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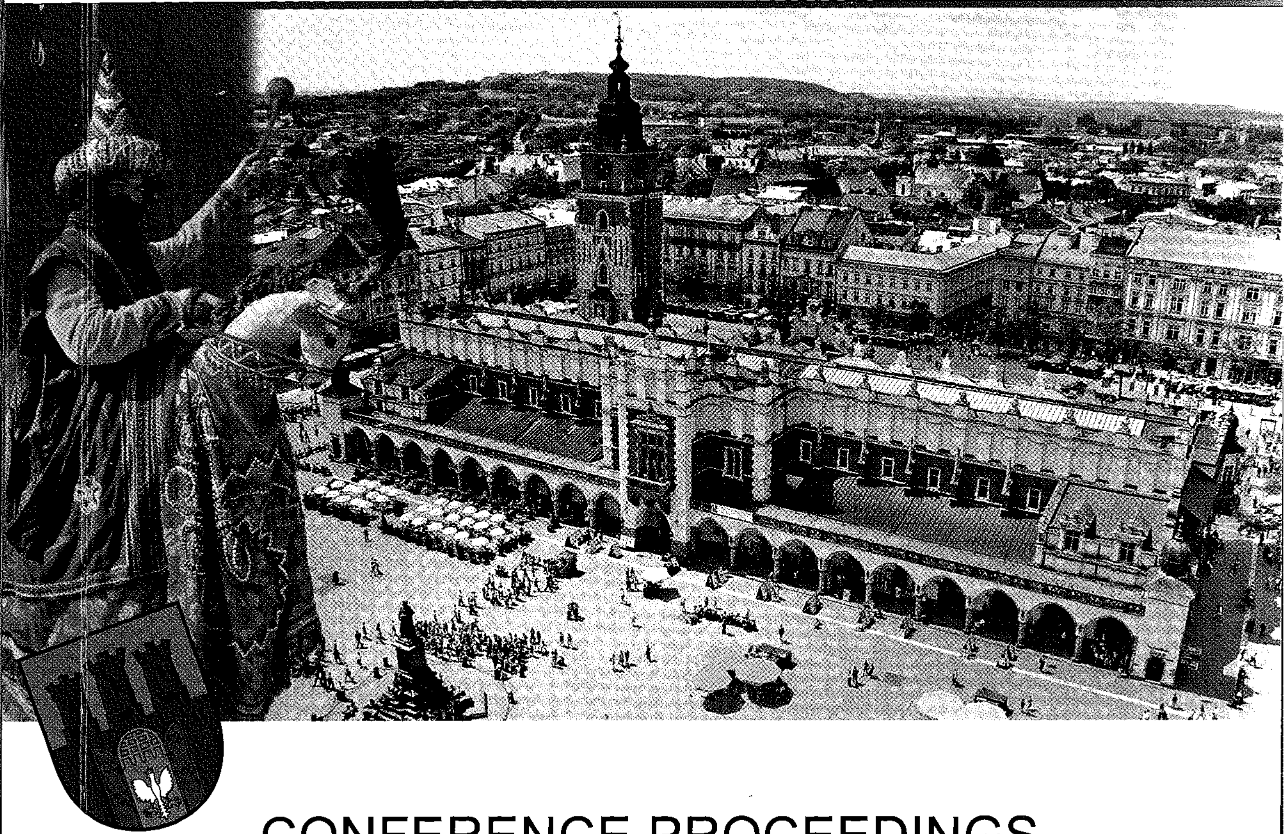

CONFERENCE PROCEEDINGS

THE 4TH INTERNATIONAL CONFERENCE ON SAFETY AND RELIABILITY

KRAKÓW, May 30 - June 02, 2006

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Warszawa, 2006

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APPLICATION OF A MODELING AND SIMULATION FRAMEWORK FOR ASSESSING THE IMPACT OF DIAGNOSTICS ON LIFE-CYCLE COST AND AVAILABILITY

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Abstract: The use of complex technologies, including mechanical and electronic components, doesn't often permit an early and effective detection of the failures. This tendency underlines the necessity to enrich the probabilistic analysis, based solely on a-priori information, with diagnostic methodologies and systems implementing them, leveraging on a-posteriori knowledge of components' behavior. The goal of this study is to propose a modeling and simulation framework to operate a technical and an economic comparison between two configurations: with or without diagnostic support.

1. 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 order to prevent an incipient failure. In this paper, the greatest efforts have been spent to represent a diagnostic system within a reliability simulation software. In such a way, in fact, it could be possible to evaluate the convenience of the implementation of diagnostics, by means of the assessment of differential availability achieved. This procedure can also be useful in the choice of the appropriate diagnostics and in its proper calibration.

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

2. Data collecting and processing

One of the most important requirements to engage in a reliability study of a system is the opportunity to have an available historical database. In the present case the information are deduced from a CMMS (Computerized Maintenance and Management System) giving a big quantity of records. Unfortunately, this kind of information are collected by maintenance operators that, sometimes may produce incomplete or wrong data. So, first of all, it was necessary to carry out a deep and accurate filtering activity to obtain useful data. The most important effort has been made to assign the real causes of a fault, identifying correctly the responsible event.

The second step was the data processing and in this phase it was necessary to consider the problems concerning with the youngness of the database. In terms of information it was translated in a limited number of data for some plant components. In order to catch information also from this peculiar kind of data, we used Time Censored Data Theory. This technique is able to consider properly all the information coming out from censored data. In this case "censored data" are the ones relating to components that at the end of the observation time are still working correctly. There are different types of censored data like, right censored, left censored or both side censored. In our study we consider the right censored ones as shown in the following figure 1.

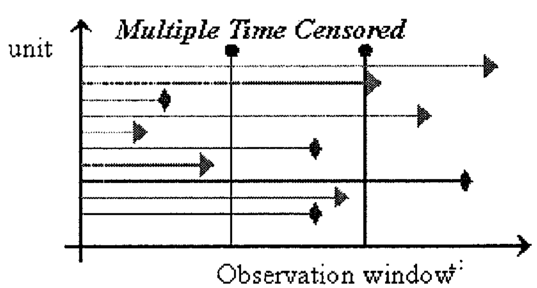

Fig. 1. A time censored data representation

In order to obtain the mean time between failures we applied the statistics known as life table technique. It is a strengthened frequency table that is able to asses, in the time discrete intervals, the failure rate of a component, using: elements that are still working; fault elements and censored elements:

$$\lambda_t = \frac{f_t}{\left(e_t - \frac{f_t}{2}\right) * \Delta t} \qquad (1)$$

Where f_t is the ratio between failed components and the components that are still working in the middle point of the observation interval; and e_t is the number of elements that are exposed to the risk. It comes from

$$e_t = R_t - \frac{c_t}{2} \qquad (2)$$

where: Rt is the number of the components that are still working when they come in the observation interval and c_t is the number of the censored elements. So it can be possible to evaluate the failure rate and its relative standard error inside discrete intervals.

We provide two goodness-of-fit statistics to compare the fit of competing distributions: Anderson-Darling for the maximum likelihood and Pearson correlation coefficient for the least squares estimation method. The Anderson-Darling statistic is a measure of how far the plot points fall from the fitted line in a probability plot. The statistic is a weighted squared distance from the plot points to the fitted line with larger weights in the tails of the distribution. Minitab uses an adjusted Anderson-Darling statistic, because the statistic changes when a different plot point method is used. A smaller Anderson-Darling statistic indicates that the distribution fits the data better.

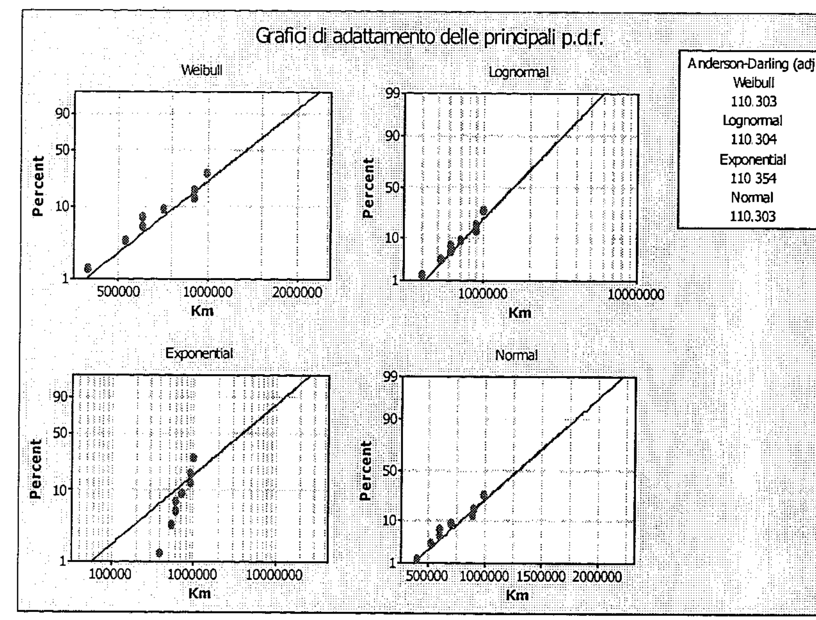

Fig. 2. Anderson-Darling statistic

For the least squares estimation, Minitab calculates a Pearson correlation coefficient. If the distribution fits the data well, then the plot points on a probability plot will fall on a straight line. The correlation measures the strength of the linear relationship between the X and Y variables on a probability plot. The correlation will range between 0 and 1, and higher values indicate a better fitting distribution.

For each component of the facility plant we perform this kind of analysis identifying its main reliability functions. The figure 3 below shows an example.

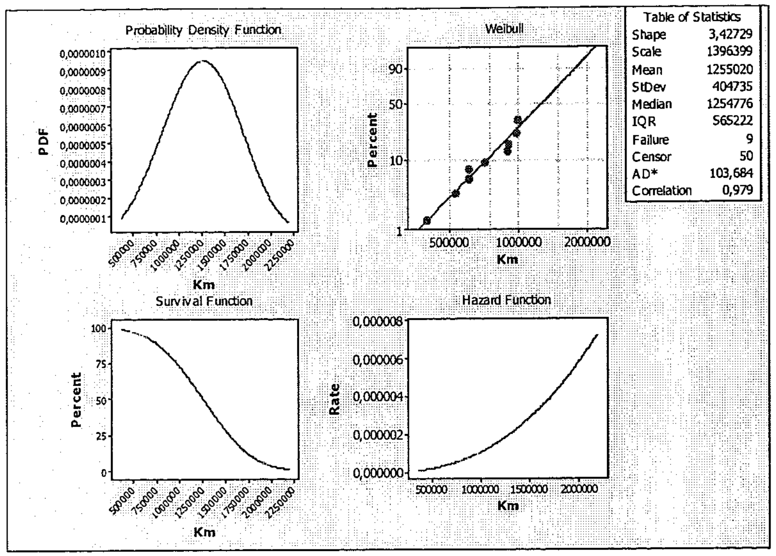

Fig. 3. Reliability function of a plant component

3. 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 4) and air conditioning unit (right side). 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.

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.

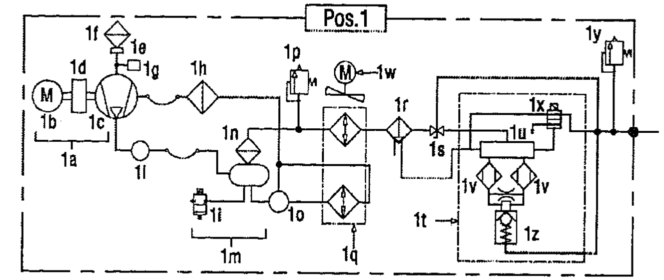

Fig.4. The facility plant

4. 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 5.

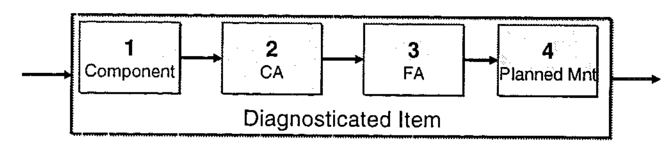

Fig. 5. RBD representation

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.

5. 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 6.

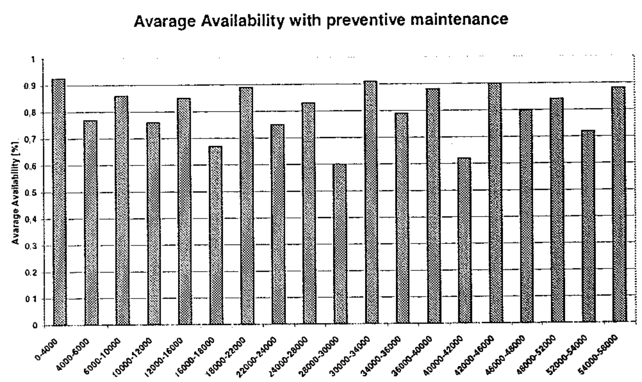

Fig. 6. System probability of operation

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 7 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.

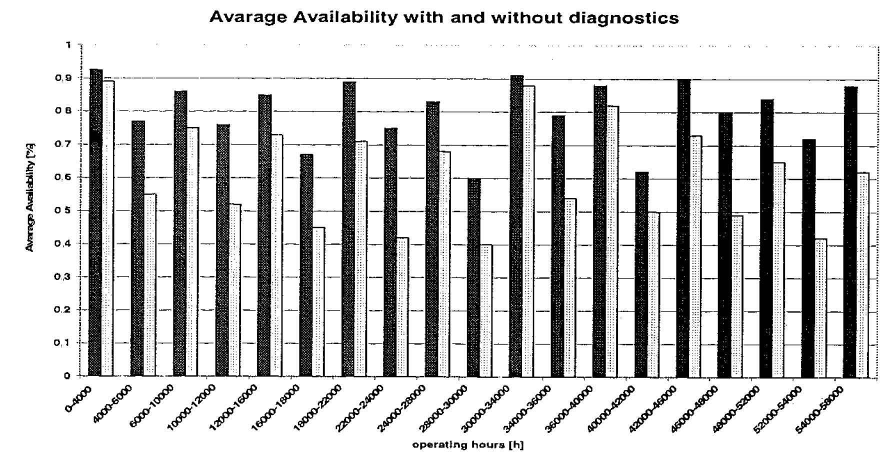

Fig. 7 System probability of operation

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.

6. 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:

$$\Delta C_i = C_i nd - C_i wd \quad (3)$$

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

7. Direct costs

The direct costs are linked to the diagnostic system installation:

ΔC1 = C1nd - C1wd = -C1wd. The cost due to the acquisition of the diagnostic system components. So C1wd = 0 and C1nd = €1500 for 6 temperature gauges and 1 pressure gauges. The electronic acquisition slot and the CPU are already available in the train electronic control system;

ΔC2 = C2nd - C2wd = - C2wd. The cost due to the human and economic resources for installation, implementation and setup of the diagnostic system on board. So C2nd=0 and C2nd is given by the following elements: Installation on board of the diagnostic system: 10 man-hours, Implementation and setup on board of the diagnostic system: 10 man-hours, Training of the maintenance teams to use the diagnostic system: 20 man-hours. So $\Delta C2_{cd} = (20+20+20) \cdot p_u$ considering negligible the cost of commercial raw materials.

ΔC3 = C3nd - C3wd = -C3wd. The cost due to material and human resource necessary to manage and maintain diagnostic system. As well as all direct cost C3nd = 0. Planning maintenance activity requires half an hour for each operation every six months, so $\Delta C_{wd} = 0{,}5 \cdot 2 \cdot c_m$ where c_m is the cost of one man-hour inside the maintenance shop, covering human and materials resource. We decided not to asses corrective maintenance costs because the diagnostic system failure rate is negligible compared to the other main components.

8. Indirect costs

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

ΔC4 = C4nd - C4wd. This cost (negative because it's a gain) is due to the reduction of preventive maintenance time. Commonly, maintenance time could be split as follows: fault research time: 40-55%; fault repair time: 30-40%; test time: 10-15%. Introduction of diagnostic system guarantees a reduction of about 80% time. This is caused by the quick failure detection and isolation gained by the automation of the fault research actions. This advantage is not quantifiable because the work sheets report only the overall maintenance time. Therefore, the maintenance operations time splitting could be a good way to improve the maintenance processes control.

ΔC5 = C5nd - C5wd. This cost (again negative because it's a gain) is due to the reduction of corrective maintenance operations, since there will be less failures thanks to the use of the diagnostic system. It could be assessed by the following formula: $\Delta C5 = [(n_{msd} - n_{mcd}) \cdot h_{msd} \cdot c_m]$, where:

- n_{msd}, it is the average stops number due to corrective maintenance operation when the facility is without diagnostic system, that is equal to 6.2. This values comes from simulation result and it is confirmed from the company database data,

- n_{mcd} , it is the average stop number due to corrective maintenance operation when the facility is supported by a diagnostic system, that is equal to 3 and it comes from simulation results,
- h_{msd} , it is the average time, expressed in hours, spent for a corrective maintenance operation not supported by a diagnostics, that is about 23 h. This value represents all the stop time,
- c_m , as above mentioned.

$\Delta C6$ = C6nd - C6wd. This cost is due to an higher availability that permits a great increase of the productivity of the capital stock (Asset). It is assessable by $\Delta C6 = [\Delta A_m \cdot H \cdot \gamma \cdot e \cdot \varphi]$, where:

- ΔA_m , it is the average increase of the facility availability, with and without diagnostic monitoring. The value is about 0.18 and it is evaluated by simulation results;
- H, it is the average time operation, carried out by the plant along a year, (6000 h);
- γ , it is the commercial value of an operation plant hour (this parameter is covered by the company privacy);
- e , it is the percentage of the available plant hours that are actually used to produce. Company calls it utilization percentage and appraises it as 75%;
- φ , it is the weight of the facility plant availability compared to the overall plant availability. Company appraises it like about 5%;

$\Delta C7 = \Delta C7_1 + \Delta C7_2 + \Delta C7_3 + \Delta C7_4 + \Delta C7_5$. This is due reduction of delay and it can be split into five different voices:

- $\Delta C7_1$: this cost is due to a longer operation time. The transport company pays the occupation of the track, to the owner of the railroad. As the following graph shows, it is proportional to the delay time, but it is not dependent from the fault cause (**a** parameter is covered by the company privacy statement),
- $\Delta C7_2$: this cost is due to a wider employment of human resources. On the train there are four travel agents: two are the drivers and the others are the crew. As the previous cost function, this one is independent from the fault cause (**b** parameter is covered by the company privacy),
- $\Delta C7_3$: this cost is due to the guardianship of the "Price Cup" clause, depending on which the Company may increase the ticket prices, as established from the National Transports Authority. Only the Company knows the value of $\Delta C7_3$,
- $\Delta C7_4$ represents the better image of the Brand. It is hardly assessable but it's still very important,
- $\Delta C7_5$: this cost is due to the costumers' refunds for the delays. As the following picture shows, it's a discontinuous function.

Step values have the following meaning:

- Y1 is the bonus value that the company refunds to the costumers if the delay is between 30 and 60 minutes (Y1 parameter is a direct function of the ticket price),
- Y2 is the bonus value that the company refunds to the costumers if the delay is over 60 minutes (Y2 parameter is a direct function of the ticket price).

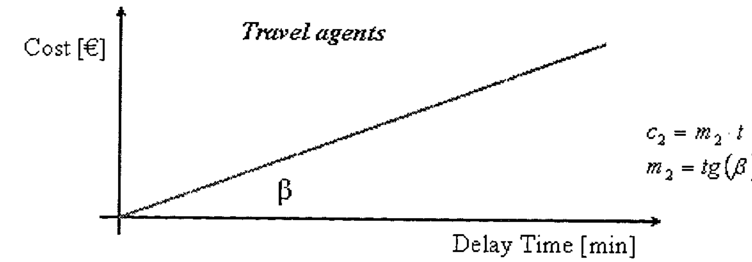

Fig. 8. $\Delta C7_2$

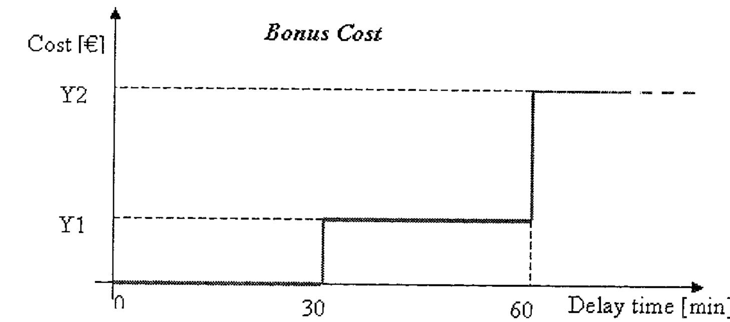

Fig. 9. $\Delta C7_5$

The overall $\Delta C7$ cost curve is reported in the figure below. As you can see, it is characterized by three different functions related to three different delay time intervals.

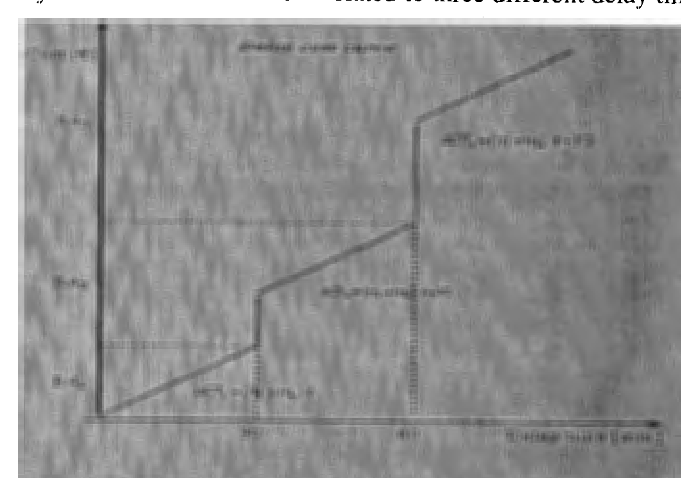

Fig. 10. $\Delta C7$

The profit coming from delay reduction is the following:

$$\Delta C7 = \Delta N_{<30} \cdot \Delta C7_1 + \Delta N_{30-60} \cdot \Delta C7_2 + \Delta N_{>60} \cdot \Delta C7_3 \qquad (4)$$

where:

- $\Delta N_{<30}$, it is the average year's difference of delays number that are lower than 30 minutes. this numerical value comes from simulation results and it is about 0.037,
- $\Delta N_{30\text{-}60}$, it is the average year's difference of delays number that are between 30 and 60 minutes. This numerical value comes from simulation results and it is about 0.023,
- $\Delta N_{60>}$, it is the average year's difference of delays number that are greater 60 minutes. This numerical value comes from simulation results and it is about 0.015.

To get a real economic benefit from the implementation of a diagnostic system the overall differential cost ΔC_{TOT} between the old and the new configurations, must be greater than zero.

$$\Delta C_{TOT} = \Delta C1 + \Delta C2 + \Delta C3 + \Delta C4 + \Delta C5 + \Delta C6 + \Delta C7 \qquad (5)$$

As previously told the early three terms are negative because they are due to the physical introduction of the diagnostic system but the main voices are the last four ones. Using these assumptions and analyzing the simulation results, the diagnostics appliances for the GPTA have shown an attractive advantage.

9. Possible improvements

In the previous paragraphs we faced the problem from the maintenance point of view. In this section we present some technical indications about a few plant components which may increase their own reliability. One of the most dangerous processes that may have a negative influence on the plant performance is the fast dirt trapping of the air filter.

We can face it monitoring the pressure drop across the filter or the temperature rise between the inlet and the outlet of the heat exchanger, as previously said, but an useful solution is to redisegn the bulkhead. A bulkhead with a better filtering function could resolve the root cause of many maintenance actions. The figure 11 shows the actual on board bulkhead.

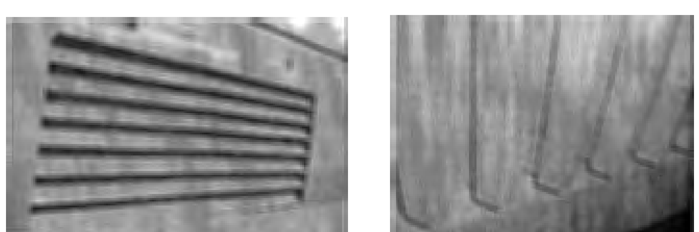

Fig. 11. The two different bulkhead

In the next Figure we indicate a possible solution that comes from another high speed train application. As pictures shows there is an important difference: the first bulkhead has got just a protective function. The second one has instead also a filtering function. If we decided to move towards the second solution, we'd need to assess the pressure drop across the bulkhead, because this solution could not permit the air to preserve enough speed for cooling.

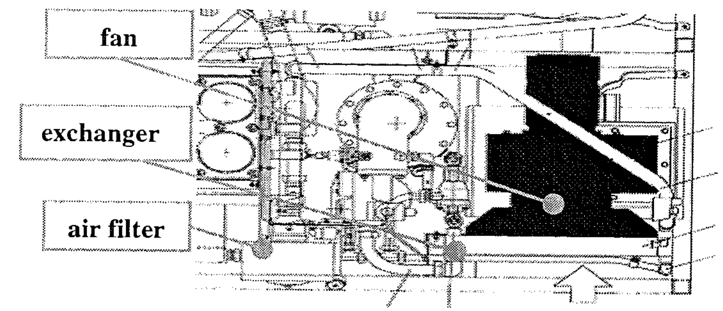

Fig. 12. The plant components behind the bulkhead

Another important undesiderable consequence of the bad facility performance is the presence of oil condensate in the forward plants that use compressed air. It is due to the ineffectiveness of the mechanic disoleator and the coalescence filter but the root cause is the general high operation temperature that doesn't guarantee a sufficient oil viscosity capable to divide it from process air. The main bad effects, due to the oil, are: the frequent out of operation states of the dryer cartridges to air dehumidification and the premature wear process of valve membranes of the forward plant components.

The solution proposed is to add a second coalescence filter, posed after the exchanger, where the flow temperature is lower and the viscosity is great enough to divide the oil. This application is already operating on a similar facility plant with good results. In the following figures is shown the position that the second coalescence filter should have and its cartridge. As you can see, the prevalent colour is red, due to the iron impurities.

Fig.13. The coalescence filter

10. 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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DYNAMIC SEARCH AREA DURING SEARCH AND RESCUE OPERATION

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Abstract: In the article there are presented problems associate with determine search area during rescue operation at sea. We compare size of the search area and search effort available which is considerably smaller. Determining of search area was based on a new model which taking into consideration local hydro-meteorological conditions. As a conclusion we proposed determining of dynamic search area as possible solutions of that problem.

1. Introduction

Search and Rescue operation is a very complicated and difficult part of work at sea. Before the SAR operation begin there have to be determined proper search area. Search area should be as small as possible and simultaneously probability of staying of searched object inside the area has to be high. Nowadays search area is determined at the beginning of the operation. For most cases it is few (two, three) hours after the disaster. The area is then searched through. Method recommended by International Maritime Organization used to determine search area allows for limit area to about 80 square nautical miles (3 hours after disaster). In most rescue operations number of rescue units is very restricted, weather conditions are bad, sea is high. It is very difficult or even impossible to search whole that area in acceptable short period of time. Time is very important factor because of the low temperature of water. Hypothermia (abnormal lowering of internal body temperature) in cold Baltic waters occurs about one hour after the survivors have been found in water. So we have to determine datum area i.e. area where it is estimated that the search object is most likely to be located, very precise.

Research team from Gdynia Maritime University has worked out a method of determining search area for South Baltic which allowed obtaining significantly smaller area. That method takes into account actual speed of surface sea current at South Baltic and also dependence between speed and direction of wind and sea current direction in Polish Search and Rescue Region. There were made experiments for different types of raft to obtain their velocity caused by wind. That method not only gives smaller search area but also datum point is determining better than in so far used methods. All further diagrams and calculates in this article are based on Gdynia Maritime University method.