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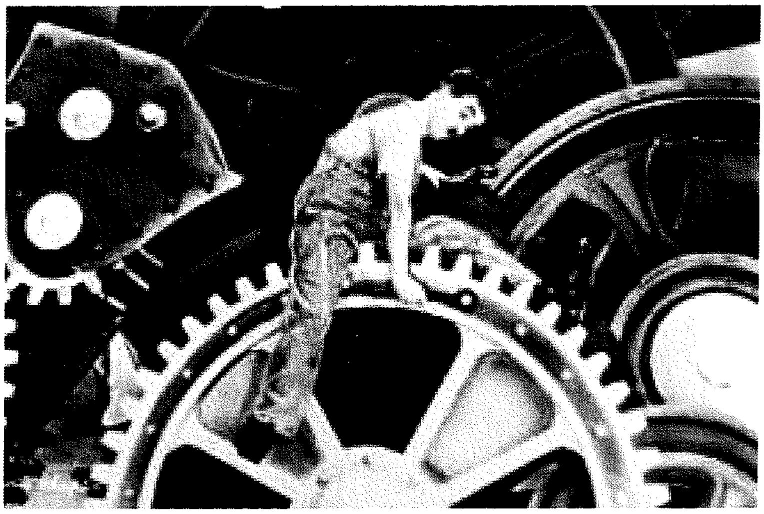

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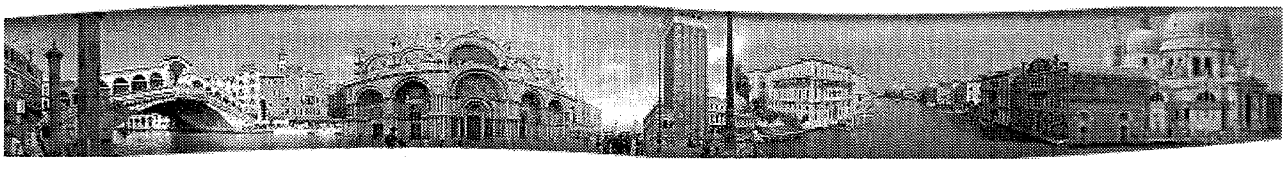

DIAGNOSTIC SYSTEMS IN MAINTENANCE MANAGEMENT: A CASE STUDY IN ITALIAN HIGH SPEED TRAIN ETR 500

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KEYWORDS

Reliability, diagnostics model, availability simulation.

ABSTRACT

Performance requirements are more and more restrictive and binding for today's production systems moving in the context of highly competitive markets. One of the most important requirements of new machines and industrial plants is to have high performances within their maintenance process. This issue can be considered as a "weak ring" of the productive system life cycle and even nowadays is too times neglected. In the present work we have concentrated our efforts on diagnostic systems, pointing out the way in which they can be a good answer to these new performance requirements for complex systems. As studies and application increase in number, it turns out clearly that implementation of diagnostics is synonymous of maintenance evolution, either technically and methodologically. This is also to be considered as a further managerial lever regarding production processes. In the present case study we have operated a technical and an economic comparison between two configurations: with or without diagnostic support The main system reliability parameters have been evaluated in both cases. The object of the appraisal, through the study of the maintenance process achieved by means of a simulation approach, is the production and treatment plant for compressed air GPTA (Production and Treatment of compressed Air Group), running on the edge of the high speed Italian train ETR500.

INTRODUCTION

In technical problems, the ultimate aim of a diagnostic system is to give as many information as possible concerning the state of a component, machine or plant.

In this paper the greatest efforts have been made in order to represent a diagnostic system inside a reliability simulation software. In such a way, in fact, it could be possible to evaluate the convenience of the implementation of a diagnostics, looking at the higher availability achieved. This procedure can also be useful in the choice of the appropriate diagnostics and in its proper calibration.

THE MODEL

Every diagnostic system is basically based on the close observation of a system. Therefore the first choice regards the kind of system to be controlled.

The simplest kind of failing system is the binary one, characterized by two basic states: in operation, not in operation.

In figure 1 is represented the model of a not diagnosed system. It consist of two different areas: the first is the working area called OP (operation). The second is the set of conditions in which the system is failed. This will be called NOP (no operation) area.

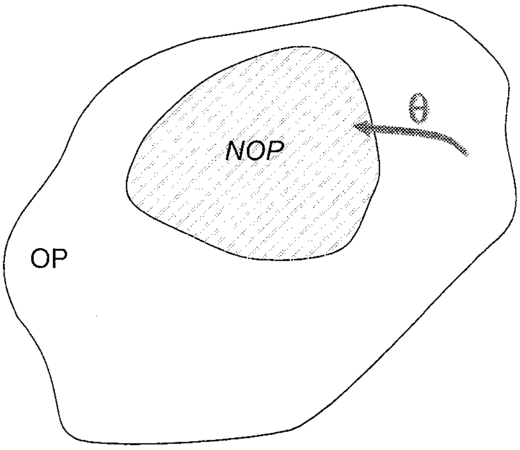


Figure 1: Not Diagnosticated System Model

The probability of failure, θ, is represented by the arrow of figure 1.

In figure 2 is represented the space of all possible states of a diagnosticated system.

There are the same two main areas OP and NOP, and other zones representing the possible states.

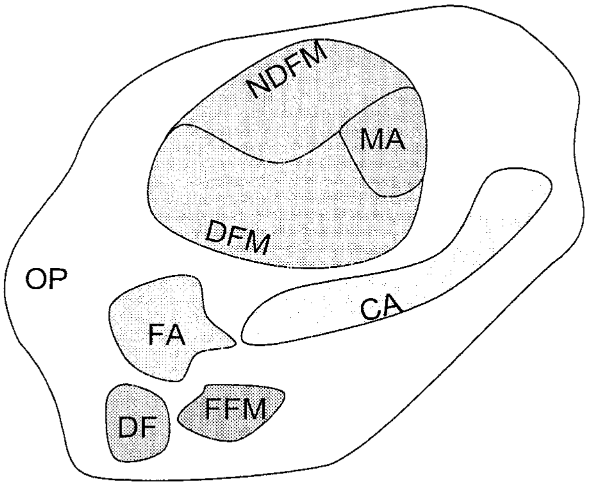


Figure 2: Diagnosed System Model

Since that this system is under the control of diagnostics, the NOP area is shared into two main fields: DFM and NDFM.

DFM (Detectable Failure Modes):
Each failure mode can be classified by its relationship with the diagnostic system. In fact any diagnostic equipment is designed for the observation of some physical signals that typically forestall a failure event. But the number of the possible failure modes is generally larger of the ones that can be observed by the diagnostic system.
The group of failures which can be detected constitute the DFM area.

NDFM (Not Detectable Failure Modes):
In this area we can find all the other failure modes that can't be detected by the diagnostics implemented.
Inside the DFM zone there's another little area representing the missed alarms.

MA area (Missed Alarm area):
Sometimes it may happen that, because of an internal error, in presence of alarm conditions the diagnostic system doesn't produce an alarm. This is a missed alarm and is represented in the diagram by the MA area within the NOP zone.
The MA area is an "α" fraction of the DFM area.
"α" is the detection coefficient, with values between 0 and 1. The better is the diagnostic system, the lower is the value of "α".

Considering the "operation" zone of the diagram, we find two areas inside, symbolizing incorrect interference of the diagnostics while the system still correctly working.

CA area (Correct Alarm area):
When the controlled parameter (or parameters) reaches a critical value, preluding to a imminent failure, the diagnostic system reveals the problem giving a proper alarm. This condition is the Correct Alarm area.

FFM (Fake Failure Modes):
Sometimes it may happen that, because of an external event, the diagnostic system produces an alarm but the system is still working. For instance a certain vibration, usually due to a failure event, may be caused by a different occurrence and isn't related to a breakdown.

DF (Diagnostic Failure):
Sometimes it may happen that, because of an internal error, the diagnostics fail leading to an alarm while the system is still working.

FA area (False Alarm area):
When an alarm is generated by an event of the FFM or DF area, this is a false alarm and is represented in the diagram by the FA area within the "operation" zone.

Since the system is not static, it can move from one area to another, as a consequence of an event concerning maintenance operations or failure.
The arrows of figure 3, liking two different zones, stand for any possible event concerning failures.

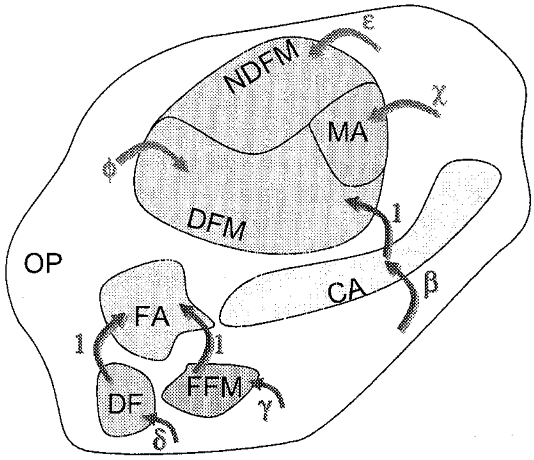


Figure 3: Possible Events Model

The transfer from one area to another has a probability of occurrence that can be variously evaluated. The main probability of change of state are the following:

β: from OP to DFM (passing through CA); when a working system fails but before it has passed from the CA area. This failure is one of those diagnosable

χ: from OP to MA; when a working system fails but the diagnostic system doesn't detect the problem while it was supposed to do it.

ε: from OP to NDFM; when a working system fails and the failure isn't one of the diagnosable ones

γ: from OP to FA (passing through DF); when an internal error of the diagnostics causes an alarm not corresponding to an imminent failure;

δ: from OP to FA (passing through DF); when an external event causes an alarm not corresponding to an imminent failure.

The probabilities of figure 3 are considered to be constant. If they are time dependent, every probability becomes a probability function: $\pi \rightarrow \pi(t)$ and figure 3 is effective only for a peculiar moment.

An interesting observation is the following: the "false alarm" is an arrival zone, while the "correct alarm" is a crossing area. This means that when a false alarm happens, something has already happened and you can do nothing about it. When, on the contrary, there's a correct alarm, the failure event is going to come, but it hasn't happened yet. In this latter case predictive maintenance plays its strategic role.

Comparing figure 1 with figure 3, we can observe the difference between the diagnosed and not diagnosed systems in terms of failure probability of occurrence. In the first case it's θ, in the second, the same probability is split by the diagnostics into $\beta+\chi+\varepsilon$.

$$\theta=\beta+\chi+\varepsilon \qquad (1)$$

If, after every correct alarm, a maintenance operation is scheduled and accomplished correctly and within a suitable time, the system doesn't move from the CA into the DFM area, but comes back in the operation zone, as visible in figure 4, where the OCM area is the "On Condition Maintenance" one.

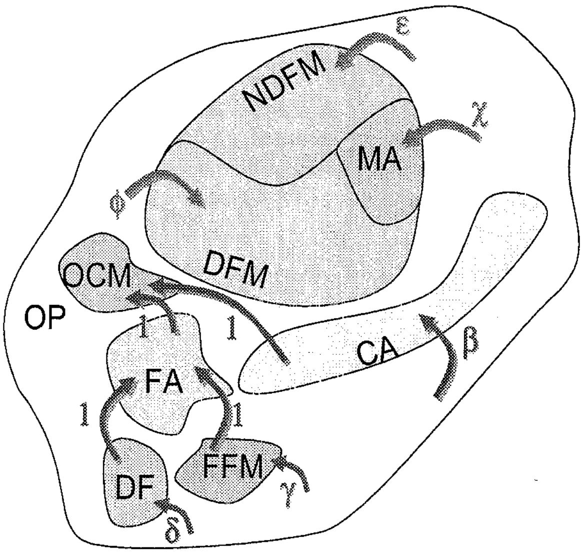


Figure 4: Events Model with On Condition Maintenance

In this way there's a reduction of the probability of failure from θ to θ':

$$\theta'=\theta-\beta=\chi+\varepsilon \qquad (2)$$

On the other hand the presence of the γ and δ coefficients, causes the negative result of scheduling unnecessary maintenance tasks, involving additive costs.
As visible in equation (2), the difference between the two configurations is $\beta=\theta'-\theta$. Hence the selection of the failure modes to be controlled by diagnostics (β) is very important. It depends on the priority criteria chosen for the system reliability management policy, as safety, availability, cost requirements.

THE DIAGNOSTICS

Sometimes diagnostics are applied to a system with a clear idea of the benefits but without a procedure to gain an estimate of the costs and of the savings introduced. The aim of the present study was first to find a simple way to represent a diagnostic system inside a reliability simulation software. Secondly we made a case study to see how appreciate the economical and availability impact of the diagnostics over the global system, by the comparison of the simulation results of two different configurations: with and without diagnostics.
Quite for every failure mode, one or more physical operating variables can be found, showing the degradation state of the system. One of these must be chosen for the diagnostics. Next there's to determine which values of the parameter are still acceptable and which aren't. In terms of the model presented in the first chapter, the question is to determine the CA area in an efficient and effective way.

If it isn't possible to control directly an operating variable, another parameter must be found, having the following requirements: firstly it must be tightly related to the degradation state; secondly it should be to easily measurable and checkable.
The use of the diagnostics causes a reduction of the failures from $\chi+\varepsilon+\beta$ to $\chi+\varepsilon$, disregarding the two final contributes $\delta+\gamma$ (errors leading to the FA end FFM areas), the reduction is to $\chi+\varepsilon$.
The percentage failure reduction is therefore:

$$\theta'/\theta=(\chi+\varepsilon)/(\chi+\varepsilon+\beta)=1-\beta/\theta \qquad (3)$$

Every time the simulation software faced a failure of one of the diagnosed items, a percentage of β/θ was instantaneously restored. The recovered percentage stands for those failure events which won't occur because of the presence of the diagnostics.
The β and the θ values depend on the system complexity and the diagnostics configuration. The weaker is the item, the bigger is θ. A better diagnostic system implies a bigger β/θ.

The goal of a diagnostic system is to know, by means of some appropriate measurements, the degradation level of the monitored component, machine or system.
In order to implement a diagnostic apparel, after having identified the physical measurements, we have to identify an alarm threshold that represents the limit over which some action must be taken. Whenever the physical parameter monitored exceeds the threshold, an appropriate procedure determines what to and in which times.
The threshold has a very important role, since it determines when the degradation level is not any more acceptable. Hence derive many consequences, relating reliability, availability, safety. For instance, it may happen that an availability target achievement doesn't lead to the same threshold to which a safety instance would have driven. In other cases, performance indexes could be preferred to others. So the parameter choice depends on the maintenance policy and requirements.

The diagnostic parameter should be easily measurable by simple and robust instruments, because often the operating conditions are very severe.

The measured physical signal may require to be treated (filtered, amplified). A good signal can also be capable of recognizing different incoming failure modes basing on the amplitude, the frequency and other signal features.

The simulation software suitable to perform this kind of operation must be flexible and capable of determine the failure or repair status of each item with a logical decision procedure requiring some user defined computations. Moreover it should be able to monitor, trace and manage availability function; it should be flexible to give the opportunity to modify any item's failure functions.

The tool elected for this application is SPAR produced and distributed by Clockwork Group.

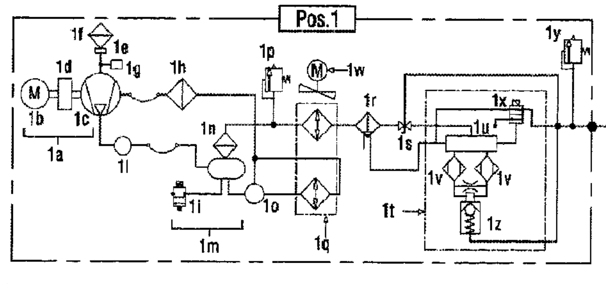
Its specific characteristic is a programming environment, called Bubble Maker, that gives, by means of a structured language, the opportunity to implement a control and decision algorithm able to modify the system configuration at any time.

THE GPTA

The case study selected is the compressed air system of high speed Italian train ETR500 PLT: the GPTA plant. On each convoy there are two Pats each of them is in the underbody of the two locomotives.

Each group produces drained and stripped air at the operating pressure between 9 and 10 bars. The two GPTAs serve the two traction engines and the other twelve conveys of the train. The use of compressed air is in braking operations and for facilities (toilettes, seats settings).

The system, composed approximately by thirty elements, is divided in two subsystems: the unit of compressed air production (left side of figure 5) and air conditioning unit (right side).



1a.	Gruppo motore-vite (1b,1c,1d)	1i	Elettr.di depressurizzazione	1s.	Rubinetto a tre vie
1b.	Motore elettrico	1l.	Sonda termostatica	1t	Essiccatore
1c.	Gruppo vite	1m.	Serbatoio olio/disoleatore	1u.	Valvola di commutazione
1d.	Giunto	1n	Disoleatore	1v	Cartucce adsorbenti
1e.	Valvola di aspirazione	1o.	Valvola termostatica	1z	Valvola di selezione
1f.	Filtro aria	1p	Valvola sicurezza	1x	Valvola di pilotaggio
1g.	Vacuostato	1q.	Radiatore	1y.	Valvola di sicurezza
1h.	Filtro olio	1r.	Separatore condensa	1w	Motoventilatore

Figure 5: The GPTA

The reliability functions, such as failure rates, probability density functions, have been deduced through the analysis of the maintenance management software "Sigma", used by the owner *Trenitalia*.

The database information, have been first statistically treated to obtain the time distributions of breakdowns, repair and unavailability functions.

SPAR software is an events based reliability simulation code, also capable to represent any maintenance action, such as preventive ("hard time" and "on condition") and corrective operations. Besides its programming interface enables the user to insert in the code some user defined variables and functions, useful in the control of the system.

Not every component of the system can be put under the diagnostics control: the selection of the most relevant items has been made using a Pareto diagram weighted with the severity of the end effect of each failure mode of every item.

The most relevant components resulting from the analysis are the heat exchanger, the fan, the thermostatic valve and the air filter, as visible in figure 6. For each of them a diagnostic control was created in the simulation software.

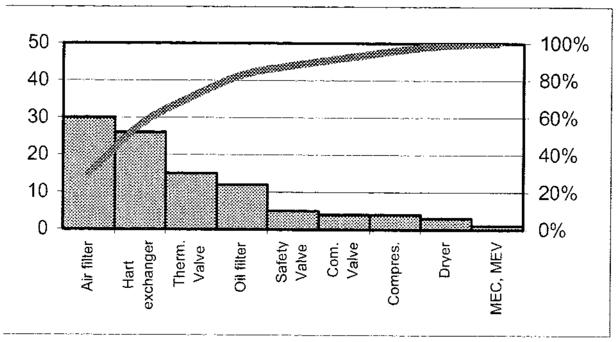


Figure 6: Pareto Diagram

THE DIAGNOSTICS MODEL

To represent a diagnostic system in a simple way inside SPAR environment, we assumed the simplifying hypothesis that every component has only one detectable failure mode.

Each diagnosticated item is represented by the model shown below in figure 7.

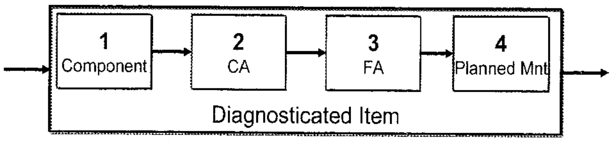


Figure 7: RBD Representation

The RBD logical structure for each component consists of four blocks: the first is the component and the other three are necessary for the representation of the diagnostic system.

Block 1: Component

The failure time distribution is related to the diagnosticable failure modes. The mean time to restoration is related to the maintenance operations not supported by the diagnostic system.

Block 2: Correct diagnostics

The block is activated by a failure event of block 1. With a proportion of β/θ, block 1 is restored immediately. These events represent the CA area. The logic is implemented inside block 2 within the *Bubble Maker* module. The repair time distribution is related to maintenance operation supported by diagnostics.

Block 3: False Alarms

With a $\delta+\gamma$ probability of occurrence, the system faces a maintenance event caused by a false alarm. The repair time distribution is related to a maintenance operation that is not really required.

Block 4: Planned Maintenance
The failure time distribution is related to the maintenance operation for the component.

The above mentioned model can be created thanks to the "Bubble Maker" tool of SPAR, capable of implement the diagnostics logic, create links between blocks, create component management logics and also define some counters to monitor the events of the system.
Following the guidelines just described, a real diagnostic system has been created on a train to validate the model.
Each one of the four components chosen (heat exchanger, oil filter, thermostatic valve and air filter) has been monitored by a specific instrument:

- a pressure gauge for the air filter;
- 3 temperature gauges for the thermostatic valve;
- 3 temperature gauges for the heat exchanger;
- a speed meter for the fan.

The outcoming electric signals had to be filtered to reduce noise and amplified by specific devices.

SIMULATION RESULTS

The most important result of the simulation is the diagram of the probability of the system to be available vs. operation hours visible in Figure 8.

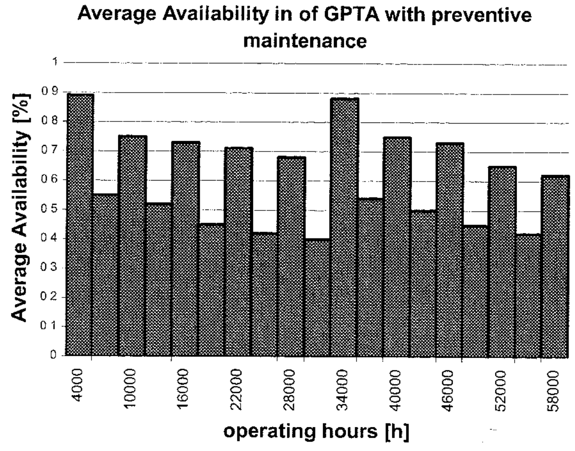


Figure 8: System Probability Of Operation

The parameters used in the simulation are 1500 simulation runs; the time horizon for each history of 58.000 hours, 9 years (corresponding to 4.400.000 km). The time intervals chosen have a width corresponding to the winter and to the summer season.
The summer and winter trends show first of all a great difference between winter and summer (being the latter much more stressing).
Wear is visible in the progressive lowering of the parameter. This is caused by an increasing failure rate of a mechanical plant.

The extraordinary maintenance operation in the middle of the life is very efficient and the system can be considered as good as new.

The average probability of operation, along 9 years, is 61%.
In order to complete a mission at least one of the two GPTAs must be working. So the lowest value of operation probability along 9 years should be 0,5.
The maintenance operators have noticed that a train with only a working GPTA faces more frequent failures due to overheating. This speeds up the degradation process of the system. Hence the correct operating conditions for the train is a parallel running of the two GPTAs, both processing half capacity with the same prevalence.
For this reason the diagnostics have been required to enhance the system availability. Before investing much money on the whole fleet, an economic evaluation could help in determining the benefits resulting from the diagnostics implementation.
In figure 9 there are the results of a GPTA supported by the described diagnostic system. The difference with the previous configuration is highlighted in a lighter colour.

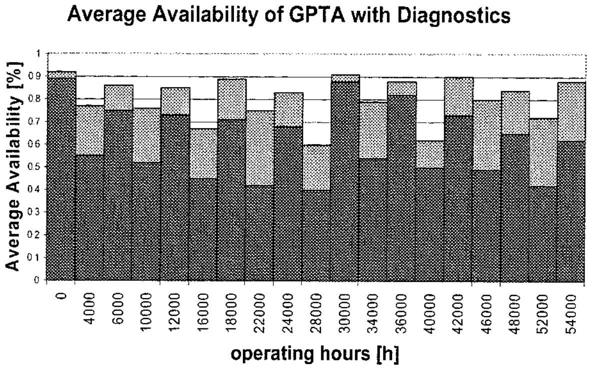


Figure 9: System Probability Of Operation

The new solution provides a remarkable overall increase of the values and a reduction of the difference between winter and summer seasons with a greater improvement for the last. Moreover the wear trend is reduced and the availability parameter never goes under 60%.
Each GPTA presents now an average value for operation probability, along 9 years, of 81% producing a performance growth of 33%.
The results just mentioned have been obtained leaving the former preventive maintenance plan with the introduction of some predictive maintenance operations based on the information coming out from the diagnostic system. In conclusion there will be fewer stops for failure as a result of a more accurate preventive maintenance.
Another interesting observation can be made looking at some figures of the simulation. To do this some counters have been introduced in the model. In table 1 we can observe the number of component failures, in the two different configurations. The left column numbers are the breakdowns of the system without a diagnostic control, while the middle column figures are the events in the diagnosed system. In the right side of the table there is the number of the correct alarms.

Table 1: Number of Failures

Component	No Diagn.	Diagn.	# diagn. interventions
Air Filter	**34.1**	**15.3**	**25.4 (era 45,4)**
Thermostatic Valve	**3.3**	**1.4**	**2.7**
Heat Exchanger	**20.9**	**8.4**	**15.2**
Oil Filter	**4.2**	**2.5**	**2.05**
Safety Valve	5.1	5.3	-

The reduction of failures of the diagnosed items is around 50-65%. In other cases, such as the "Safety valve" the counter has nearly the same value.

These data confirm a good simulation structure and a profitable diagnostic improvement of the system.

In table 2 there is the number of end effects due to some failure within the system. Again there are the results of the two configurations.

Table 2: Number of Events

End Event	No Diagn.	Diagn.
Max temp.	**62.5**	**27.53**
Oil outside GPTA	**62.5**	**27.53**
Water outside GPTA	4.30	4.13
Out of safety	0.10	0.14

The reduction of critical events controlled by the diagnostics (in bold characters) is of about 65%. In all the other cases the counters don't vary significantly.

The new Pareto diagram of figure 10 shows how the first histograms values are smaller than before, thanks to the diagnostics control. The greatest causes of failure have therefore been reduced with a general system reliability improvement.

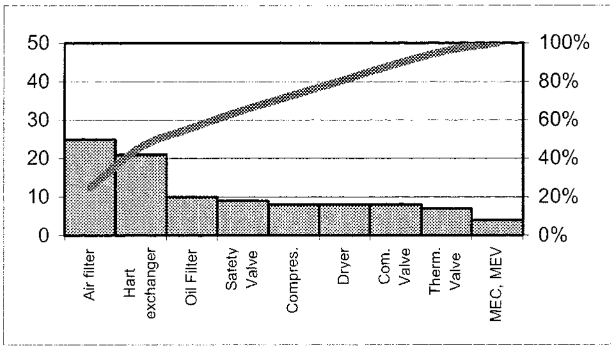


Figure 10: Pareto Diagram with Diagnostics

The first results coming from the exercise of the train provided with the diagnostics have confirmed the results of the simulations, with an increase of availability, although they're not enough for a statistic.

ECONOMIC EVALUATION

The reliability improvement rising from the application of diagnostics to the system has been discussed in the previous paragraphs, underlining the good results. But what about the costs and the benefits? Even when safety or other similar issues are prominent respect to economics, an evaluation of convenience is required. The simulation model can be an useful tool to estimate the availability improvement and hence the indirect cost reduction.

In the present case study the differential costs (initial and management) between the two configurations have been considered.

In the general case the costs difference will be expressed as follows:

$\Delta C_i = C_i nd - C_i wd$

Where the suffix *wd* stands for "with diagnostics" and *nd* for "no diagnostics"

Direct costs

The direct costs are linked to the diagnostic system installation:

$\Delta C1 = C1nd - C1wd = -C1wd$: costs due to the acquisition of the diagnostic system components;

$\Delta C2 = C2nd = -C2wd$: costs of installation, implementation and setup of the diagnostic system on board

$\Delta C3 = C3nd - C3wd = -C3wd$: cost due to material and human resource to manage and maintain diagnostic system;

Indirect costs

These are the most relevant costs and they are caused form the diagnostics introduction:

$\Delta C4 = C4nd - C4wd$: reduction of preventive maintenance time. Diagnostic system guarantees a reduction of 90% time due to failure detection and isolation;

$\Delta C5 = C5nd - C5wd$: reduction of corrective maintenance time, since there will be less failures thanks to the diagnostic system;

$\Delta C6 = C6nd - C6wd$: an higher availability permits a great reduction of out of service costs especially in productive plants, transportation services and so on

$\Delta C7 = \Delta C7_1 + \Delta C7_2 + \Delta C7_3 + \Delta C7_4 + \Delta C7_5$: reduction of trains time lags. This voice can be split into:

$\Delta C7_1$: longer time in line;

$\Delta C7_2$: wider employment of human resource (travel agents);

$\Delta C7_3$: lower guardianship of the "Price Cup" criteria

$\Delta C7_4$: better image of the enterprise brand

$\Delta C7_5$: costs of the costumers' refunds for the violation of time timetable

$$\Delta C_{TOT} = \Delta C1 + \Delta C2 + \Delta C3 + \Delta C4 + \Delta C5 + \Delta C6 + \Delta C7 \quad (4)$$

To get a real economic benefit from the implementation of a diagnostic system the sum in equation (4) must be greater than zero.

Using these assumptions, the diagnostics appliances for the GPTA have shown an attractive advantage.

CONCLUSIONS

In the present work a model of a system controlled by diagnostics has been created with the purpose of forecasting its reliability and availability performances.

The model has been applied to a simulation software in order to analyze the GPTA system as a case study.

The first simulation has described the system *as is* while in the second a diagnostic system was chosen to achieve an improvement of the performances.

The most interesting goal of this research is the comparison of the two different solutions in terms of reliability, maintenance and, last but not least, costs. If this is done correctly, many alternative configurations might be compared and help the decision process.

The technical solution proposed presents low costs and remarkable managerial flexibility.

As a result of the case study, the comparison of the two configurations has highlighted the advantages coming from the introduction of a diagnostic system. The simulation results can also help in the correct sizing of the diagnostics to be implemented. The first effect related to the exercise of the diagnostics is the reduction of failures for the monitored components and of critical events determined by these breakdowns. As a consequence corrective maintenance actions and the undesired stops have decreased of significant numbers.

The following economic evaluation of the GPTA has shown how advanced maintenance techniques are a real profit centre with better performances and lower costs.

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