Industrial Maintenance Metrics based on Simulation and Fuzzy Logic

Agostino G.Bruzzone
MISS - DIP
Via Opera Pia 15, 16145 Genova, Italy
Email agostino@itim.unige.it - URL st.itim.unige.it

Chiara Briano
BRBStudio,
Genoa Voltri Terminal –Office Tower 16158 Genoa, Italy
Email chiara.briano@liophant.org - URL www.brbstudio.com

Simone Simeoni
Liophant Simulation
Via Molinero 1, 17100 Savona, Italy
Email simone.simeoni@liophant.org - URL www.liophant.org

KEY-WORDS
M&S, Fuzzy Logic, VV&A; RCM, AI.

ABSTRACT

This paper is focused on the development of a model for applying Reliability Centred Maintenance (RCM) on complex system by integrating simulation and artificial intelligence (AI); the application is related to maintenance planning of groups of gas turbine power plants. This paper will explain the reasons, the criticalities and the lessons learned during the development of the research, leading to the realisation of a Fuzzy Logic Schedule Evaluator (FUSE).

INTRODUCTION

Complex industrial systems are subjected to the impact of many stochastic components especially in maintenance procedures; in effect the market evolution during the last years provided a growing opportunity in development of maintenance services. It was evident during the last 10 years that complex objects, such as planes, helicopters, gas turbines, and even big vehicles could provide interesting opportunities in service improvements. Improving the maintenance it becomes possible to increase reliability and availability with direct impact on final user costs and savings; for instance a SAR (Search and Rescue) fleet of helicopters could be drastically reduced if the availability is improved by a more efficient maintenance planning, in this case some component have a “restoring time” of over 18 months, so reducing lead time of some of these element to 12 months (i.e. by a better inventory planning and spare parts use) could provides the same quality of service reducing 30% the aeromobile fleet and saving several million dollars per helicopter.
Similar problem impact bus fleets of a mass transportation company, obviously with different impact of availabilities, lead times and costs, but very interesting saving on the large fleet of vehicles.

These cases are related to complex entities, where a predefined preplanning of operations is requested in order to guarantee the safety and efficiency; obviously in these cases, where maintenance is mostly preventive, it becomes possible to have high margins by a smart organization respect to cases where the breakdowns are mostly pure stochastic events with very large standard deviation respect mean expectations.
To provide an additional case it is interesting to compare the problem of maintenance in Fossil Power Plants and Gas Turbines; the first kind of plants are usually very high tailored, and pre-planned maintenance have a different impact respect Gas turbines, where the high solicitation requires very detailed pre-planned actions at precise time events. In this framework to use models in order to improve the overall efficiency it is quite critical and could provide significant savings. This paper present a case study just related to a group of Gas Turbines distributed over 11 plants; it is interesting to note that during the last 10 years the Service Business Unit was growing to a leading positing in term of profits in all major Power Plant providers, guaranteeing usually 50% of the profits with just 10% of the personnel; this is a confirmation of the investments of the Power Plant users in this sector and of the interesting opportunities for providing additional improvements in the sector, guarantee a durable benefit. In most case, advanced Power Plant users, today requires special contracts supporting not only turn-key, but operation and management and even more; the case presented is related to an user interested in establishing a set of procedures and tools for guaranteeing a on-line control of Service performances and actions for continuous improvements.

APPLICATION FRAMEWORK

If we consider the problem to manage effectively the service of Gas turbine power plant it is important to define the boundaries of this framework; first of all each of these plants produce several thousand dollar of power each day and so each additional day of “non-

Proceedings 16th European Simulation Symposium
György Lipovszki, István Molnár © SCS Press, 2004
ISBN 1-56555-286-5(book) / ISBN 1-84233-106-x(CD)

production" introduce very high costs. In addition the dynamic components of turbine and generators requires continuous special inspections due to high mechanical/thermal solicitations, where the intervals are technically predefined and related to the use of the different machines. It is evident that Gas Turbine use is strongly dependent on a large quantity of stochastic components, first among the others the behaviour of the demand and the market evolution; based on these parameters the request could require to work intensively, to put the machines "out of line" or to operate at "110%" with additional stress; the consumption of Equivalent Hours (the technical parameter for use of these components) is highly variable for each machine. In addition during each inspection the quantities of components to be substituted is variable based on a very unpredictable set of technological aspects. In term of management the lead time to have the spare parts available, due to their "construction complexity" and high technologies involved, is sometime pretty long (over 6 months) and involve sensible investments; these lead times are obviously stochastic as well as the related costs (due to the market situation and to the urgency of the requests, introducing expensive expedition activities). Similar problems affect the refurbishment/revamping of components (i.e. blades) that due to the nature of the processes (i.e. recoating) involve stochastic times, quantities and quality. All these factors combined provide a very complex framework with many interactions among different aspects. In addition the preventive planning of the power plants, especially if the number of turbines is quite high, introduce strong correlations among the different events: for instance two inspections in the same site could not be feasible due to available space for mounting/dismounting the components, while technical constraints could request to stop a turbine before to overpass some limit threshold.

The Power Plant users have additional needs, often stated in a contract, to guarantee to have minimum production capability during the different part of the days/week/year, and/or concentrating/distributing maintenance operations. In addition the relationship among the different site considering the planning horizons of about 5/10/15 years with 10 power plants it is evident that a delay/shift in an inspection affects all the following events with possible critical results.

This brief description provide an evident framework of the necessity to move forward to extensive use of modelling and simulation as support for developing an effective planning also in the simple case of a single user single provider with a limited number of power plants. In effect the authors developed in the past several models for being applied to this sector, involving case with multi users scenarios, geographical service clustering operation, new warehousing solutions etc.; in effect the research presented year is based on a case developed in cooperation between BRB, DIP Genoa University for a Power Plant Provider, on a group of about 11 combined cycles of a common user. These power plants planned to be completed in 2003-2004 have a related service agreement introducing the necessity to apply maintenance procedures in accord with the RCM theory; this explicit request from the user justified the development of an ad hoc model for analysing the planning and simulating the inventory level of inspection kits.

PROJECT OUTLINE

It is interesting to provide an overview of this project timeline in order to report the evolution of this M&S (Modelling & Simulation) project and the impact of reusability, portability and other aspects that affects these developments. As already mentioned the authors had experience in cooperation with major Power Plant Providers in developing models in the past to face different aspects (development of new regional maintenance organisations, introduction of outsourcing, optimal planning etc.); around the beginning of the new millennium the authors developed for a Construction & Engineering company, with a Power Division, a solution for being integrated with ERP (Enterprise Resource Planning) for supporting management of service division; this solution had to face a wide set of open issues:

- Large Set of Information Dbase and Tools
- Overlaps among Management Systems
- Miss-Integration in IT systems
- Management Gaps in Covering Service Processes
- "Early Preliminary Phase" of new ERP Implementation Project
- New Logistics and Organisational Changes
- Limited Historical Experience in Gas Turbines
- Short Delivery Time

Due to these scenario the author proposed a solution based on the development of new system to be integrated with ERP based on well defined business procedure, but able to support decision making process from managers also stand alone.

The Solution integrated a Simulator, as core engine for providing estimations, risk analysis and time/cost/quality figures, a new common database, a decision-making module, and some optimisation units for inventory management and inspection scheduling.

This solution was applied to some industrial cases with success, however it was requesting significant investments to be acquired and implemented.

The origins of this project were to develop a support for a specific project (service contract for 11 power plants) imposing a reduced budget and development time for providing a solution to this case; the application case was very similar to the previous mentioned however the final power plant user provided just guidelines and fixed budget for guaranteeing application of RCM policies to the acquired power plants.

The Power Plant Provider requested a specific ad hoc solution that was able to provide real benefits to the final user and eventually to be extended to other cases,

but obviously confirmed the constraints in term of time and budget and look around for possible providers to the different requested lines (i.e. FMECA analysis).
The authors presented a modular proposal and started to negotiate the details; it was immediately evident that the full integrated solution (even if this company was using an ERP already supported for integration) was not suitable due to the resources involved in this specific project. During the contacts it emerged the interest for a module able to provide a smart evaluation/optimisation of the gas turbine planning; in this way it was possible to provide a convenient proposal based on the reuse of conceptual models developed by the authors for the integrated solutions, to be implemented in a light tool.
The modules originally were two fuzzy evaluators, one focusing on inventory management (estimating the critical level of the items/components combining costs, lead time, critical level on inspection etc) and another one focusing on scheduling issues; both modules was applying fuzzy rules in order to consider the stochastic nature of the parameters and were integrated with the simulator in order to have an iterative automated optimisation/validation of the results.
The critical arising point was that the simulation model to be used in this case was not including many parameters fundamentals for some optimisation module (i.e. details of the item logistics and material flows due to the fact it is much less detailed) so it was difficult to reuse the optimisers within this project. Vice-versa the schedule evaluator was much more reusable and it was possible to be implemented by available data as support for the critical phases of settings and validation. So the project was outlined, however due to the fact that a significant amount of resources was allocated to traditional FMECA analysis to another provider, it was decided in this phase to develop just the schedule fuzzy evaluator without optimisation. The fuzzy optimiser in effect was using a simulator in close loop for iterating the alternatives and evolving to overall planning improvements; the solution defined was to develop the fuzzy evaluator and to keep open space for further developments of the optimiser. The technical requirements were fixed and the conceptual model was verified in order to guarantee the consistency, introducing changes and updates based on the specific case; for instance the original model was much generic, emphasising multi-customers/users, while in this case the single user allowed to a different tailoring with more attention on single power plant site reports. Reporting and Key Performance indexes were redefined based on the user needs as well as user interface and database integration. In the middle of the project, after the completion of conceptual model definition, during early phase of implementation a specific management problem show up. The Power Plant Provider had the necessity to evaluate different kit configuration to serve these power plants, based on some preliminary analysis carried out; however the evaluation was required in pretty short term and without increasing the budget, so a part of the development phase, that was proceeding quite efficiently, was moved to adapt a Monte-Carlo simulator for inventory evaluation.
The authors decided to provide quickly two alternative models for evaluating these phenomena: an analysis based on queue theory and a Monte-Carlo simulator adaptation from a similar case already available. This approach was very satisfactory because allowed in very short time, whit the resource available, to support the decision, providing a comparison between the preliminary independent estimations developed by the company and the queue model, but also correcting these quantities by the more comprehensive Monte-Carlo model. The results obtained allowed to support the relation between power plant user and provider in defining the kits to be used in the inventory.
In the meantime the project evolved and the implementation was completed; the first critical issue was the model setting, originally based on similar case experience from the authors.
However during the accreditation procedure with the model users, it arises that some of the hypotheses from the developers were too general and don't guarantee to provide a common baseline with the traditional reference of the company; so it was decided to proceed to a supervised setting & testing in order to guarantee the model consistency; this approach required some additional time, due to the necessity to coordinate developers and users, however it was necessary to guarantee the accreditation. After this phase common tests were developed and the results were evaluated as fully satisfactory from the evaluation model.
After the completion of the project, during the final phase of period of guarantee, the team of the Power Plant Company, more directly involved in overall planning of inspections was interested to review the models and the simulation; this provided an opportunity to define possible developments in order to cover additional aspects with special attention to a stochastic more detailed simulation of planning and inventory levels. Currently the authors are finalising a proposal for proceeding in this direction by the development, in multi steps, of different modules for simulating others groups of power plants with high details and introducing evolutionary optimisers (in close loop with this new simulator) for inventory and schedule; while the final phases of the project expect to have a full integration with global "industrial optimisation" of the planning. These new modules will be integrated with original fuzzy evaluator for providing support to the hierarchical estimation of the critical components of a planning provided by the optimiser.

FUZZY MODEL INTRODUCTION

The idea of realising a Fuzzy Schedule Evaluator was born from a real case to be analysed. The biggest Italian company specialised in Power Plants realisation and maintenance, had to build for an major customer a group of 11 Combined Cycle Plants. The agreement

between the company and its customer included the maintenance service for all the plants following the principles of RCM (Reliability Centred Maintenance).
The previous fruitful cooperation among the company and the authors, led to think to a possible advanced research to be presented to the final customer as a value added service. In effect the Authors had previous experiences in developing ERP-Integrated set of tools for maintenance and stock level control, applied in different real industrial contexts, including software for Failure Modes and Effect Analysis (FMEA/FMECA), a scheduler and a simulator integrating Artificial Intelligence (AI) techniques such as Genetic Algorithms (GAs). The interest on the subject, led the research to be developed on the subject of scheduling maintenance actions on the plants. Combined Power plants in fact have various kind of maintenance interventions, the most important of them are Minor Inspections and Major Inspections, that are made respectively each year and each three years of activity of the plant, depending on the Equivalent Operative Hours (EOH) of work, typical of each turbine. Different kind of maintenance requires also different kind of maintenance kits, composed by spare parts characterised by utilisation probability coefficients and time for refurbishment. This is the reason why another theme on which the study in object had focused was the determination of the criticality of each different kit of spare parts. Usually, the starting point for the definition of maintenance planning is the fixing of the start-up date for each plant, called PAC date. PAC dates of all plants are usually distributed on a timeframe in such a way to optimise resources and successive maintenance plans, in order to have a homogeneous distribution of workloads. Starting from the settled dates, the maintenance interventions could be planned based on a series of limits and constraints. Policies and constraints in a maintenance plan for power plants could be of various kinds, but the most important are:

- Strong constraints (e.g. contractual the customer does want the stop for maintenance in a specific month of the year)
- Regular constraints (e.g. the distance between two minor inspections, where the turbine producer provide just recommendations of the review interval)
- Weak constraints (e.g. requests of preference. not specified in the contract framework)

These and other rules are the basis of the logical processes introduced in the FUSE model. All the constraints have been introduced in the schedule evaluation system following the rules of Fuzzy Logic.

THE FUZZY EVALUATION MODEL

The goal of FUSE research was to determine an evaluation system based on advanced techniques in order to provide a measurement of performance for a maintenance plan determined by Subject Matter Experts (SME), and able to identify where are located criticalities, so that experts can correct punctually the main weaknesses of the planning.
The rules on which the evaluation schedule model is based are the rules of maintenance for Power Plants, plus specific rules introduced by the company for a better management of the resources. Every rule has been introduced in the model according to Fuzzy Logic. This technique allows considering a wider range of possibilities than traditional techniques. Introducing a different weight for different kind of constraints and considering more cases than simply *true* or *false* for the respect of each condition, the Fuzzy Logic allows to analyse in a more precise way a problem like the evaluation of maintenance planning of power plants, that is typically very complex, non-repetitive and so not very provided with historical data.
The complexity of the problem is increased by the fact that power plants to be maintained can be property of different customers, or located on different sites, or both conditions. These conditions have been considered in the logic of the model because are fundamental for the definition of some of the rules that allow to evaluate planning. An additional problem is connected to the availability of resources for maintenance in terms of spare parts. As previously mentioned, different kits are used for different inspections, and inside kits there are different spare parts with their own usage/consumption probability and lead-time for refurbishment. In order to determine the need of spare parts and their availability in relation to the maintenance plan, a further analysis on the kit criticalities has been made in the framework of the cooperation. The problem was in effect to define if the forecast number of kits for each kind needed was sufficient for the basic hypothesis on which the plan was structured. As mentioned, the PAC dates of each plant will determine more or less the period of the years in the timeframe in which the different maintenance inspections of each plant should be made. So, defining the occurrence in the same time of same kind of inspections on different plants, it is possible to define how many kits for each kind are necessary to respect the sequence of inspections, considering contemporaneous or too near interventions. The Company divided the plants into groups considering them as they were belonging to different customers, based on an homogeneous distance among different PAC dates, but mostly on the analysis of different kits criticalities. The groups of customers cycle among their plants the different kits they have, so the planning and the kit availability are very strictly connected.

THE LOGIC RULES AND CLASSES

Fuzzy Logic principles need to follow a process based on Fuzzyfication and Defuzzyfication of data. For this reason the authors followed the below mentioned approach. First of all, the model considers some parameters that are typical of each plant, such as EOH conversion coefficient (in hours), last minor inspection date, last major inspection date, customer name and site. Plants information is one of the input files of the model, containing all constraints, while a second input file with maintenance planning completes the data set. The data available include among the others:

- Group id. Number and Name,
- Location Site (different plants could be on the same site),
- Customer name (the same customer can hold various groups on different sites),
- Last information update instant (if not yet working, it's the forecasted start up date),
- Working hours in the last update (delta from the last major inspection)
- EOH factor for considering strain and stress of components
- Last minor inspection date (this includes also major dates due to the fact that major inspection includes always a minor one)
- Last major inspection dates
- Interval between two minor inspections, same group
- Interval between two major inspections, same group
- Weight for the constraint on interval between two major same group
- Interval between a minor inspection and a major inspection, same group
- Weight for the constraint on interval between a major inspection and a minor inspection same group
- Interval between two minor inspections on different groups on same Site
- Weight for the constraint on interval between two minor inspections on different groups on same Site
- Interval between two major inspections on different groups on same Site
- Weight for the constraint on interval between two major inspections on different groups on same Site

The scenario to be analyzed is really complex, in fact it was necessary to consider intervals and constraints for each planned maintenance. In order to do this it was implemented a Fuzzy Logic Module inside. Also to carry out an estimation of the maintenance planning considering all the intervals and the constraints it was applied Fuzzy Logic.

MINOR INSPECTION CONSTRAINT					
				8900	
TV		0	4150		0.00
V	0	4150	8300		0.00
G	4150	8300	10375		0.71
L	8300	10375	12450		0.29
TL	10375	12450			0.00

After this session the model estimate if it is possible stop the group in the month for the planned maintenance. It was possible to define five different classes to convert this constrain in Fuzzy Values where TV means Too Close, V means Close, G means Perfect, L means Far and TL means Too Far. In the example the interval between the next Planned Maintenance and the previous activate the G Class with a value of 0.71 and the L Class with a value of 0.29. In the same way it was defined the class for the interval between two major inspection, a minor and a major on the group the site and the customer. Due the importance to respect of the constraint between two major inspections in the definition of the classes it's necessary to assign a specific weight to the respect of the different intervals.

Schedule Performance Metrics

The origins of these initiatives are related to the market evolution of power plant service, with special attention to Gas Turbine, obviously in this area the target functions are related to some aspects:

Quality of the service
Power Plant Availability
Delays in Operations
Cost of the Services
Inventory Costs
Expedition Extra Costs
Direct & Indirect Costs
Constraints Respect
Contractual Terms
Technical Requirements
Other Aspects

The authors decided to use for measuring the overall performance to combine together the different terms by applying the overall fuzzy model by a hierarchical approach that was able also to consider the time distance in the future of the event versus an horizon fuzzy factor, defined by the user, to have a smooth estimation of impact of far future problems (i.e. overlapping of two major inspection in 15 years in the future is much less critical than the same event in the next 12 months, because in the first case it could be easily correct in advance, while the second don't leave degree of freedom). The Model attributes excellence to the planning with a reading key, which enables to understand where the most critical points are. The simulator uses a hierarchical approach to identify the excellence of the input planning. The final excellence is the results of the excellence of the planned maintenance of the each group of the scenario. The planned maintenance quality is defined using Fuzzy Rules in order to estimate the respect of the constraints. For each planned maintenance the model calculates the intervals between each planned maintenance in order to verify the compatibility with the input constrains and these are converted in Fuzzy measures using Triangular Membership Classes with 50% overlapping.

Simulation Model Metrics

The simulator was estimating delays on the inspections due to the unavailability of kits; the different kits with their lead times and with the necessity to refurbish part of the relative inventory was defined as stochastic components; obviously these delays represent usually just shift from the predefined planning, however they could introduces additional problems as well as power plant stoppage with very high costs. The authors developed a risk level factor as metrics, this was the probability to overpass a cumulative number of delays during a timeframe over a set of turbines; to this risk level corresponded an expected mean and standard deviation on the delays on major and minor inspections (aspects with different impact). By the simulation it was possible to obtain an estimation about the current situation, and the obtainable situation with a different number of kits; these results provided a significant improvement in term of delay reduction. Currently the results obtained are confirming the expectations and the statistical database of effective performance is growing.

CONCLUSIONS

Based on these developments it was possible to complete in quite short term, with very reduced resources a challenging problem. The stronghold in this development was an extensive development of the expertises and experience in this field: it was evident that previous conceptual models were well defined and guaranteed possibility to be tailored. Vice-versa the implementation, data integration, and target functions were requesting a significant cooperation developers/users. It was confirmed that management criteria are heavily related to the case study, however the flexibility of the original model architecture allowed to proceed successfully in retuning the model to new policies, providing satisfactory reference baseline.

REFERENCES

1. Boyce M.P. (2001) "Gas Turbine Engineering Handbook", Butterworth-Heinemann
2. Bruzzone A.G. (2004) "Power Plant Service Evaluation Based On Advanced Fuzzy Logic Architecture", Proc. of SCSC2004, San Jose`, Julye
3. Bruzzone A.G., Kerckhoffs (1996) “Simulation in Industry ”, Genoa, Italy, October, Vol. I & II, ISBN 1-56555-099-4
4. Bruzzone A.G., Colla G., Mosca R., Scavotti A. (1998) “Simulation as Verification Support for Qualitative Risk Analysis in Industrial Facilities based on Fuzzy Logic”, Proceedings of Emergency Management Conference, Boston, 4-9 April
5. Bruzzone A.G., Giribone P., Revetria R., Solinas F,, Schena F. (1998) "ANN as a Support for the Forecasts in the Maintenance Planning", Proceedings of Neurap98, Marseilles, 11-13 March
6. Bruzzone A.G., Colla G., Mosca R., Scavotti A. (1998) "Simulation as Verification Support for Qualitative Risk Analysis in Industrial Facilities based on Fuzzy Logic", Proceedings of Emergency Management Conference, Boston, 4-9 April
7. Bruzzone A.G., Mosca R., Pozzi Cotto S., Simeoni S. (2000) "Advanced Systems for Supporting Process Plant Service", Proceedings of ESS2000, Hamburg, Germany, October
8. Bruzzone A.G., Mosca R., Simeoni S., Pozzi Cotto S., Fracchia E. (2000) "Simulation Systems for Supporting Gas Turbine Service Worldwide", Proceedings of HMS2000, Portofino, October 5-7
9. Bruzzone A.G., Simeoni S. (2002) "Cougar Concept and New Approach to Service Management by Using Simulation", Proceedings of ESM2002, Darmstad Germany June 3-5
10. Bruzzone A.G., Mosca R. (2002) "Simulation And Fuzzy Logic Decision Support System As An Integrated Approach For Distributed Planning Of Production", Proceedings of FAIM2002, Dresden, July 15-17
11. Bruzzone A.G., Giribone R., Revetria R. (2002) "Integrating Small & Medium Enterprise in an Eprocurement using Java Applet Technology", Proceeding of SCI2002, Orlando, July
12. Bruzzone A.G. (2002) "Supply Chain Management", Simulation, Volume 78, No.5, May, 2002 pp 283-337 ISSN 0037-5497
13. Bruzzone A.G., Revetria R., Briano E. (2003) "Design of Experiments and Montecarlo Simulation as Support for GAS Turbine Power Plant Availability Estimation", Proceedings of MIC2003, Innsbruck, February 10-13
14. Cox E. (1994) "The Fuzzy System Handbook", AP Professional, Chestnut Hill, MA
15. Elliott T.C., Chen K., Swankamp R., (2002)"Standard Handbook of Powerplant Engineering", McGraw-Hill, NYC
16. Giribone P., Bruzzone A.G. & Tenti M. (1996) "Local Area Service System (LASS): Simulation Based Power Plant Service Engineering & Management", Proc.of XIII Simulators International Conference, New Orleans LA, April
17. Giribone P., Bruzzone A.G. (1997) “Design of a Study to use Neural Networks and Fuzzy Logic in Maintenance Planning”, Proceedings of Simulators International XIV, SMC’97, Atlanta, Georgia, April
18. Giribone P., Bruzzone A.G. (1998) "Development of Innovative Maintenance Support Techniques", Proceedings of Applied Informatics'98, Garmisch-Partenkirchen, Germany, February 23-25
19. Levitt J. (2002) "Complete Guide to Preventive Maintenance", American Management Association
20. Montgomery D.C. (1997) "Design and Analysis of Experiments", Wiley & Sons, NYC
21. Robinson C.J., Ginder A.P. (1995) "Implementing Tpm: The North American Experience", Productivity Press Inc
22. Wang L.X. (1997) "A Course in Fuzzy Systems and Control", Prentice Hall, Upper Saddle River, NJ
23. Wiereman T. (1999) "Developing Performance Indicators for Managing Maintenance", Industrial Press, NYC
24. Zadeh, L. (1965) "Fuzzy Logic for the Management of Uncertainty" Janusz Kacprzyk Editor