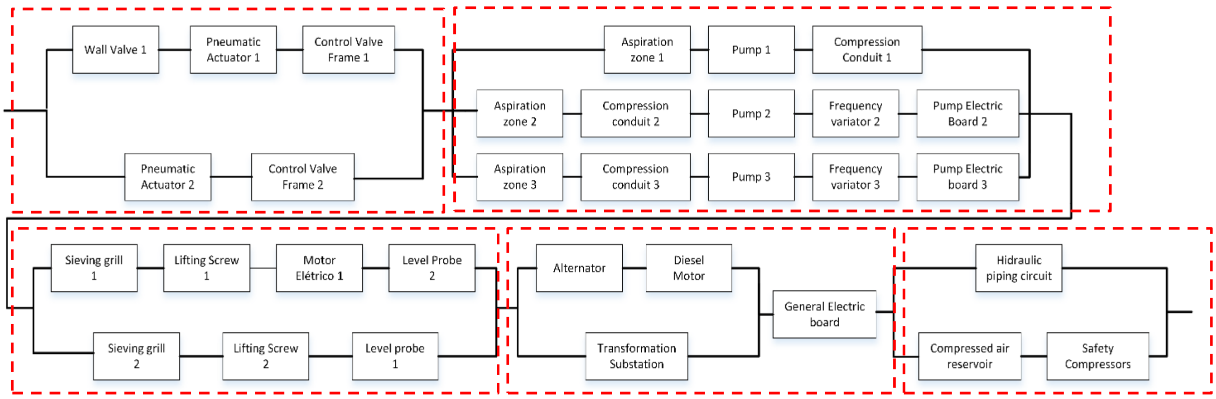

Figure 4 - RBD Extended for the system

4.6. Results

The next step to obtain the system reliability was the acquisition of the component's reliability. To do this, the MTBF and the operating time - t, were used into exponential probability function. This failure distribution can be used whenever the failure rate of the components is constant, indicating that they stand in useful life on the bathtub curve.

The reliability, R(t), of a system is described as the probability that the system remains in good operational contitions since the time zero until the time t (in which the reliability is calculated), giving that it was operational at $t = 0$.

Based on the RBD described before it was possible the calculus of the system after defining the reliability of each component for the 20 years of functioning (figure 5). As expected the reliability decreases with time and for the 6th year of functioning there is a balance between the system failure and success probability which suggests a realization of preventive maintenance concerning this value of interval between interventions. Contrary to what would be expected (by the behaviour of the function) there is an increase of reliability, motivated, as already mentioned, by the rehabilitation made to the entire electro pump group in 2016. This increase can be explained by the fact that whenever an equipment (or component) is intervened its reliability is fully restored (as primary approximation) and the functioning time starts from zero (considering that the equipment is placed "as good as new").

Due the fact that the equipment's didn't worked continuously in time the reliability calculations were made considering the *Duty Cycle* of operation.

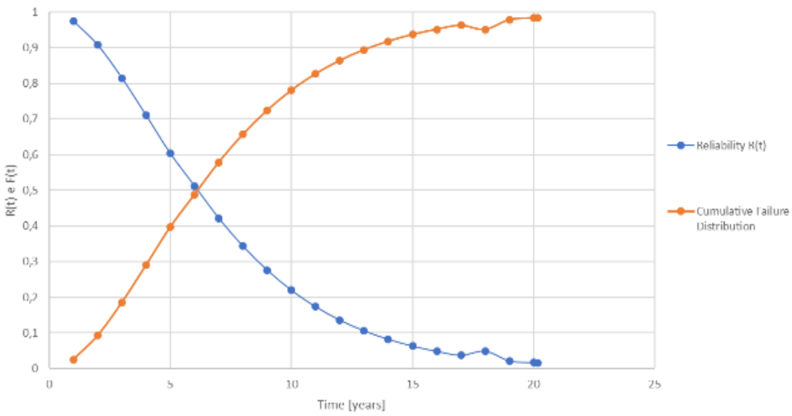

Figure 5 - Reliability and cumulative Failure Distribution for Jamor Lift Station

Table 1 – Infrastructure' failure rate

Stage	Failure rate $[h^{-1}]$
A	$5.07 \cdot 10^{-5}$
B	$1.63 \cdot 10^{-4}$
C	$1.92 \cdot 10^{-4}$
D	$6.20 \cdot 10^{-5}$
E	$5.64 \cdot 10^{-5}$
Total	$5.25 \cdot 10^{-4}$

Failure rate calculation was made according [5] for the reliability block diagram design presented before (figure 4). For a parallel system composed by equal components failure rate is given by the failure rate of the component plus the number of components. However, one approximation was made because the system wasn't composed by equal components (equal failure rates), thus an average value was considered. For a series system the failure rate is given by the sum of the partial failure rates. For this case, it was considerer the sum of the stage of treatment failure rate.

The monitoring of the failure rate is very important and advantageous not only because it is indicative of the phase of life occupied by the system in the curve of the bathtub, but also, because it is possible to extract an MTBF for which it would be prudent to perform intervention in the equipment's to predict the occurrence of failure.

To estimate system's availability were used the principles of series and parallel systems. Component's Availability calculus was made through the formula valid through the verification of $MTTR \ll T_{operation}$ allowing to characterize maintenance events as punctual:

$$A = \frac{MTBF}{MTBF + MTTR} \tag{2}$$

In this case, about 85% of equipment's failure have operational times greater, in at least two orders of magnitude, than reparation times (MTTR) which legitimizes the use of the formulas presented above.

Verifying formula 2, notice that availability is presented as a ratio between maintainability and reliability (MTTR and MTBF, respectively). Also, MTBF is greater in at least one order of magnitude which explains the fact that availability is highly dominated by MTBF, and therefore, by reliability.

Considering the mission of 242 weeks, meaning, approximately 20 years, the value obtained for the availability was $\boldsymbol{A(t) = 0.98132}$, which means that during the mission, the lift station didn't fulfil its function during about 5 weeks.

To understand why indicator is constant trough time the following availability formula was taken from [7]:

$$A(t) = \frac{MTBF}{MTBF + MTTR} + \frac{MTTR}{MTBF + MTTR} \cdot e^{-(MTBF^{-1}+MTTR^{-1})\cdot t} \quad (3)$$

Since $MTTR \ll MTBF \ll T_{operation} = t$ two situations can be verified:

- The first term of the availability formula comes $\frac{MTBF}{MTBF+MTTR} \approx MTBF$
- The second term is approximately zero due to the asymptotic behaviour of negative exponential function which tends to zero for high values of t.

5. Mitigation Actions

By looking at figure 2 it's possible to notice that criticality is ruled essentially through severity presenting higher incidence in levels 3 and later. Being this indicator a weighting of three different scales, it was observed that "reparation time" and "influence" were the ones that highlights.

The reparation time is highly influenced by the burocratic time needed to proceed the investment process (validation of reparation costs). This situation could be overcome by internal politic investment readjustment that potentialize a response readiness.

Regarding failure frequency it's possible, knowing reliability curve comportment, the definition of preventive maintenance (PM) to restore equipment's reliability avoiding critical levels. Internally, it was defined that the following inequation should be fulfilled:

$$R(t) \geq 50\% \quad (4)$$

The first step was to identify what would be the ideal time to perform PM, as a function of MTBF of each equipment, in order to minimize maintenance costs but respect the reliability requirement. To do that 3 different times were analysed to understand they differences (figures 6,7 and 8).

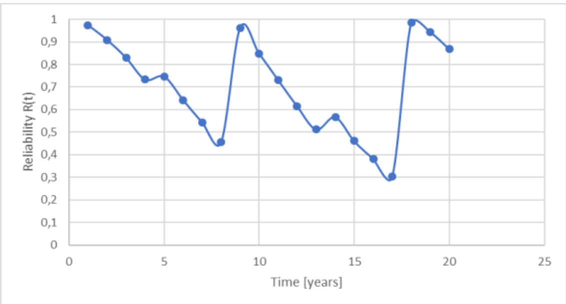

Figure 6 - Reliability Evolution with MP = 0.85 MTBF

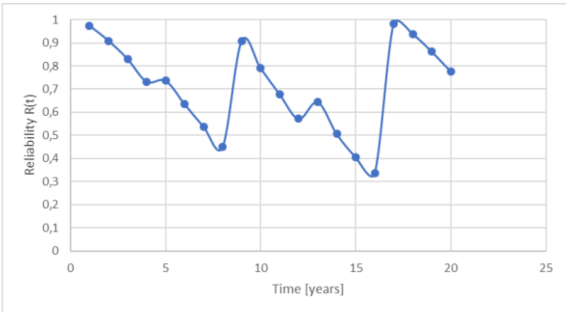

Figure 7 - Reliability Evolution with MP = 0.80 MTBF

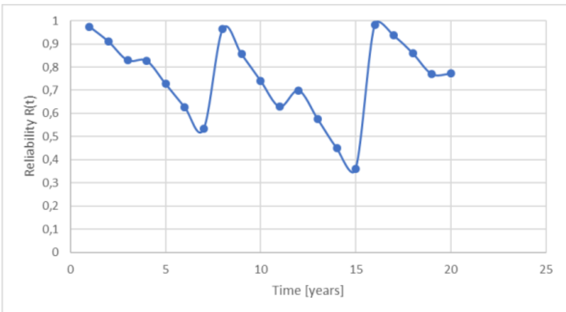

Figure 8 - Reliability Evolution with MP = 0.75 MTBF

Due to the small variations of reliability across the time analysed to perform PM, the value $MP = 0.85\ MTBF$ was chosen because it minimizes the dislocation of operational team costs. However, for not fulfilling the requirements a tuning of the model was necessary.

In order to increase the minimum value of reliability was necessary the stipulation of a MP time uniform for each stage within the lift station. To do that all the MTBF were gathered and the minimum value for each stage was chosen obtaining the figure 9. Knowing that maintenance costs are highly dependent on the number of interventions performed, it’s clear that minimizing maintenance costs implies optimization of MP time. Several values were studied reaching a frame of 6 months (figure 12).

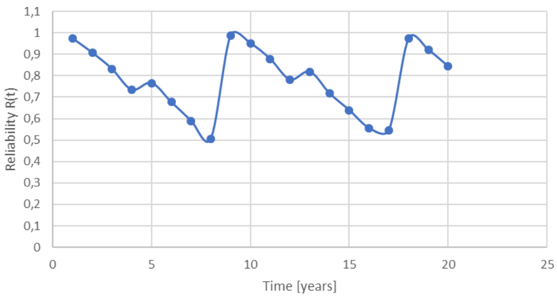

Figure 9 - Reliability Evolution with different MP per stage

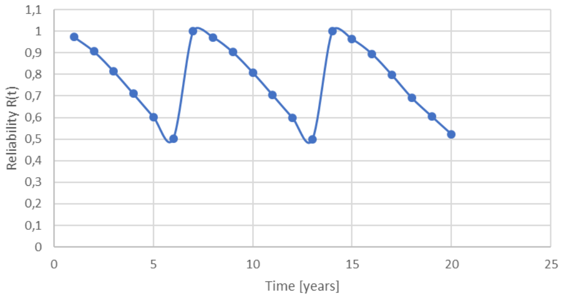

Figure 10 - Reliability Evolution with MP = 6 months

While the solution presented on figure 9 counts with 18 interventions over the 20 years interval, in figure 10 this number is reduced in 90%.

Mitigation’s action study was based in figure 13 were prevention actions were enunciated materializing in preventive maintenance execution. In fact, the action on severity as a way to increase the level of equipment availability could be made, however, given the reality of the type of investments present in the group, it is estimated that the application of protection measures, aiming at the reduction of severity, as the acquisition of warehouse stock may be impractical for a large universe of equipment given its high purchase price. However, such a study could not be performed since it was not possible to compare the cost of warehouse with the gain in terms of reduction of monetary maintenance costs due to lack of data.

Effect Category	Prevention (decreases Occurrence)	Protection (decreases Severity)
Operation	Interlock operation of sensitive components with a safety check to avoid damage	Prepare specific training and procedures to allow falling back to a safe degraded mode in an emergency
Maintenance	Increase the frequency of inspections and preventive maintenance operations	Keep spares on-site so that time to repair is shortened

Figure 11 – Typical mitigation actions performed, adapted from [6]

6. Conclusions

This paper had as main goal the definition and implementation of a methodology and solutions that allow measuring operability level of maintenance network, equipment’s and functioning’s stages availability as measures of the service level provided. The development of the pilot project began with an analysis of the applied curative maintenance interventions, where it was possible to characterize the maintenance events by the typologies of equipment in space and time.

Towards equipment’s criticality classification it were created three different levels resulting from formula 1, composed by a product of two distinct classifications, severity and frequency. For the severity, a classification methodology was developed based on criteria of cost, time of inoperability (considered, by approximation, equal to MTTR) and impact on the main function of the infrastructure, while for the frequency considered the average time between failures of the equipment’s. This classification allowed to identify critical equipment of the Lift Station, ie, which equipment should be managed with special attention given its propensity to failure and due to the serious consequences, that arise from it.

In order to identify the repair needs, an infrastructure reliability analysis was performed considering the system composed of all the critical components. For this analysis it was used the negative exponential distribution. This approximation considers most of equipment’s in useful life as verified in figure 5. It was possible the obtention of probability failure evolution which lead to an ideal MTBF, by successive approximations, always taking account on operational requirement (formula 4) and maintenance costs minimization.

Considering formula 3, it was verified that availability is practically constant trough time due to MTBF and MTTR differences on order of magnitude.

In conclusion, throughout this paper several methodologies were created leading to the following conclusions:

- The recording of work orders in the maintenance management software used in the group is, now, very directed to the internal cost regulation. This situation is expected to change as an asset inventory process ends, which will require the use of the location code at level 8, which is essential to the development of the methodology.
- Values of MTBF, MTTR and functioning time of the equipment's aren't obtained in an automatic way, due to lack of communication between maintenance management and Supervisory Control and Data Acquisition - SCADA software's, situation that will be changed with the new maintenance management software contract.
- The monitorization of performance level associated to a specific infrastructure is non-existent. With this methodology will be possible the application of these results on similar infrastructures of the group extending its application to all the infrastructures of the group

It is hoped, therefore, that this work may contribute to an improvement of maintenance management in all AdP Group companies.

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