DECISION-MAKING SUPPORT FOR OPTIMISING THE MAINTENANCE OF NATURAL GAS COMPRESSOR STATIONS

Authors:

Jérôme Blondel, Leïla Marle, Olivier Turc
CRIGEN, GDF SUEZ
361 ave Président Wilson BP 33
93210 Saint-Denis La Plaine

Akli Abdesselam
GRTgaz, Direction Technique
6 rue Raoul Nordling
92277 Bois-Colombes Cedex

Summary

The purpose of this study is to help GRTgaz optimising the maintenance of its natural gas compressor stations. Availability stations modelling is therefore proposed, taking the probability of failure of basic functional elements (BFE) and preventive and corrective maintenance actions into account. It also includes maintenance and system downtime costs. The system modelling was created in stochastic Petri nets with predicates.

1 Introduction

GRTgaz manages a gas transmission network in France and uses databases related to the technical features and operation data of its facilities.

CRIGEN, the GDF SUEZ Research and Technologies Division for Gas and New Energies, provides its methodological support to GRTgaz for the development of policies in the fields of asset and industrial safety management.

The present study deals with the asset management of basic functional elements (BFE) at natural gas compressor stations, using feedback data. The purpose is to help GRTgaz optimising the frequency of its preventive maintenance. Consequently, a proposal was made to model BFE availability at compressor stations, taking the failure probabilities (with effect of ageing) and preventive and corrective maintenance into account. The modelling also incorporates the downtime costs of the system and the maintenance costs.

The modelling was carried out with stochastic Petri nets with predicates and the software used was the Petri net module of GRIF, developed by SATODEV. The results obtained in terms of frequency of failure, percentage of planned and unplanned downtime, and especially costs, make it possible to suggest areas where preventive maintenance frequencies can be optimised.

This study also provides an evaluation of the available data and a scientific approach combining feedback data and expert judgement.

2 Definitions and hypotheses

Only critical components in terms of downtime are taken into account in this study. Accordingly, the basic functional elements (BFE) of natural gas compressor stations were broken down into nine parts, each of them having sub-components:

- Ultimate security system, comprising filters, instrumentation and valves;
- Process valves, comprising instrumentation, continuous valves, and on-demand valves;
- Filtration system, comprising filters;
- Natural gas compressor (NGC), comprising control systems and NGC with auxiliaries;
- Turbine, comprising a turbine with auxiliaries;
- Cooling tower;
- Safety valve;
- Air admissible circuit, comprising a filter;
- Oil circuit, comprising filters, a lubrication pump system, and aero oil.

Subsequently, the sub-components (note that there might be multiple instances of a given sub-component) will themselves be broken down into maintainable units. Note also that he input data, modelling, and results presented here pertain to one particular station (confidential).

2.1 Series system

BFE of natural gas compressor stations is considered as a series system (Procaccia et al. 2011) with respect to its nine parts identified as critical, just like each of these parts with respect to its sub-components, and each of these sub-components with respect to its maintainable units. Accordingly, the downtime of any maintainable unit can itself cause BFE downtime.

2.2 Two modes of operation

Each maintainable unit has two modes of operation:

- "Continuous" mode, when the failure in the maintainable unit has an impact on the compressor station as soon as it appears;
- "On-demand" mode, when the failure in the maintainable unit only has an impact on the compressor station as of the moment when a demand is actually made upon the maintainable unit.

In the case of "on-demand" mode, it is considered that the (random) time between two demands made upon the maintainable unit follows an exponential distribution. The frequencies of demand are defined at the level of the sub-component and are therefore applicable to all its maintainable units.

When a demand is made upon a maintainable unit that is in operation, the duration of said demand is assumed to be negligible. On the other hand, when a demand is made upon a failing maintainable unit, the effect of said failure (which starts as of the moment of demand) lasts until the maintainable unit is put back into operation, regardless of the duration of said demand.

2.3 Mean Time To Failure (MTTF)

It is considered that the time between placing/re-placing a maintainable unit "in operation" and its next failure follows a Weibull distribution of parameters η and β. The "Mean Time To Failure" (MTTF) without preventive maintenance of a maintainable unit is given by:

$$MTTF = \eta \cdot \Gamma(1 + 1/\beta) \quad \{1\}$$

with Gamma function defined by:

$$\Gamma(\mathrm{x}) = \int_0^\infty \mathrm{u}^{\mathrm{x}-1} \cdot \mathrm{e}^{-\mathrm{u}} \cdot \mathrm{du} \quad \{2\}$$

Parameter η is the scale parameter (in time units) and parameter β is the form parameter (without unit).

2.3 Preventive maintenance

For each maintainable unit, these two parameters define the preventive maintenance actions:

- preventive maintenance period τ, with the preventive maintenance actions performed at times $t_0+\tau$, $t_0+2\times\tau$, $t_0+3\times\tau$, etc. (provided the corresponding maintenance resources are available), defined by failure as of $t_0=0$
- duration of preventive maintenance d (as of the moment when the corresponding maintenance resources are available), including supply times and inactivity times due, for instance, to the stopping of maintenance actions during nights and weekends.

These preventive maintenance action parameters are defined for each maintainable unit. Indeed, the maintainable units have been defined in such a way that each preventive maintenance action corresponds to a maintainable unit. Nevertheless, when the preventive maintenance actions do not cover the entire sub-component, the result is a "residual" maintainable unit which is not subject to preventive maintenance action.

Each preventive maintenance action on a maintainable unit has the effect of rendering that unit (and therefore the system) unavailable for a duration equal to the corresponding preventive maintenance duration to which is added any waiting time for the availability of the corresponding maintenance resources.

At the end of a preventive maintenance action, the maintainable unit in question is restored to a state that is "as good as new", i.e. any ageing effects of the maintainable unit are "reinitialised".

2.4 Corrective maintenance

The corrective maintenance actions start as soon as the failure in a maintainable unit is detected (provided the corresponding maintenance resources are available).

- When a maintainable unit is in "continuous" mode, the failure is detected as soon as it appears.
- When the maintainable unit is in "on-demand " mode, this happens as soon as a demand is placed upon the failing maintainable unit, or following a preventive maintenance action on it.

It is assumed that the (random) time between the start (as of the moment when the corresponding maintenance resources are available) and the end of the corrective maintenance action of a maintainable unit follows an exponential distribution. The Mean Times To Repair (MTTR) are defined at the level of the sub-component and are therefore applicable to all of the maintainable units that comprise it.

Each corrective maintenance action on a maintainable unit has the effect of rendering that unit, and therefore the system, unavailable for a duration equal to the corresponding corrective maintenance duration to which is added any waiting time for the availability of the corresponding maintenance resources.

At the end of a corrective maintenance action, the maintainable unit in question is restored to a state that is "as good as new", i.e. any ageing effects of the maintainable unit are "reinitialised".

2.5 Maintenance resources

The maintenance resources used to perform preventive and corrective maintenance actions are limited in such a way that at any time, the number of resources used to perform any maintenance action may not exceed a certain value.

When the maintenance resources that are needed to perform a desired maintenance action are not available, the maintenance action in question is put on hold until the necessary maintenance resources are available. In the case of "conflict" (i.e. when multiple maintenance actions on hold could start at the same time), priority is given to corrective maintenance actions and, secondly, the choice is made in an equiprobable manner. All maintenance actions in progress must be terminated before releasing the corresponding maintenance resources.

The maintenance resources that are needed to perform corrective maintenance actions are defined at the level of the sub-component and are therefore applicable to all of the maintainable units that comprise it.

The maintenance resources that are needed to perform preventive maintenance actions are defined for each maintainable unit.

2.6 Costs

System downtime implies a cost per time unit. This cost is independent of the cause of the downtime (corrective maintenance or preventive maintenance).

Each corrective maintenance action implies a fixed cost. These costs are defined at the level of the sub-component and are therefore applicable to all of the maintainable units that comprise it.

Each preventive maintenance action implies a fixed cost. These costs are defined for each maintainable unit.

3 Methodology

3.1 Reliability input data

The first step consists of estimating the associated failure rates for each piece of equipment on the basis of feedback data.

According to Lannoy (1996), the Bayesian approach applies when:

- there is not much feedback data;
- such data are “contaminated” by changes to the design, by changes to operation or by maintenance;
- it is desired to re-update previous estimates if new feedback observations become available.

In this case, there is not much feedback data, or even none at all for certain equipment families for which no failures were observed. This high level of reliability invalidates the frequency-based approach and does not make it possible to obtain an accurate estimate. The Bayesian approach is an alternative that makes it possible to take into account all of the knowledge available in order to attain the best and most accurate possible estimate.

The Bayesian approach was therefore applied for those equipment families with little feedback:

- either by using offshore reliability data (OREDA);
- or by consolidating local data (specific to a particular site) via national data (considered as prior in this case).

When OREDA data were used, Fisher Information weighting was performed in order to ensure a balance between prior and likelihood, with respect to information contribution.

In addition, it was necessary to ensure a correct match between the feedback and prior knowledge. It was sometimes necessary to weight the data according to the match level.

Expert data was also collected in order to compare the expert assessment to the results obtained. Accordingly, a questionnaire was used to collect two expert assessments: one from an expert in reliability and maintenance of the equipment studied, and the other from an expert in the operation of compressor stations.

As can be seen in Figure 1, for six equipment families, the result of the assessments is in line with the result of the feedback. Expert 1 was the more pessimistic in terms of reliability and expert 2 was more optimistic.

For the other families, the two experts were more pessimistic, giving higher failure rates than the feedback data.

The two expert assessments were incorporated using the Bayesian approach by giving equal weight to both experts.

All of the Bayesian calculations were performed using REXPERT software.

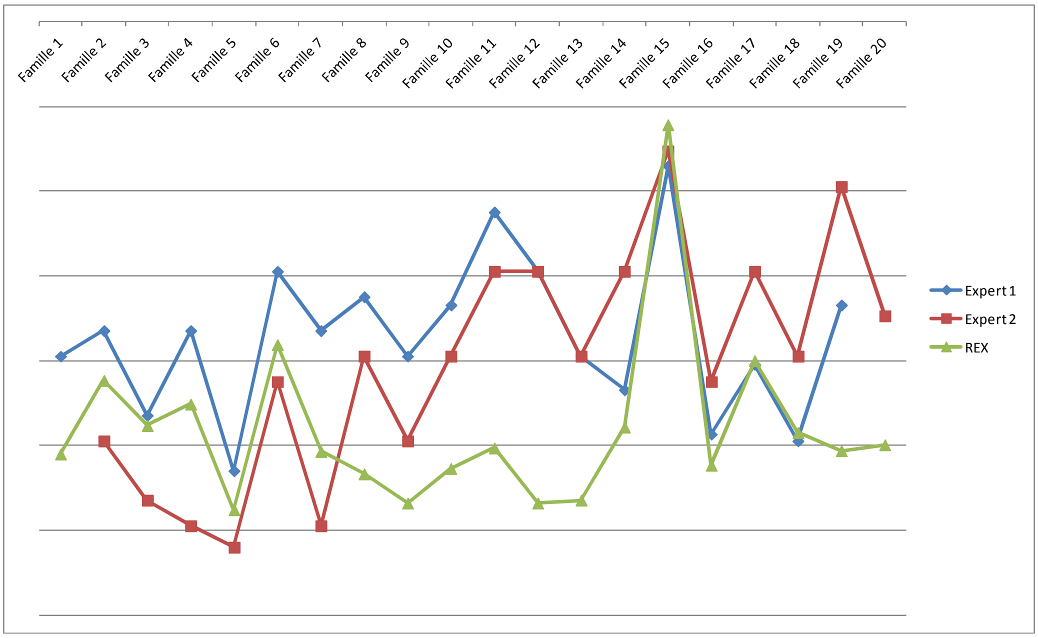

Figure 1. Comparison of the results provided by each expert compared to the GRTgaz feedback data (the values of the failure rates are masked for confidentiality reasons)

Organising the failure data into a hierarchy subsequently made it possible to identify critical equipment families according to their impact on the downtime of the facility (total for the site or partial for a workshop, for example).

The demand frequencies and the "mean time to failure" come from feedback data. (It should be noted that the MTTF were defined taking account of the current preventive maintenance periods and the formal parameters applicable to Weibull distributions.)

3.1 Maintenance input data

The periods (expressed in years) and the durations (expressed in hours) of preventive maintenance actions come from the current GRTgaz maintenance policy.

The average repair durations (expressed in hours), the costs of preventive maintenance actions and corrective maintenance actions, the maintenance resources needed to perform preventive maintenance actions and corrective maintenance actions, as well as the form parameters applicable to the Weibull distributions (β) come from expert judgement, based on GRTgaz's expertise.

The maximum number of maintenance resources that can be used at any given time is defined at four maintenance operatives, on the basis of GRTgaz's expertise.

The system downtime cost per time unit was estimated via GRTgaz's expertise.

3.3 Modelling

The modelling was carried out in stochastic Petri nets with predicates (Dutuit et al. 1997), using the Petri net module from GRIF software. This TOTAL software is developed by SATODEV (www.satodev.com).

Each maintainable unit was modelled separately. The architecture of the model presented in Figure 2 shows all the "groups" which each contain the model of a maintainable unit as presented in Figure 3.

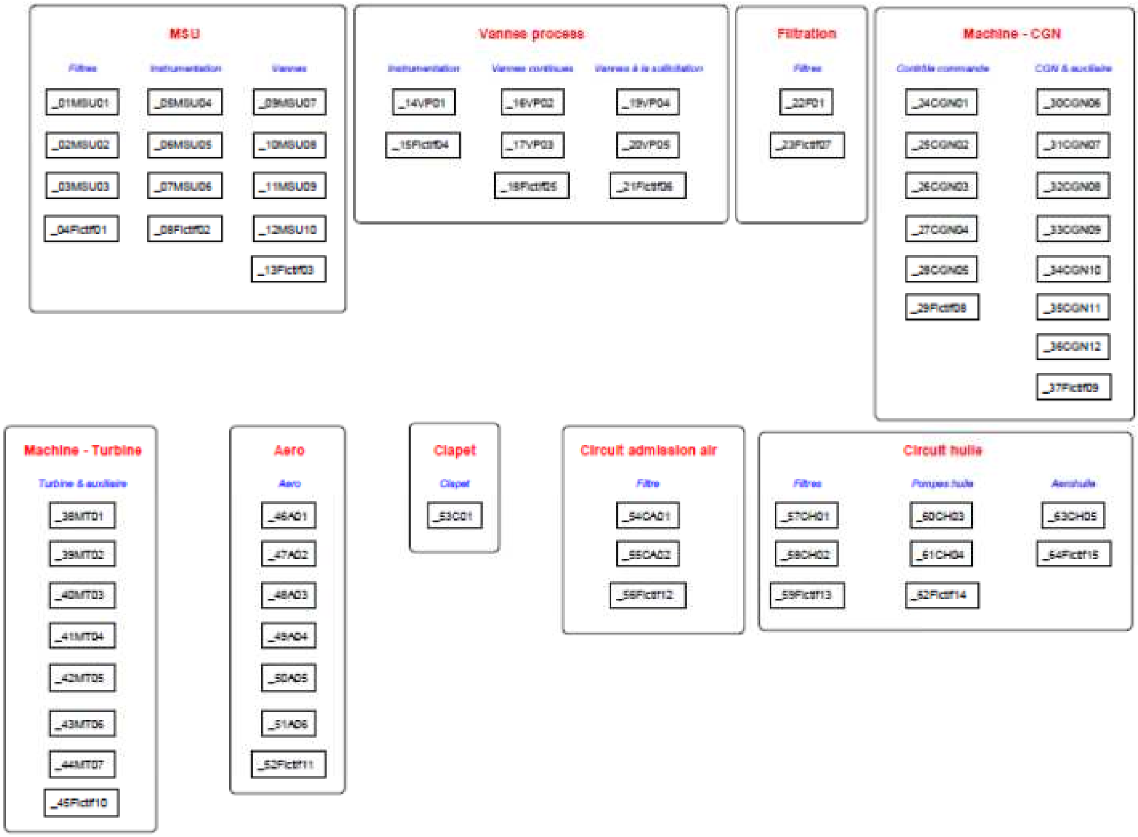

Figure 2. Architecture of the model

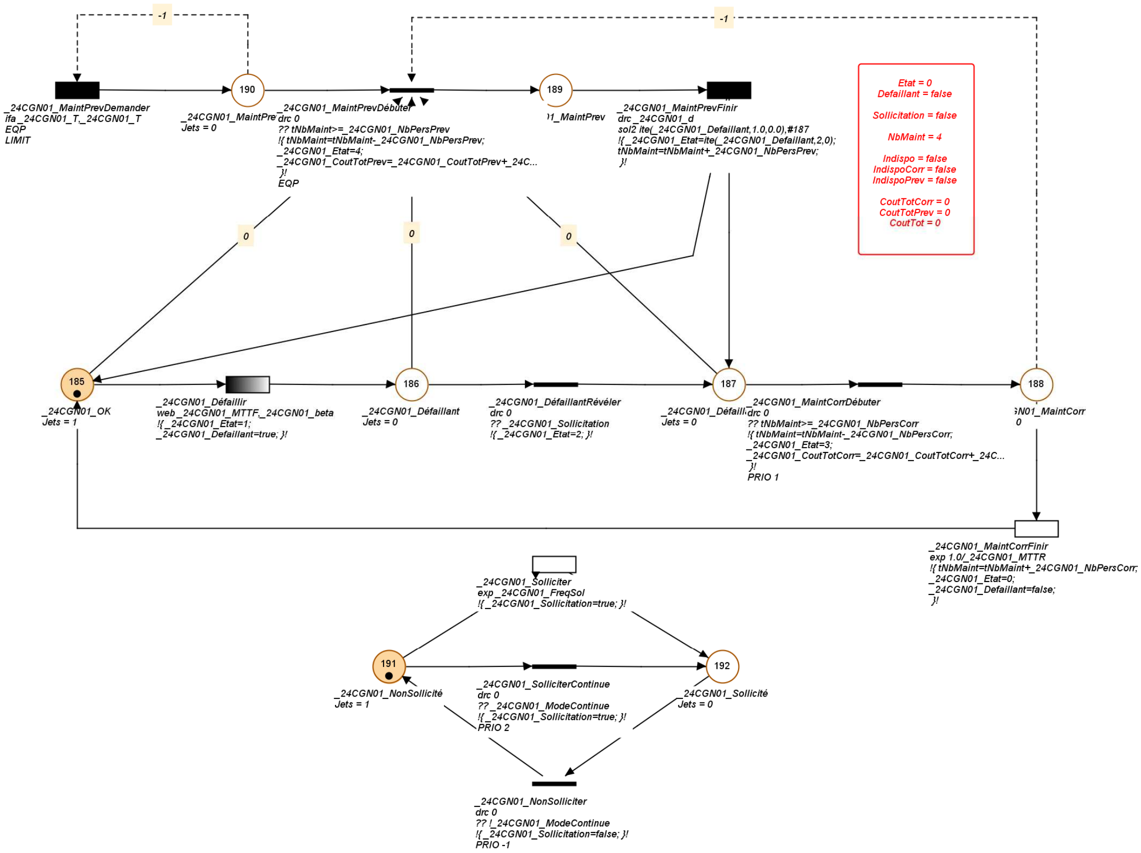

Figure 3. Model of a maintainable unit

Places 185 to 188 in Figure 3 make it possible to model the failure of the maintainable unit in question, the detection of said failure, and the associated corrective maintenance action.

- The failure occurs according to the Weibull law defined in the hypotheses.
- The failure is detected as soon as a demand is placed upon the maintainable unit.
- Lastly, the corrective maintenance action begins as soon as the required maintenance resources are available, and ends according to the duration defined in the hypotheses. During the corrective maintenance action, the number of maintenance resources defined by the hypotheses is subtracted from the number of available resources, then added once the action is terminated. In addition, each time a corrective maintenance action starts, the total cost is increased by the cost defined by the hypotheses.

Places 189 to 190 in Figure 3 make it possible to model the preventive maintenance action of the maintainable unit in question.

- The request for such a maintenance action happens according to the period defined in the hypotheses.
- An “on demand” maintenance action then begins as soon as the required maintenance resources are available, and ends depending on the duration defined in the hypotheses.
- During the preventive maintenance action, the number of maintenance resources defined by the hypotheses is subtracted from the number of resources available, then added once the action is over. In addition, every time a preventive maintenance action begins, the total cost is increased by the cost defined by the hypotheses.

A variable state of the maintainable unit is defined with the following values:

- 0 when the maintainable unit is operational (initial state);
- 1 when the maintainable unit is failing and said failure has not been detected;
- 2 when the maintainable unit is failing and said failure has been detected;
- 3 when the maintainable unit is undergoing corrective maintenance;
- 4 when the maintainable unit is undergoing preventive maintenance;

Accordingly, the maintainable unit is failing when said status variable is not 0 and causes downtime of the sub-system to which it belongs when the status variable is equal to or greater than 2.

It should be noted that a preventive maintenance action may not begin while a corrective maintenance action is in progress. In addition, if a preventive maintenance action begins while the maintainable unit is failing and if said failure is not detected, then said failure becomes detected once the preventive maintenance action is terminated.

Places 191 to 192 in Figure 3 make it possible to model the demand on the maintainable unit in question. Said demand is permanent in the event of “continuous” demand on the maintainable unit, or it is then defined according to the demand frequency stipulated in the hypotheses.

3.4 <u>Results</u>

The results were obtained from 10,000 simulations over an analysis period of 30 years. Here after some examples of results:

- The annual average failure frequency of the entire system;
- The main contributors to failure frequencies;
- The average unplanned downtime percentage of the entire system (due to failures);
- The main contributor to unplanned downtime;
- The average planned downtime percentage of the entire system (due to preventive maintenance actions);
- The main contributor to planned downtime;
- The average total downtime percentage of the system;
- The main contributor to total downtime.

Figure 4 shows the contribution of planned and unplanned downtime to total downtime.

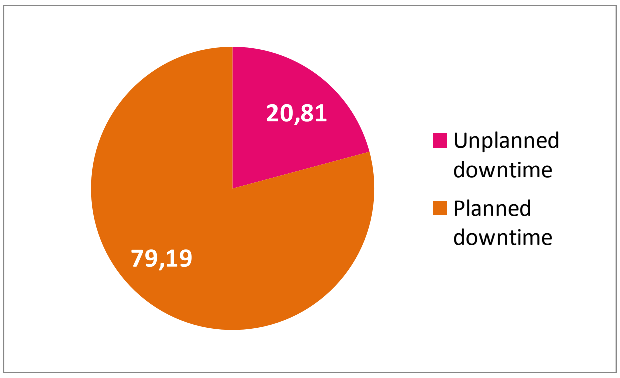

Figure 4. Contribution of planned and unplanned downtime to total downtime

3.5 Modelling validation

The simulations carried out on the basis of the Petri net models under the observed reliability and maintenance conditions make it possible to find the availability data observed in the system. This matching between the results of the simulations and the observed availability makes it possible to validate the proposed model.

Based on this model, changes to the preventive maintenance frequencies were made: +50%, +100%, +150%, +200% of the initial period.

In order to evaluate the effects of the maintenance policy modification, different simulations were realised with different values of the β parameter. In addition to the simulations based on the initial values of β, two others sets of simulations considered β+0.5 and β+1. These important values of the β parameter, corresponding to a more important materials ageing, leads to more failures. The different simulations allow the validation of the modelling as the given results confirm experts opinion.

Figure 5 below shows the change in total availability of the system, planned downtime (due to preventive maintenance) and unplanned downtime (due to corrective maintenance) as a function of these various frequencies.

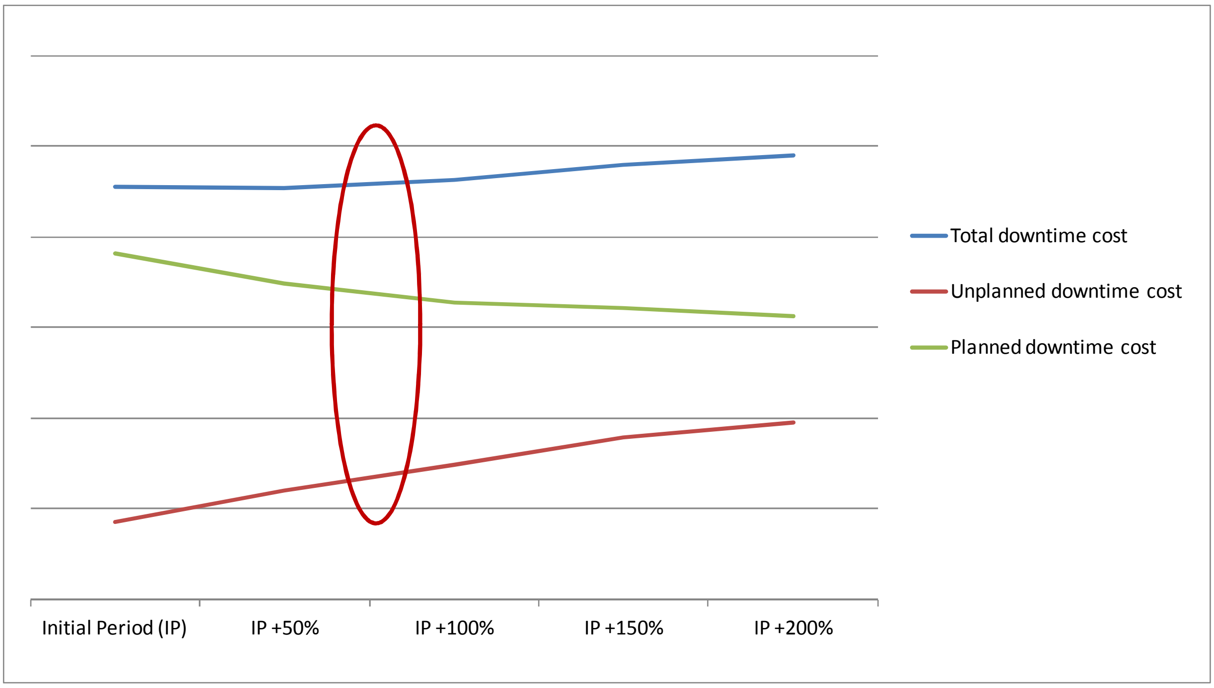

Figure 5. Change in downtime as a function of the frequency of preventive maintenance.

In one hand, a drop in downtime due to preventive maintenance results of the increase in frequencies. In the other hand, the corrective maintenance, and thus the number of failures, increases. These two observations also make it possible to validate the model that restores the expected behaviour of the system.

In term of results, this figure shows also that total downtime remains stable, with the two above-mentioned trends cancelling each other out. An increase was also observed in total downtime when preventive maintenance frequencies were doubled. This gives a limit that cannot be exceeded if we wish to maintain the same level of availability while reducing preventive maintenance.

Indeed, the initial results show that preventive maintenance frequencies can be doubled, thus reducing preventive maintenance costs by 50%, while maintaining the same level of system availability. However, a more refined analysis is needed in order to identify the optimum frequency for critical equipment in terms of availability and cost.

As presented here in a global approach, a similar analysis is carried out for each sub-system. The results show that for certain equipment the preventive maintenance reduction margin is less important. A more refined analysis is in progress to identify the optimum maintenance frequency for critical equipment. This analysis incorporates the costs related to maintenance and downtime. It is important to note that the sub-systems concerned by safety challenges and for which there are statutory maintenance actions are taken into account in the model, but are not the subject of changes to maintenance policy.

4 Conclusions

This study made it possible to highly the value of using Petri nets to model an industrial facility. Taking into account the reliability and maintenance characteristics of the system (MTTF, MTTR, preventive maintenance actions, etc.) as well as the organisational constraints on maintenance (number of operators, work priorities, etc.) is essential.

The modelling is possible for a whole system (compressor station), but also for sub-systems (equipment), that makes it flexible.

The simulations based on this model make it possible to compare multiple scenarios on the basis of a group of performance and cost indicators. Consequently, they provide important and reliable decision-making support for maintenance optimisation.

This modelling, already implemented at one station, is being deployed at all GRTgaz stations. The possibility of reusing the model's building blocks and adapting them to the specific data and architecture of each station facilitate and optimise the study duration and cost.

To conclude, this study allowed the improvement of the maintenance approach and gives interesting gains perspectives.

5 References

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