Two Methodologies to Support Gas Turbine Power Plant Availabilty Estimation: Design of Experiment and Montecarlo Simulation

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Abstract - Maintenance is an important aspect in order to guarantee the efficiency of industrial facilities. For power plants the high availability ratios can be obtained only with preventive maintenance but the result costs increases rapidly. In order to reduce the cost level of the maintenance activity, on-condition maintenance is carried out on an increasing subset of components. Only using appropriate reliability models can identify the optimal mix between preventive and on-condition maintenance. Some time the data required by such models are inadequate or missing and the performances of the implemented system can fall quite rapidly. The authors propose an innovative approach based on a hierarchical Montecarlo simulator able to estimate properly the power plant reliability and, at the same time, improve its performances by a fine-tuning of its parameters. A real life case study is than presented and discussed, even with economical consideration.

Key Words - Reliability, Fuzzy Logic, Model Estimation, Montecarlo Simulation, Design of Experiment

1. Introduction

The availability and reliability of a complex system is influenced by a wide range of stochastic factors (i.e. component failures, control breakdowns, etc.), then it is difficult to create "ad hoc" reliability analytical models allowing simulation as the only approach. Particularly Montecarlo simulation has proven to be very effective in the evaluation of the general availability ratio as well as a way to improve the maintenance plans.

Maintenance simulation, however, involves several complex aspects (i.e. model conceptualisation, data collection, statistical analysis on input data, forecasts, etc.) that require ad hoc approach to be solved. Lack of data is one of such key aspect that engineers and managers have to face in order to provide a real useful simulation. Among the various aspect of the maintenance related to economical aspects (spare parts inventories, maintenance workload, etc.) two key parameters have to be properly estimated:

- MTBF: Mean Time Between Failure;
- MTTR: Mean Time To Repair.

The MTTR parameter is easy to estimate since it can be obtained a priori from a work schedule or as a summary of the performed maintenances, while the MTBF is some time very hard to estimate. Since MTBF can be obtained only from sampling real life components or by applying complex analytical models, it is generally available only for high - standardized products (i.e. lamp bulbs, microchips, etc.).

The proposed approach involves the design and implementation of a general-purpose hierarchical Montecarlo simulator in which are known some of the MTBF parameters and a procedure for the estimation of the unknown one. By using Analysis of Variance (ANOVA) techniques the authors successfully identified a configuration of the simulator able to reproduce the behaviour of a real power plant.

2. The Implemented Approach

The values of the MTBF for each component in each possible failure configuration are generally known in term of probabilistic distributions, in fact several studies were carried out by many authors in order to define a closed form for such distribution, but for some cases empirical models obtained by historical real data histograms are still used. For certain components the real distribution of the MTBF can only be guessed using similarity with other components whose reliability parameter are better known. By using simulation is possible to estimate the effect of a failure on a real system and, at the same time, estimate the maintenance related cost; such costs, in fact, can involve many factors (i.e. resources, spare parts, know how and skills) and raise the economic effort of the programmed maintenance planning. The most applied simulation approach for maintenances related studies is generally the Montecarlo technique; such methodology is quite easy to apply and requires a preliminary data-mining phase to be really effective. In the presented approach Montecarlo simulation parameters are self-tuned by the simulator itself during the Verification and Validation phase (V&V) by applying the Design of Experiment (DoE) technique to the simulator parameters. In this way the model is driven to its correct configuration step by step. The implemented model is hierarchically structured on different levels, where there are Series, Parallel and “Almost-Parallel” components (see fig. 1).

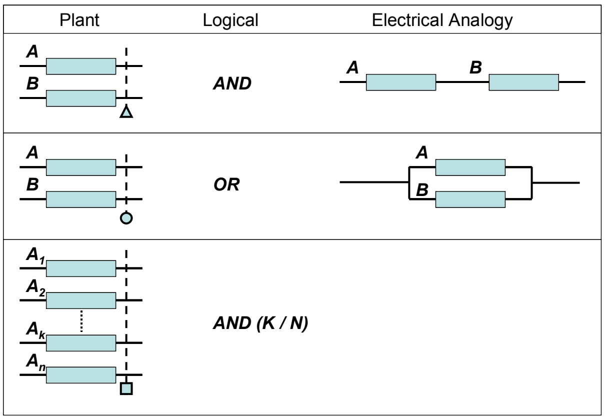

Figure 1: The Components Analogy Schema

A series component can be considered available only if all its components are available, a parallel component is considered available also if only one of its subcomponent is available while a “ <k/n> almost parallel” component can be considered available if are available not less than k subcomponent on a total of n. Example of such components can be considered looking at the following table.

Table 1: Example of Components Classification

Item	Classification	Logic
Motor	Serial	AND
Pump B	Parallel	OR
Cooling	<3/4>Almost Parallel	AND(K/N)

As it is possible to notice, the complex of a Motor – Pump can be considered available only if both the motor and the pump are not in a failure state. For a backup pump group the service is granted also if only one of the backup pump is out of failure. The last case is typical of modular plant components in which the service is divided among the various modules with some extra capacity, in such way the cooling service can be carried out also by 3 cooling tower on a total of 4 and the *Cooling Tower Group* can be classified as “<3/4> Almost Parallel”. The presented conceptualisation is very useful for direct application since it can be easy understood and described directly in the plants blue prints simply using the symbols presented in figure 1.

Since “<k/n> Almost Parallel” means that at least k of n components must work properly to avoid the whole system failure, both the series and parallel systems can be described in term of such classification as in table 2.

Table 2: Component Schema Generalization

Schema	Alternative Classification	Base Component Schema
Serial	<N/N> Almost Parallel	Almost Parallel
Parallel	<1/N> Almost Parallel	Almost Parallel

By using a unique model of component the entire conceptualisation process of a complex plant can be downsized and the proposed approach can be applied to a wider range of applications.

The basic component for building the Montecarlo Simulator is then based on the <k/n> Almost Parallel schema; the state of such component is defined by the Boolean set presented in table 3.

Table 3: Example of State Classification

State	Variable	Value
Working	On_Failure On_Maintenance	FALSE FALSE
Under Failure	On_Failure	TRUE
Under Maintenance	On_Maintenance	TRUE

The components start its life in working state and remains there until a programmed maintenance event is reached or a failure occurs. During programmed maintenance failures cannot occur while a recovery from maintenance can postpone a programmed maintenance event.
For each component only one MTBF has to be specified in order to reduce the number of unknown parameters, such MTBF will be used to tie up the event of failure of the component, while the nature of the failure and the related MTTR will be fixed within a second step (see figure 2).
The MTTR is then related to the nature of the failure and to the availability of the maintenance task force. Simulation of the task force can be obtained by using the WSS&S Maintenance Simulator Module integrated in the proposed methodology.
By using the WSS&S Task Force simulator, the user can determine the correct repairing time taking into account the nature and the organization of the work as well as the availability of the various resources. Such approach was developed for the *Arsenale di Taranto,* a Base of the Italian Navy, in 1998 and has proven to be very effective.
The maintenance process is divided into Tasks (a set of allocated resources) and than organized in Jobs (sequence of tasks) scheduled according to a Phase set (list of scheduled jobs).
At every simulated step the resource available at plant maintenance facility are evaluated and the intervention requests accomplished according to their priority.
Programmed maintenance is carried out according the maintenance schedule defined for each component in the system, also the maintenance time is determined using the WSS&S simulation module.

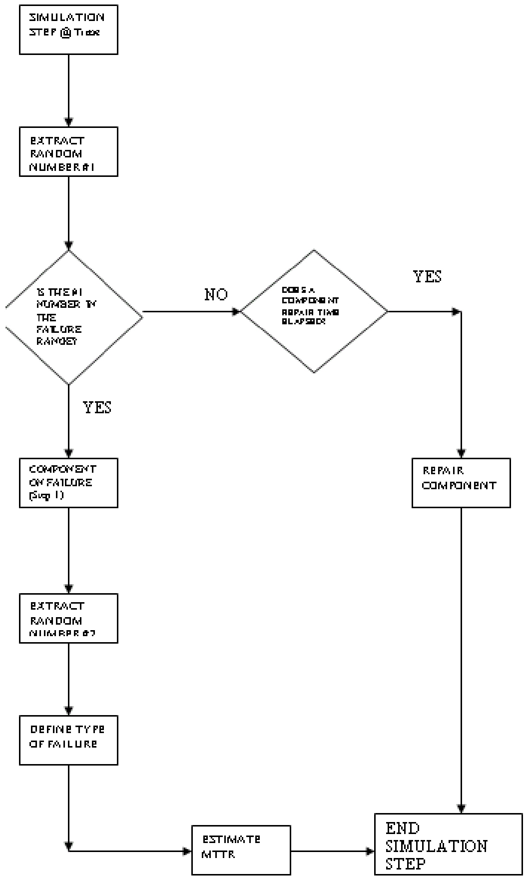

Figure 2: The Simulation Process

3. The TARAS Hierarchical Montecarlo Simulator

TARAS is a general-purpose hierarchical simulator designed to implement the proposed approach for a real power plant. Such tool provides a powerful GUI (Graphical User Interface) able to help the designer to define the components functional schema of the simulated systems simply with a few mouse clicks. For each component a Database provides, through a JDBC-ODBC™ connection, the failure mode and maintenance procedures; in this way the user can keep update the configuration of the simulator while he is performing maintenance on the enterprise data management. Since part of the reliability analysis is obtained by analogy with other systems (i.e. failure rates), the system can manage different scenarios and provide tradeoffs among the various solutions. The general GUI is presented on figure 3: in such picture it is possible to notice the Plant Tree in which each component is placed according to its hierarchical position. Thus a plant can be decomposed in macro systems and, step-by-step, decomposed in low-level components. Such approach can offer great advantages in terms of conceptualisation capability since it can offer a complete top-down approach for the functional schema and a bottomup methodology for the failure mode analysis. Starting from the entire plant as the root of the tree, the user can easily identify the main sub components and then explode them up to the simplest item for which the failure rate is generally known. In the proposed example a cooling tower is a sub component for which the failure rate is unknown, by decomposing it into the TARAS tree the various low level parts (i.e. valves, pump blades, transmission belts, etc.) are identified and their failure rate can be obtained from the literature.

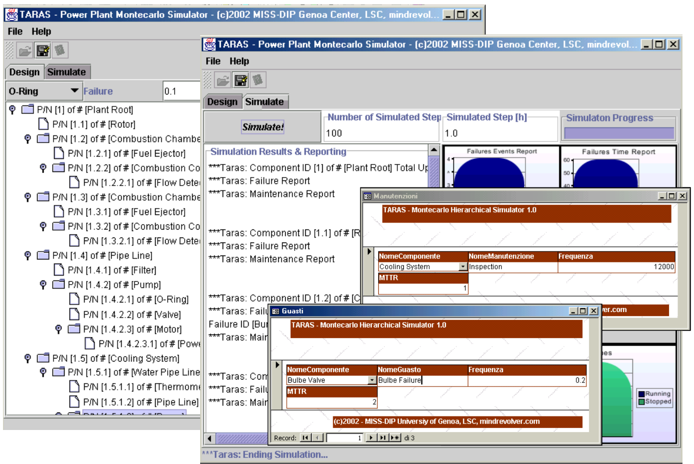

Figure 3: TARAS Graphical User Interface

4. DOE for MTBF Parameter Fine Tuning

For the failure rate that cannot be estimated by looking at their subcomponents, it is necessary to provide an estimation of the MTBF in order to fine-tune the model. A way to accomplish such task can be obtained by using Design of Experiment (DoE) techniques.

At the beginning of the fine tuning procedure the model is loaded with all the known parameter, and the unknown k-MTBF$_i$ are estimated with the double of their longest scheduled maintenance intervals while the interaction i is set equal to 1. As an example, it is possible to consider for component H that has a scheduled maintenance every 10000 hours, a first MTBF tentative of 20000h. All the k-unknown parameters are then estimated and the simulation is run. Such preliminary simulation is used to evaluate the MSpE (Mean Square Pure Error) time evolution in order to estimate the appropriate simulation ending time. As target function the average of the ratios between the simulated failures and the expected ones, weighted by their repair costs, is calculated; in such way the fine-tuning procedure will operate on the most expensive gaps. The next step is to place $i = 2$ and to start a 2^k design taking as lower bound and upper bound of the k-unknown respectively:

$$\min MTBF_{i+1} = \frac{1}{2} MTBF_i$$

$$\max MTBF_{i+1} = 2 MTBF_i$$

Using the sensitivity analysis the gap between the simulated objective function and the expected one can be calculated. By using the F-test, a subset of k' unknown on a total of k can be calculated and a regression metamodel is determined, by using such metamodel the values of the k' unknown minimize the gap between the expected value and the simulated one. Taking into accounts such k' values a new step is initiated until the maximum number of step is reached and/or the gap is acceptable. The entire fine tuning procedure is presented in figure 4.

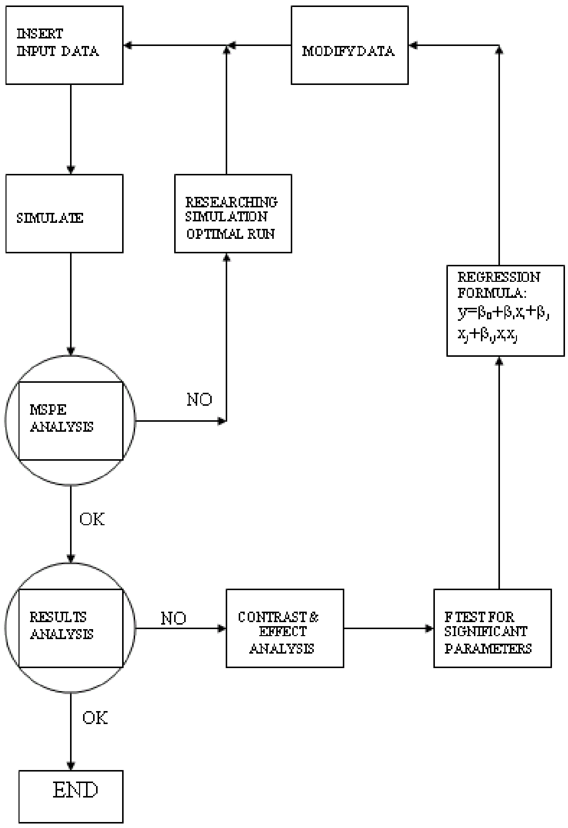

Figure 4: The DoE Based Parameter Tuning

The simulation model is based on Monte Carlo method: the model generates a random number in a range and then shows, according to the number extracted, which components are not working, if there are, why and their MTTR.

For what concerning programmed maintenance, it is sufficient to see when the last failure occurred in order to see if the part has to be substituted; in this case it is to be considered the fact that a part has to have a maintenance

intervention only when it is still working, not when it is broken, neither while it is repaired.
The input parameter is the failure probability for each component, that could be already determined or not, for this last case the first step foresees to insert a random input data, then to simulate and to analyse the MSPE: if it is ok, the optimal simulation run time is found, else the run length has to be modified.
Then there are the results to be analysed by the contrast theory on the parameters, the F test on them, in order to know which are significant and then using the regression formula to find the solution to be inserted in the input data.

5. The Experimental Campaign

The model has been applied to a gas turbine power plant whose scheme is presented in figure 5:

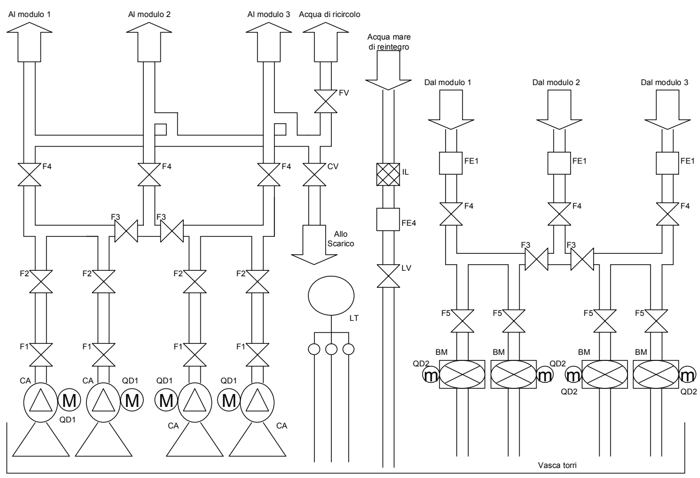

Figure 5: Technical scheme of the power plant

The data provided for the experimental campaign cover a period of about five years, in which all the intervention types have been classified and catalogued, taking into account also the fact that the maintenance policies evolved with time, guaranteeing a maintenance management more responding to the real plant issues. Table 4 represents all the maintenance activities, subdivided by the different intervention types, for years 1997-2002.

Table 4: Plant Maintenance Activities, classified per year and typology

	1997	1998	1999	2000	2001	2002	Total
AN	2	73	108	124	96	31	434
PI	0	6	3	1	0	1	11
MP	0	12	136	301	291	142	882
FA	0	19	28	2	10	1	60
RG	0	0	0	0	0	2	2
MC	0	3	8	14	4	1	30

It is worth underlining that the greatest part of the preventive maintenance intervention are performed during the programmed plant stop during summer holidays (around the 15th of August) in order to perform maintenance in a “masked time”: that is why the number of preventive maintenances are so low.
In particular the study focuses on the anomalies and the emergency intervention; in order to do this, it is worth to identify and evaluate the peculiar activities for every single item; the aim of this approach is to standardize activities trying to divide them in actions where possible. A deductive classification has applied identifying the so-called “Top Events”, which are the cause of failure or deviation from the original item’s mission, referring partially to the FMECA methodology, with the main difference that the events occurred are analyzed “a posteriori”, implying an assessment of the activity types, of the resources employed and the intervention execution priority.
Classification is provided on the basis of historical data derived by the closed working orders stored in the plant Information System. In order to successfully couple these data with the item families, some procedural steps need to be performed:

1. divide the plant in elementary functional groups;
2. distribute anomalies and emergency intervention among the different items, sorting the executed activities;
3. distribute anomalies among the functional groups.

Functional groups are defined as a set of similar items; two or more items are considered similar if they present some particular features:

- similar sub-components;
- similar maintenance conditions;

- similar spare parts;
- various working conditions.

After defining the functional groups and classifying them, the following step provides the analysis of the anomalies and the emergency interventions, considering the costs related to the item and the number of failures sorting them by the repairing cost as in a Pareto Diagram. As an example, figure 6 represents the diagram for the Electric Engine item.

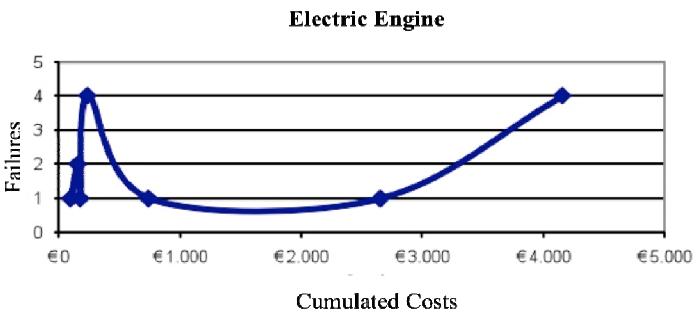

Figure 6: Power Plant Electrical Engine Failure Analysis

Although the Pareto analysis was able to obtain some indicative considerations, allowing the individuation of the most critical components, Monte Carlo simulation is the best solution to identify the most suitable maintenance policy to be adopted. The simulation inputs in the model are the following:

- the Items' Failure Rate λ;
- the Simulation Run Time t^* (expressed in hours);
- the Number of Simulation Runs N_0.

The first two inputs are determined in the initial phase of data settings, but the simulation run time, together with the number of runs, must be a significant value; in order to do this, a Mean Square Pure Error (MSpE) analysis must be performed, and the figure 7 shows the trend of this function calculated as follows:

$$MSpE_t(t) = \frac{\sum_{i=1}^{n}\left(Y_i(t) - \frac{1}{n}\sum_{k=1}^{n} Y_k(t)\right)^2}{n-1} \qquad (1)$$

where $Y_i(t)$ is the value of the objective function for the *i-th* run of n total runs.
After a certain number of runs the MSpE function reaches stability: this is the optimal number of replications –or the optimal run duration- to be launched.

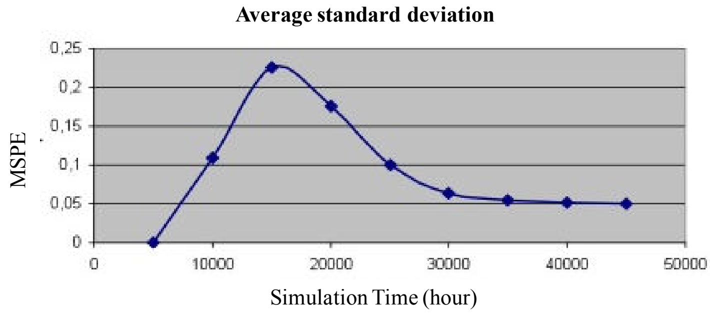

Figure 7: MSpE Graph

Analyzing the MSpE curve, for the item examined in example, a value of 39800 hours is an optimal duration for the simulation run time, as confirmed also in figure 8, that represents the trend of the experimental error for the same component.

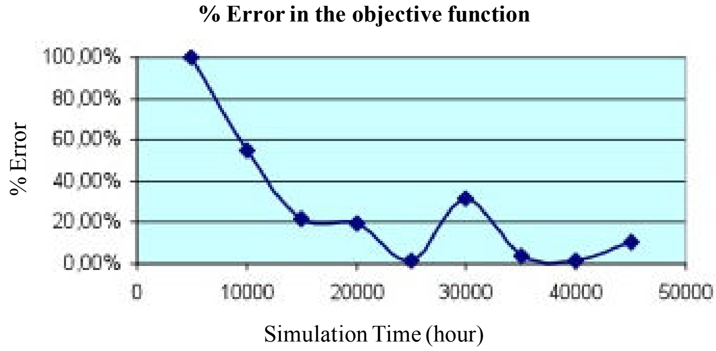

Figure 8: Experimental Error Graph

As seen on figure 8, after a run time of 39800 hours the experimental error is less that 5%, confirming the suitability of the value set as run time.

As model outputs, some parameters have been considered in order to evaluate the reliability of the single item and the belonging functional group; in particular it has been examined:

- utilization Coefficient, representing the item workload in the analysis time, it is devoted to identify the functional group operating with the higher workload.
- Theoretical Availability, that indicates the availability value that every item should have theoretically
- Simulated Availability, that represents the availability value of an item considering programmed maintenance and failures. It is calculated taking into account the right failure rate and the data obtained by the simulation and historical data. The formula for the simulated availability is the following:

$$Simulated\_availability = \frac{Total\_up\_time}{Total\_up\_time + Total\_down\_time} \qquad (2)$$

- Actual Availability, that considers also the waiting time due to the temporary resources unavailability because already taken up by other maintenance interventions more urgent, introducing the concept of limited resources and intervention priority.

- Failure Rate, calculated on the basis of the FMECA methodology for every item of a functional group and for the functional group itself considering the relationships among the different items.

- Reliability, assessed for each item during the time interval between two programmed maintenance operations. For the functional groups reliability is calculated starting from the total failure rate using the lower frequency of programmed maintenance.

Table 5 provides an example of simulation results.

Table 5: Example of Simulation results

GRP	Description	Reliability	Availabiity	Costs for corrective maintenance
VA	Sea water basin	0,7049	0,9983	3680
CT 3073	Conductivity meter	0,6071	0,9986	120
CT 3097	Conductivity meter	0,2586	0,9557	5062

6. Economical Considerations

In addiction to the determination of the parameters mentioned above, an economical analysis has been performed in order to identify which are the most critical items in terms of costs.

Upstream to this analysis, it is necessary to identify the maintenance types considered for the economical treatment, dividing them into preventive and corrective maintenance.

The preventive maintenance is defined as "a planned strategy of cost-effective treatments to an existing system that preserves it, retards future deterioration, and maintains or improves its functional condition, without significantly increasing the structural capacity", while the corrective maintenance can be defined as "the maintenance required when an item has failed or worn out, to bring it back to working order".

In this work, two different types of both corrective and preventive maintenance have been identified: for the former there are the Emergency Services (PI), and the Anomaly Resolution (AN), while, for the latter, the Periodical Programmed Maintenance (MP) and the Annual Programmed Maintenance (FA) have been identified:

- The PI intervention includes all the maintenance and repairing operations that are urgent and cannot be postponed in order to guarantee the business continuity and the plant safety.
- For Anomaly Resolution (AN) it is intended all the operations considered as the "normal" problems encountered by the plant; they must be fixed, but they are not so urgent to not be postponed to the appropriated time slot. Any case the supervisor has to evaluate the "weight" of the intervention required.
- The MP operations regard all the programmed maintenance activities to be performed more than once a year on plants, items and equipments without stopping the plant production or workability. Also for this kind of operations the safety regulations must be respected.
- The FA operations finally concern all the maintenance activities performed once a year in relation to the worked hours, foreseeing also the plants stop in order to proper execute the intervention on particularly sensitive items like turbines or gas compressors.

Once identified the maintenance types, as a first step, a generic evaluation has been provided, determining the maintenance costs as a function of the repairing time, multiplied by a fixed hourly cost, depending on the maintenance type.

Table 6 represents the recap of the activities performed and the hours employed for each maintenance workgroup for the failure maintenance intervention.

Table 6: Activities Performed and Worked Hours for AN and PI intervention by workgroups

Workgroup	Activities	Hours
WG1	119	1608
WG2	140	652
WG3	18	367
WG4	42	862

Table 7 represents the subdivision by the operative specialties instead of the workgroup; showing a strong preponderance for the mechanical activities in the failure maintenance intervention.

Table 7: Activities Performed and Worked Hours for AN and PI intervention by operative specialties.

Specialty	Activities	Hours
Mechanic	137	1975
Instrumental	140	652
Electric	42	862

For what concern the programmed maintenance (MP & FA), the results are presented in Table 8, it is worth underlining that in this case there is no distinction between workgroups and specialties because the workgroup WG3 is involved only in failure maintenance, and the mechanical, instrumental and electrical specialties are covered respectively by WG1, WG2 and WG4.

Table 8: Activities Performed and Worked Hours for MP and FA.

Specialty/WG	Activities	Hours
Mechanic/WG1	72	3248
Instrumental/WG2	915	6439
Electric/WG4	128	820

Summarizing all the activities, both for corrective and programmed maintenance, the results obtained for the four different workgroups are determined and presented in Table 9.

Table 9: Activities Performed and Worked Hours by each workgroup for failure and programmed maintenance.

Workgroup	Activities	Hours
WG1	191	4856
WG2	1055	7091
WG3	18	367
WG4	170	1682

Further dividing by the operative specialties, the results presented in Table 10 are obtained, underlining a significant presence of instrumental operations; necessary for the system analyzed (the cooling tower system) that contains a huge number of actuators, converters and transmitters.

Table 10: Activities Performed and Worked Hours by each specialty for failure and programmed maintenance.

Specialty	Activities	Hours
Mechanic	199	5223
Instrumental	1055	7091
Electric	170	1682

Moreover, also the workload percentage - divided in corrective and preventive maintenance - has been determined and the results are presented in Table 11.

Table 11: Workload percentage

Activity	Hours	%
Preventive	10547	75,1%
Corrective	3489	24,9%

Table 11 highlights that the corrective maintenance has a 25% impact on the overall number of worked hours.

Considering then a fixed cost depending on the maintenance type, it has been possible to determine the manpower maintenance costs, divided also in this case by the activity type (preventive or corrective maintenance), as presented in Table 12.

Table 12: Manpower Costs for Maintenance Type

Activity	Manpower Costs
Preventive	210140 €
Corrective	71300 €

The total costs for spare parts have been calculated on the basis of the working orders for all the maintenance activities and they are estimated to be about 265000 €. It is worth also highlighting that some maintenance activities are not included, like the minute maintenance, the parts lubrication and other activities, in particular regarding piping systems. Downstream it has been possible to calculate the total costs as a sum of the spare parts costs and the manpower costs, with the results represented in Table 13.

Table 13: Total Costs Recap

Spare Parts Costs	265419 €
Manpower Costs	281440 €
Total Costs	546859 €

Once analyzed the costs, another interesting aspect is provided by the workload percentage determination among the different workgroups, starting from the availability values of each workgroup and there presented in Table 14.

Table 14: Workgroups Availabilty Values

Workgroup	**Overall Availability**
WG1	55536 h
WG2	18512 h
WG3	18512 h
WG4	18512 h

The availability values shown in Table 14 are then the denominator of the ratio determining the workload percentage, while the numerator is represented by the total worked hours represented in Table 9. Table 15 represents the workload percentage calculated as follows:

$$WP = \frac{WorkedHours}{Availabilty} \quad (3)$$

Table 15: Workload Percentage for each workgroup:

Workgroup	**WP %**
WG1	8,7 %
WG2	38,3 %
WG3	2,0 %
WG4	9,0 %

Analyzing the results provided in Table 15, it is worth underlining that the workload is significant for the instrumental activities in charge to WG2, due to the high level of automation of the system examined. In order to better examine the output data provided by the analysis performed, a further development of this work should be a comparison with the workload determined by the other systems of the plant not examined now.

After the general economical considerations, another economical analysis, this time specific for each functional group, has been performed, introducing a specific index, called Maintenance Economical Index (MEI), for all the functional groups of the plant.

The MEI is calculated as follows, as a function of the the preventive and corrective maintenance costs:

$$MEI = \frac{PMC}{PMC + CMC} \quad (4)$$

Where PMC are the Preventive Maintenance costs and CMC the Corrective Maintenance Costs.

An item without any problem will have a MEI equal to 1, because CMC are equal to zero and no corrective maintenance has been performed; this condition is the optimal one, while, on the contrary, the more are the costs for unexpected maintenance (CMC), like in case of failures that require corrective maintenance, the more the MEI will decrease. Thus, an item will be not critical if it has a high MEI value, but, unfortunately, this condition is just necessary but not sufficient, because other parameters, like the availability and the reliability, have to be taken into account. Considering so all the three factors, availability, reliability and costs – and consequently the MEI -, a new index identifying the criticality of each item or functional group has been determined multiplying these three parameters; this index is defined as *"Overall Index" (OI)*.

The OI calculation gives a sensible perspective of the item/functional group criticality because of the multiplication of three factors belonging to the [0,1] interval: the optimal conditions for an item are availability, reliability and MEI equal to 1, so, consequently, also OI will be equal to 1. On the contrary, moving away from the optimal conditions, multiplying three factors less than 1, an OI near to 0 will be calculated.

On the basis of the OI calculated, the items/functional groups are classified in five different bands, as represented in the Table 16.

Table 16: Band assignment related to OI values

OI Value	Band
0 - 0,01	5
>0,01 – 0,1	4
>0,1 – 0,3	3
> 0,3 – 0,9	2
>0,9 – 1	1

Analyzing Table 16 it is clear that a functional group belonging to Band 5 is very critical and needs a deep reorganization with further analysis regarding the maintenance policy adopted and, in particular, the item functionality. Meanwhile, a functional group belonging to Band 1 is considered reliable, often available and with a low cost for what concern the corrective maintenance; for "Band 1" functional groups a preventive maintenance program with a wider interval should be adopted.

The other functional groups, belonging to bands 2, 3 and 4, present an intermediate situation, with mediocre characteristics and a significant improvement margin; this improvement can be implemented acting on some of the failure modes with appropriated methodologies like FMEA (Failure Mode and Effects Analysis) or FMECA (Failure Mode, Effects and Criticalities Analysis).

7. Conclusion

The simulation model allowed having an overview of a gas turbine power plant situation regarding the maintenance policies; the critical components evaluation has been carried out considering the most significant engineering factors like the items availability and reliability, with a consideration on the economical aspect calculating costs for corrective maintenance operations. he TARAS model, on the basis of the historical data provided, has determined availability and reliability values, while ad hoc economical assessments allowed defining the cost factors for each item and functional group. Some components revealed to be critical and inadequate in terms of the three parameters examined, highlighting the necessity of reorganization.

The dynamic simulation model – because the parameters of interest are continuously updated by the database – with the integration of the economical analysis, allows determining the response of the components to the maintenance policy adopted, identifying different criticality levels for every functional group in order to help decision makers in focusing their attention on the items belonging to the most critical level classes; integrating also the simulation results with other analysis like FMECA, MAGEC and others based on cause – effects, or with feasibility analysis of item substitution like LCCA (Life Cycle Cost Analysis).

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