SERVICE OPTIMIZATION FOR SYSTEM-OF-SYSTEMS BASED ON POOL SCHEDULING AND INVENTORY MANAGEMENT DRIVEN BY SMART SIMULATION SOLUTIONS

Agostino Bruzzone, Marina Massei, MISS DIPTEM University of Genoa
Via Opera Pia 15, 16145 Genova, Italy
Email {agostino, massei}@itim.unige.it - URL www.itim.unige.it

Enrico Bocca, Simulation Team
Via Molinero 2, 17100 Savona, Italy
Email enrico.bocca@simulationteam.com - URL www.simulationteam.com

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ABSTRACT

The aim of this research is to support service and maintenance of pools of System-of-Systems, such as power plants or vessel/aircraft fleets by using simulations model dynamically integrated with smart optimizer driven by Artificial Intelligence techniques.
The proposed methodology permit to create a framework to evaluate, optimize and test the service and maintenance policies (involving both inventory and scheduling); this framework is based on a simulator combined with an intelligent optimizer
The authors proposed a new metrics to evaluate the real performance of pool service management of the whole complex system and support the optimization processes.

INTRODUCTION

The work performed by the authors in this research is to verify the benefits of the integration of simulation models with Artificial Intelligence (AI) techniques in complex system service and maintenance; in fact in most of the case the complex systems rely and require very expensive and sophisticated maintenance/service support; in fact this problem become even more difficult when the complex systems due to their interaction evolve becoming a system-of-systems; in this case the use of simulation is usually the only reliable approach to face the difficulties related to the management of their service/maintenance; in particular in this context it is critical to consider some KPI (Key Performance Indexes) with special attention to availability, costs, resource utilization, readiness. From this point of view one interesting opportunity for improving these KPIs and for guaranteeing better overall performances is to develop pool management strategies able to generate synergies in this complex framework; in fact in the real industrial and business case provide many opportunities to apply "pool management" to system-of-systems; in fact there are several frameworks where to apply this approach and authors have completed successfully several R&D projects for major companies on this subjects such as:

- Service for fleets of helicopters and resources devoted to provide Search and Rescue
- Service for fleets of resources (i.e. Buses, Metro, Trams, etc.) for a mass transportation companies
- Service for different fleets of tank vessels supporting different chemical industries
- Industrial Plants Service Pool Management

In fact along the years the authors have developed methodologies and simulation models to face these challenges and in particular they have developed LAPIS (Lean Advanced Pooling Intelligent optimizer and Simulator) suite, integrating M&S (Modeling & Simulation) and AI, to support decision making over this context; therefore this paper proposes an example applied to power plants service over a pool of different sites and units; the results obtained from the simulator are used for demonstrating the potential and benefits of the new methodology proposed as well as validation support.
This papers focus in fact on applying LAPIS to power plant pool management for optmizing their service over a wide spectrum of target fucntions.
In addition by this approach is possible to control and optimize different aspects of system-of-Systems maintenance, as power plant pools, in terms of different hypotheses in term of the balance between service quality (i.e. availability), cost estimation and constrain respect; the case study proposed represent an example of system-of-systems simulation able to manage all the aspect above mentioned and to guarantee good results in a real industrial case.. The research activities are synthesized in the LAPIS model description and the

validation of this approach is obtained by the experimentation on a real power plant case study application (the data proposed in the analysis are modified due to confidential reason).

SERVICE & MAINTENANCE FOR A POWER PLANT POOLS

A pool of power plants is a set of power plant sites where multiple units of different machines are operating; for instance today in most of the case the traditional power generation relies on combined cycle power plants: each plant have usually more than one combined cycle each one incorporating just a main machine a Gas Turbine, a Steam Turbine and two Generators; each machine is composed by several systems (i.e. main and secondary systems) as well as by several auxiliary systems (i.e. Aqua Demi, HVAC, firefighting etc); in several case the subsystems are even very complex (i.e. Digital Control System, Burning Control System etc.); in addition the maintenance for such components is driven by preventive actions related to their use (equivalent operative hours) and on failures; the first component is strongly related to the power demand and utilization modes of each plant that is strongly affected by exogenous stochastic factors, while the failures obviously are characterized by high complex statistical distribution combining different phenomena (i.e. basic failures and rare catastrophic events).

It results evident that to provide efficient service such set of power plants corresponds to define a pool management strategy for a system-of-systems; the paper focuses in fact in the identification, design and engineering of best service and maintenance policies for such system-of-systems; in the proposed case it is considered a group of combined cycle power plants (4 up to a dozen); this management need to operate considering available resources (i.e. personnel), scheduling and available timeframes (i.e. technical, commercial and contractual constraints), inventory (i.e. spare part storage and replacement policies), acquisition/refurbishment policies (i.e. for item subjected to regeneration such as several layers of Gas Turbine Blades).

The final aim is to define the preventive service and to support decisions able to optimize costs and power plant availability and, at the same time, to reduce the risks and to guarantee a robust management in case of unexpected breakdowns,

It is interesting to note that today availability concept evolved and it is more important respect to the traditional availability a new estimator related to the plant profitability; therefore the availability it is still a very important factor, but the choice to use just that parameter was even due even to the fact that estimating profitability was quite complex until few years ago due to data availability and format; today, due to the high variability in demand and especially in energy prices over time, the target function to be maximized is often the profit achievable by a plant evaluated by a combined estimation of capability and prices integrated over time; the goal is to have the unit operative as much as possible during the most profitable timeslots; special algorithms for estimating this kind of target function are proposed by the authors (Bruzzone , Madeo, Tarone F 2010).

The final solution should include the definition of schedule, inventory management by fixing compatible timeframes with the service time cycles of each item; this solution needs to optimize concurrently availability, profitability, costs and technical commercial constraints that are often defined based on the specific case and point of view (i.e. different from user to service provider); it is evident that such application represents a very hard problem that to be solved need to be approached by the innovative techniques combining simulation and optimization as proposed in this paper.

In fact within real applications the stochastic factors (i.e. failures, repairing time, spare part delivery times, item refurbishment lead times) combined with the complex processes (i.e. refurbishment processes, commercial procedures, technical constrains) have a strong influence to the overall performance of the maintenance solutions. By the innovative approach proposed in this paper the solution is defined by applying a DSS (Decision Support System) combining stochastic simulation and intelligent optimization; therefore the positive results achieved in several previous application suggest this as appropriate approach to solve this problem (Bruzzone & Simeoni, 2002)

POWER PLANT POOL MANAGEMENT

Due to high order of interactions among different entities, stochastic factors, different objects and a lot of target functions each Power Plants Service represent itself a pretty complex framework.

In fact, often, many machines (i.e. generators, gas turbines, steam turbines, boilers) in multiple sites need to be maintained concurrently both in term of preventive maintenance as well as in term of failure recovery; for this reason modern service strategies deal with pooling the power plants and generating synergies to compensate the high degree of complexity. In the power plant maintenance case propose there are many important elements (i.e.

rotors elements have a cost of a million USD each, hot gas parts require specific controls), therefore for sure Gas Turbines and, in particular, their blades represent the most critical element to be optimized in term of service due to their costs, lead times and sensibility to different operative modes.

Each machine have many components that need to be checked, substituted and/or refurbished; for many types of turbine blades, for example, is possible the refurbishment or re-coating: it corresponds to an hi-tech process devoted to rebuild blade surface of the blades; depending by the model of the blades the process can be repeated one, two or even three times before to require the substitution with new ones; in addition the refurbishment of used component is usually costing about 1/10 respect acquisition of new elements (and a layer of gas turbine blades cost about 1 million dollar, while each single turbine include several layers), that means that an optimized management able to rotate among different sites and machines a blade layer maximizing the refurbishment is able to guarantee very big savings; therefore it is necessary to consider that at least some percentage of the elements subjected to the refurbishment processes should need to be substituted each time this is applied by new ones due to the too deep damages on the material (this is usually defined as scraping percentage in power plant blades or other regenerating items).

In this context, typical stochastic phenomena are failures, scraping percentages and the quantity of components/items/subsystems to be substituted, duration of inspections as well as duration of minor and major revisions. There are complex constraints among the maintenance over different components in the same unit, site or for the same users (i.e. space for dismounting the machines or wiliness to concentrate the operation in the same time frame). Due to this fact optimizing the preventive maintenance scheduling is not enough to manage effectively this system-of-systems, but it is required to define inventory management policies in coordinated way and to plan refurbishment activities: so it becomes necessary to simulate long term scheduling to check mutual influence of different choices, to check transversal constraints. In fact the Preventive Maintenance of many components is regulated by Equivalent Operative Hours (EOH) able to consider not only the their use, but also special operational mode that are reducing component life cycles (i.e. startups, shot downs, etc.); the EOH value is evolve obviously as a not deterministic variable due to many factors; the authors defined a set of parameters to characterize each machine that combine solar working hours of the plants (related to power production), the intensity of the use Power Plants (related to the demand variations) and the mode of use (related to the policy for managing the machines by the users); that parameters are affected by stochastic factors and the results generates a complex behavior of the components; in fact currently the LAPIS simulator is able to be integrated with DCS and keep up-to-date on the EOH of each system in the power plant pool.

Through this example is easier to understand the complexity of the service and the emerging of complex behaviors in this system-of-systems; to keep the system under control and to guarantee good performances in this case it is critical to understand that the optimization process should be related to different target functions defined based on the specific case; in general the two main components of the these target functions for power plant service are related to service costs, power generation profitability and plant availability.

These are obviously competing functions and requires a multivariable combined optimization.

From other point of view the degrees of freedom for controlling and improving the power plant service management are related to the following main elements:

- Power Plant Preventive Maintenance Scheduling
- Power Plant Component Inventory Management
- Refurbishment Component Planning & Sequencing

The goals of this research was to create a power plants manager, that interact with an intelligent decision support system to estimate correctly the plant performances and to optimize resources, inventory and scheduling.

The approach proposed in this paper permits different and interactive modes: automated optimization integrated with the simulation as well as what if analysis; so the different solutions and policies are simulated driven by the intelligent optimizer or by the users and estimates the KPIs; the optimizer proposed for this case is based on GAs (Genetic Algorithms)due to the high number of variable and the strong influence of stochastic factors that could drive to local minimum traditional optimization techniques (Bruzzone, Signorile 1998).

In addition the approach is very robust and reliable even for evaluating different performance in term of service and maintenance of Power Plants considering market change (Bruzzone, Giribone 1998).

Therefore Pooling Power plant maintenance is based on the idea of a concurrent collaborative planning and management of the service over a set of plants; in fact combining different machines, sites and power plant users it becomes possible to create a pool of entities requiring service and to identify how to manage the pool of resources for satisfy them; the success and the benefits in this care are strictly connected to the possibility to revamp items dismounted from one machine or plants and to use on another one reducing the acquisition of new components; these results are achievable by defining an effective sequence of major and minor inspections and a coordinated schedule; in fact it becomes possible to optimize the reuse of elements without affecting the availability of the power plant acting on the schedule of the service operations, refurbishment actions and on the inventory.

In Power plants many kinds of components may be reused more than one time after a refurbishment process (usually considering the percentage of scraped item for each treatment); to reduce new item acquisition by increasing refurbishment component uses it is necessary to finalize an optimized management of the inventory and an effective scheduling; the service planning, for instance, should be adapted anticipating or delaying the inspection/revision in order to have refurbishment items from other plant available in time; this require to correctly major and minor revision schedule taking into account technical and commercial constrains (i.e. component life cycle vs. EOH or period of the year where it is not allowed to conduce maintenance operation due to the service contract); this activity should be based on a comparative analysis on cost reduction and profitability improvements over a stochastic scenario and in presence of risks.

This approach is even more effective in large sets of plants, that require service within the same timeframe; in this case the good results emerge by a collaborative management obtained by maximizing the sharing of refurbished and new items as well as the demand. Creating a common power plant pool is possible to optimize inventory management, component safety stocks in order to reduce costs and to improve the profitability and availability over all plants and to optimize shared resources. (Bruzzone, Bocca 2008).

M&S FOR POWER PLANT SERVICE & MAINTENANCE.

There are consolidated experience in managing service and maintenance in industrial power plants; modeling in simple case the service quality obtained from different management strategies the results is that pooling always improve the service levels (Taragas 1989);

A reliable support for manager of service part inventories are demand pattern identifier based on statistical methods (Cerda et al. 1997; Sugita et al. 2005; Paschalidis et al. 2004; Muckstadt 2005; Beardslee et al. 2006).

Several authors investigates the methodologies for optimize inventory management and service for similar cases (Cohen 1990; Silver 1991; Nahmias 1994; Harris 1997).

The use of statistical techniques is effective to support service and maintenance modelling and to validation and verification of the conceptual model (Hill 1997; Hill 1999; Aronis et al. 2004).

The demand of spare parts for supporting service and maintenance procedures is an critical variable to model and requires specific and accurate analysis (Grange 1998).

In the past was developed multi location inventory models combining simulation models and optimizers (Federgruen, 1993; Kochel 1998; Nielander 1999); to optimize inventory and transportation cost polynomial-time algorithms was used (Wang & Cheng 2007). Some Traditional algorithms applied to maintenance optimisation may be questionable (i.e. Hallefjord et al. 2003)

The combination of Linear and non linear approaches (Gupta, Zhang 2010) was investigated on specific target function as well as Scheduling approach in combination with inventory optimisation (Fan et.al 2009).

Complex techniques, such as genetic algoritms, permit to approach multi-objective optimization (Srinivas & Deb 1994).

In power plants maintenance the decision management about replace and order new item referred to limited life cycle components was analyzed by separate and join optimization (Armstronga 1996)

Supply and inspection of components must be considered by the mathematical models developed (Chen et al. 2009).

The Simulation Team DIPTEM researchers have long experience in these methodologies and techniques applied to this sector (Giribone, Bruzzone & Tenti 1996).

Some innovative approach was proposed, based on simulation, by the authors to support management strategies in the identification of best solutions considering multiple constraints and target functions (Bruzzone et al. 1998).

In fact it was also developed a methodology for supporting pooling strategies for multiple power plant service (Bruzzone, Mosca, Pozzi, Cotto, Simeoni, 2000) as an innovative approach for defining criteria for serving the sites by clustering the machines in subsets able to guarantee compatible timeframes respect life cycles of spare parts, components and items; this approach leads to the optimization of availability, costs respecting technical commercial constraints.

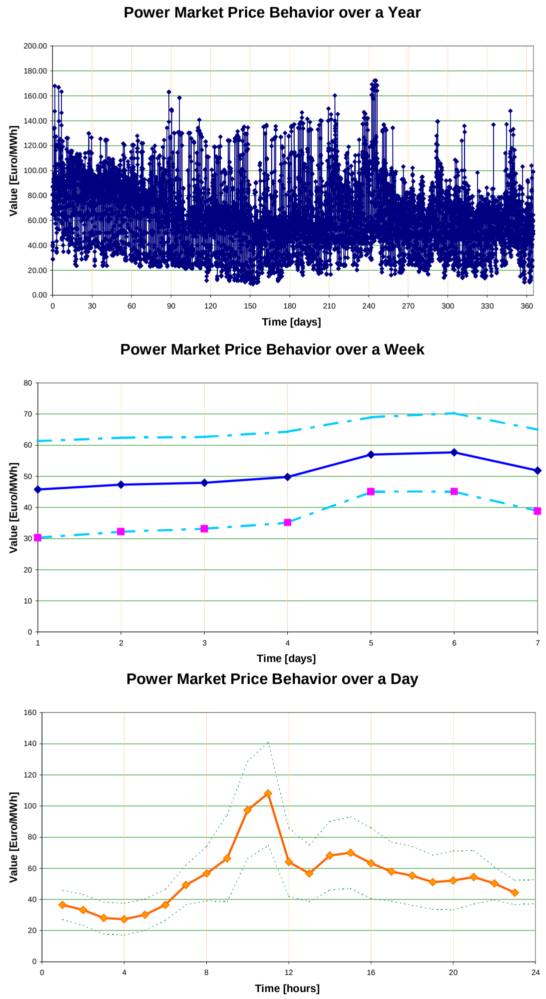

Figure 1 – Power Market Price Behaviours

Therefore the improvement of power plants performances in terms of service and maintenance, go trough fast supply chain, flexible stock management, lean process that became key elements for a correct management DSS; so the integration of operation, administration, maintenance and business have a relevant importance on the power plant performances such as efficiency, reliability, availability, environmental impact and lifecyclecost (Bruzzone, Mosca Simeoni, Pozzi Cotto, Fracchia 2000).
The difficulties in the definition of a correct service and maintenance procedures in power plants need to be approached by modeling the revamping and refurbishment processes for specific components as well the inspections, revisions and turnover strategies which permit to minimize spare parts acquisitions costs; increasing the number of machine (units) involved in the maintenance services it is critical to be able to track each component for each unit and to be able to process and elaborate this context (Bruzzone, Simeoni 2002)

NEW PERFORMANCE INDEXES

In order to identify the optimum in terms of service the authors proposed a specific metrics that permit to balance, in weighted way, cost and availability.
The costs are defined considering refurbishment and acquisition of spares, the availability is defined in relation to the value of the market price for energy considering that in different days, hours and months (see fig.1), unavailability of the items (and then of the plants) correspond to profit lost of profit. Profit lost is different in different time frame.

$$SP = k_a VA + k_c VC$$

$$OCe = \sum_{i=1}^{np} Ace_i + \sum_{i=1}^{np} Rce_i + \sum_{i=1}^{np} Sce_i$$

$$na_{ij} = \mathrm{int}\left[\frac{\Delta T_i}{LC_j\left(nre_j + 1\right)}\right] \qquad nr_{ij} = \frac{\Delta T_i}{LC_j} - na_j$$

$$Act_i = \sum_{j=0}^{nc} na_{ij} ca_j \qquad Rct_i = \sum_{j=0}^{nc} nr_{ij} cr_j$$

$$VC = \frac{Act_i + Rct_i}{Oce}$$

SP	service performance
ka	availability importance factor
kc	cost importance factor
np	number of plant in the pool
nc	number of maintenance components
nre_j	maximum number of possible refurbishment for j-th component
ΔT_i	time frame for maintenance of i-th plant
OCe	Effective Overall Cost
Ace_i	Component Acquisition Cost for i-th plant
Rce_i	Component Refurbishment Cost for i-th Plant
Sce_i	Extra Cost due to stop for i-th Plant
ca_j	unit acquisition cost for j-th component
cr_j	unit refurbishment cost for j-th component
VC	cost performance index as ratio effective vs. minimum theoretical service costs

$$GT = \sum_{i=1}^{np} GT_i \qquad GT_i = \int_{ti0}^{t_i 0+\Delta T_i} P_{N_i} f(t)dt$$

$$G'_i(\bar{t}^{i^*}_{F_{isp}}, \bar{t}^{i^*}_{F_m}, \bar{t}^{i^*}_{F_M}) = \int_{t_i 0}^{t_i 0+\Delta T_i} P_{N_i} g_a{}^i(t, \bar{t}^{i^*}_{FM}, \bar{t}^{i^*}_{Fm}, \bar{t}^{i^*}_{Fisp}) f(t)dt$$

$$g_a{}^i(t, \bar{t}^i_{FM}, \bar{t}^i_{Fm}, \bar{t}^i_{Fisp}) = g_{isp}{}^i(t, \bar{t}^i_{Fisp}) g_M{}^i(t, \bar{t}^i_{FM}, g_m{}^i(t, \bar{t}^i_{Fm})$$

$$g_M{}^i(t, \bar{t}^i_{FM}) = \begin{cases} 0 & \bar{t}^i_{FM} \le t \le \bar{t}^i_{FM} + \Delta t^i_{F_M} \\ 1 & t > \bar{t}^i_{FM} + \Delta t^i_{FM} \\ 1 & t < \bar{t}^i_{FM} \end{cases}$$

$$g_m{}^i(t, \bar{t}^i_{Fm}) = \begin{cases} 0 & \bar{t}^i_{Fm} \le t \le \bar{t}^i_{F_m} + \Delta t^i_{Fm} \\ 1 & t > \bar{t}^i_{Fm} + \Delta t^i_{Fm} \\ 1 & t < \bar{t}^i_{Fm} \end{cases}$$

$$g_{isp}{}^i(t, \bar{t}^i_{F_{isp}}) = \begin{cases} 0 & \bar{t}^i_{Fisp} \le t \le \bar{t}^i_{Fisp} + \Delta t^i_{Fisp} \\ 1 & t > \bar{t}^i_{F_{isp}} + \Delta t^i_{F_{isp}} \\ 1 & t < t^i_{Fisp} \end{cases}$$

$$R^e{}_i = \int_{t_i 0}^{t_i 0+\Delta T_i} P_{N i} g^i{}_e(t) f(t)dt$$

$$\bar{t}^{i*}_{F_{isp}}, \bar{t}^{i^*}_{Fm}, \bar{t}^{i^*}_{FM} \quad / G'_i(\bar{t}^i_{F_{isp}}, \bar{t}^i_{F_m}, \bar{t}^i_{F_M}) < G'_i(\bar{t}^{i^*}_{F_{isp}}, \bar{t}^{i^*}_{F_m}, \bar{t}^{i^*}_{F_M}),$$

$$\forall \bar{t}^i_{F_{isp}}, \forall \bar{t}^i_{F_m}, \forall \bar{t}^i_{F_M}, \forall k,$$

$$|\bar{t}^i_{F_{isp}}(k) - \bar{t}^i_{F_{isp}}(k-1)| < \lambda_{isp} t_{Fispl},$$

$$|\bar{t}^i_{F_m}(k) - \bar{t}^i_{F_m}(k-1)| < \lambda_m t_{Fml},$$

$$|\bar{t}^i_{FM}(k) - \bar{t}^i_{F_M}(k-1)| < \lambda_M t_{FMl}$$

$$Av_i = \frac{\int_{t_i 0}^{t_i 0+\Delta T_i} ge^i(t)dt}{\Delta T_i} \qquad \text{Prod}_p = \frac{1}{GT} \sum_{i=1}^{np} \frac{R_i^e}{\Delta T_i}$$

$$\text{Prod}_c = \sum_{i=1}^{np} \frac{R_i^e}{\Delta T_i \cdot G'_i(\bar{t}^{i^*}_{F_{isp}}, \bar{t}^{i^*}_{F_m}, \bar{t}^{i^*}_{F_M})}$$

$$VA = \frac{\sum_{i=1}^{np} \frac{PN_i \cdot R_i^e}{G'_i(\bar{t}^{i^*}_{F_{isp}}, \bar{t}^{i^*}_{F_m}, \bar{t}^{i^*}_{F_M})}}{\sum_{i=1}^{np} PN_i}$$

$t_i o$ initial time for i-th plant

f(t) Power Price at t time

$g_a{}^i$ nominal operative state

$\bar{t}^i_{FM}$ vector with time of m_1Major revision for i-th plant

$\bar{t}^i_{Fm}$ vector with time of m_2 minor revision for i-th plant

$\bar{t}^i_{Fisp}$ vector with time of m_3 inspections revision for i-th plant

$\bar{t}^i(k)$ element k-th of the vector $\bar{t}^i$

$\bar{t}^{i^*}_{FM}$ optimal set of Major revision time for i-th plant

$\bar{t}^{i^*}_{Fm}$ optimal set of Major revision time for i-th plant

$\bar{t}^{i*}_{Fisp}$ optimal set of Major revision time for i-th plant

$g_e(t)$ effective operative state based on decided planning

GT Theoretical maximum revenues

GT_i Theoretical maximum revenues of i-th plant without any planned maintenance

G'_i Maximum revenues of i-th plant with optimal Planning maintenance

R^e_i effective revenues based on decided planning

t_{Fispl} technical/contractual interval between inspections

t_{Fml} technical/contractual interval between minor revisions

t_{FMl} technical/contractual interval between major revisions

λ_{isp} technical/contractual tolerance between inspections

λ_m technical/contractual tolerance between minor revisions

λ_M technical/contractual tolerance between major revisions

$\Delta t_{FM}{}^i$ theoretical/contractual duration of major review for i-th plant

$\Delta t_{Fm}{}^i$ theoretical/contractual duration of minor review for i-th plant

$\Delta t_{Fisp}{}^i$ theoretical/contractual duration of inspection for i-th plant

The aim of the application of the model is to find the best & feasible schedule and inventory management in order to optimize the general performance of the plants. The best result is evaluated by considering expected prices of power along days/weeks/months/years. To do this, and test different scenarios, is possible to use historical data of power consumption integrated with trend hypothesis.

Using Genetic Algorithms integrated with a simulation it is possible to estimate the fitness function in term of value and confidence band related to the different performance indexes considering the complex relationships among variables and parameters; the authors realized LAPIS framework in order to support the optimization and analysis of service and maintenance planning & policies as well as for supporting decision making in this framework,

MODEL VARIABLES

The main purpose of the simulation model defined by the authors is to be a DSS able to properly evaluate the KPIs over complex scenarios; the LAPIS is stochastic discrete event simulator integrated with an Optimizer based on Genetic Algorithms; in fact key performance indexes are affected by several variable such as:

- Effective Planning for each Plant
- Effective substitution/mounting Sequencing for compnents subjected to refurbishment
- Schedule Performances quantify the respect of time constraints such as :
  - Inspection/Revision exceeding the allowed time due to delays/problems (i.e. extra time for a revision due to spare part shortage)
  - Technical Times Interval among inspections/revision not respected (i.e. too many EOH before substituting some blade layer)
  - Dates not acceptable due to contract constraints (i.e. desire to avoid maintenance in some months with higher power prices or viceversa desire to concentrate all the maintenance within summer holiday break)
  - Too short interval among two sequential different machine inspection/revision on the same site respect desired value (i.e. desire to avoid to operate them concurrently inside the same power building due to interference and lack of space)
  - Too long interval among two sequential different machine inspection/revision on the same site respect desired value (i.e. desire to operate them concurrently inside the same power building creating synergies with service resources and kits)
  - Too few machine concurrently unavailable respect desired value (i.e. desire to distribute the maintenance to guarantee average power generation capability of the plant users)
  - Too long interval among two sequential different machine inspection/revision on the same site respect desired value (i.e. desire to operate them concurrently inside the same power building creating synergies with service resources and kits)
- Power Plant Number of Stops and Duration
- Inventory behavior for each Component
  - Warehouse Quantities
  - Stock-out Times, Importance and Quantity (i.e. how many spare parts of the component are missed, how critical it is the component for plant operations and how much it costs to acquire through unconventional channels)
  - Component Service Level
  - Component Rotation
  - Expected Final Status of the Component at the end
    - Quantities and values of spare parts of the component distinguishing among new ones and refurbished at the different levels are mounted in the machines/plants at the beginning of the contract
    - Quantities and values of spare parts of the component distinguishing among new ones and refurbished at the different levels are mounted in the machines/plants when service contract expires
    - Quantities and values of spare parts of the component distinguishing among new ones and refurbished at the different levels are available in the warehouses when service contract expires Costs & Profitability detailed as:
  - New Spare Part Acquisition Costs
  - Refurbishment Costs
  - Warehouse Fees
  - Expediting Fees
  - Initial Costs for the defined Configuration
  - Plant Expected Profitability
- Risk Reports
  - Risks of Service and Maintenance Delays
  - Risk on Component Shortage
  - Risk of Power Plant Stops (Number and related duration)

The model implements many alternative management policies for power plants service as well as estimation criteria and these are defined inside the simulation model.
In fact are several simulation parameters that need to be set in order to properly estimate the performances such as:

- Replication Number for each scenario evaluation in order to estimate the stochastic factor influence
- Pseudo Random Number seeds (or automatic initialization)
- Simulation Duration
- Power Plant Pool Configuration
- Inventory initial configuration
- Initial Scheduling
- Operative Management Criteria
- Inventory Management Policies
- Policies for restoring of Safety Levels
- Policies for managing Expediting
- Policies for Interchanging compatible Components
- Policies for Cannibalization of Components in planned maintenance occurrences
- Policies for Cannibalization of Components due to failures

- Policies for processing Automatic Collected Data related to Power Demand and Plant use
- Policies for managing contract duration
- Definition of Technical Constraints
- Definition of Contractual Constraints
- Definition of Resource Constraints

In fact the initial conditions set in the model are used to start the simulation of a specific scenario; during the simulation run the model reproduce the operation in service and maintenance of the plants considering unexpected failures, managing initial schedule and inventory.
In order to verify and validate the model on all the events, costs and indexes the simulator generates a log file that contains all estimations of different stochastic components compared to initial planning and management strategies

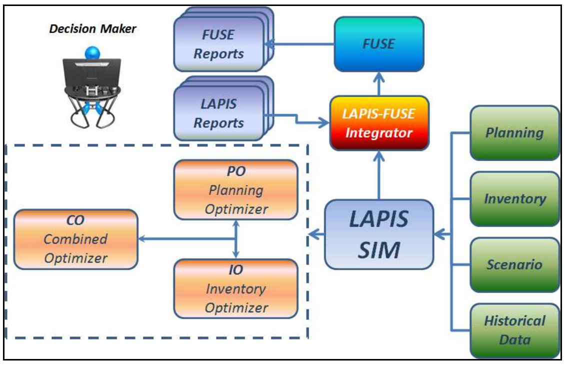

Figure 2 – LAPIS General Architecture

LAPIS simulator generates a lot of reports that represent, also in graphical mode, the temporal evolution of the following variables:

- Each Plant Unit EOH
- KPIs
  - Profitability
  - Costs
- Component Consumption
- Component Levels on the Warehouses
- Refurbishment Quantities
- Failures
- Inspection, Minor and Majors Revisions

LAPIS ARCHITECTURE & COMPONENTS

As anticipated, LAPIS solution is the combination of simulation and optimization (see figure 2), as sown in the architecture scheme the simulator is connected to each component (is the core of this proposed approach).

The box called "FUSE" is an interesting module of the system, where the application of Fuzzy Techniques is used to evaluate the interaction among technical (machine lifecycle), operational (interference among inspections), contractual (periods preferable for maintenance) and commercial factors such energy request from the market (Bruzzone et al. 2004).
In fact LAPIS is fully integrated with this fuzzy logic performance evaluator, developed in previous researches, devoted to evaluate the quality of the planning of maintenance operations by a hierarchical approach (Bruzzone & Williams 2005). Fuzzy Logic is very useful in this context due to the uncertainty on variables and constraints (Cox 1994).
Failures, planned maintenance events, critical time points such as shut downs, start-up, contract closure, item delivery and several other events are driving the time advance in LAPIS simulator; while the power demand behavior and unit EOH (Equivalent Operating Hours) are computed by the integration of the function between two consecutive events.
The stochastic variables are computed by using Montecarlo Tecniques, the simulator for each time and in each run extract the value of the variable from distribution function.
The probability distribution of the variables was identified analyzed by statistical techniques (Test Chi^2 T and by the Subject Matter Expert in order to identify the best fitting of the real data with the known Probability Distributions.
For several reason (few historical data, short history, errors in records, confidential nature of the information etc.) in most of the cases without strong historical background the authors used Beta Distributions to model stochastic variables.
In fact Beta distribution allows to integrate easily the expert estimations with historical data in order to have consistent data.
There are three types of optimization modes supported by LAPIS architecture:

- Planning Optimizer (PO)
- Inventory Optimizer (IO)
- Combination of PO and IO

All the optimization models deal with the dynamic interaction among the GAs optimizer and the stochastic discrete event simulator.
The optimizers, as anticipated, use Genetic Algorithms (GAs) in order to find robust and cost effective solutions (Bruzzone A.G., 1995).
In this application the GAs are initialized from a set of solutions called "population" including proposals of the users; the genetic operators referred to fitness

function, obtained by running automatically the simulator, to guide the search and improving solutions (Bruzzone, Bocca 2008); the genetic algorithms include:

- selection
- recombination (crossover)
- mutation

The optimizer elaborate the population and evaluate their fitness by running automatically the simulator and it recombines the solutions by the above mentioned algorithms for several generations; the parameters of the GAs could be set by the user as well as the weights of the fitness function to be used for each optimization.

LAPIS FRAMEWORK

Due to its complexity the model need a very high quantity of input data, it is so hard to modify this data to create different scenarios maintaining it consistent; in fact most of data needed for running the simulation (such as existing planning, technical data of items and spares, levels of the storage) are extracted by the company ERP System; therefore in LAPIS an easy interface is defined to quickly check and change hypotheses for creating different scenarios.

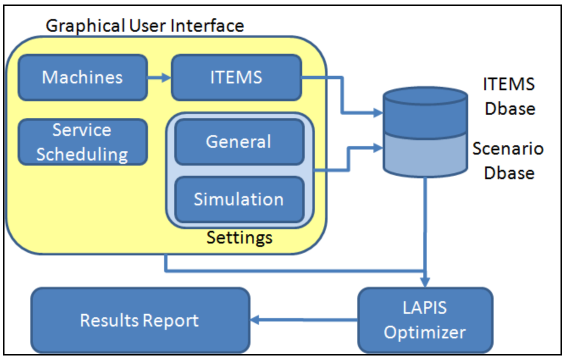

Figure 3 Lapis Function Configuration

Figure 3 show the LAPIS components, the user can interact with the model by using a Graphical User Interface (GUI) with whom is possible to modify the input parameters and the settings (of the model to change the characteristics of the scenario and also of the simulator) (Bruzzone & Simeoni, 2002).
The scheduling contains the data about the interventions planned by the user to make maintenance to each power units of the pool.
The scheduling depends both of contracts and customer; it is not a fixed variable but the user must input it by using the GUI.
Each complex plants is composed by different item with different characteristics and then different needs in terms of maintenance. The analysis by the simulation of the maintenance policies of each component may be and hard and unproductive work, for this reason in combined power plants the maintenance procedures are driven by the most important item that is the Turbo Gas (TG)
The template of the sequence of events has the following order: I-I-PR-I-I-GR (I=Inspection, PR=Partial Revision and GR=General Revision).
All the characteristics of the Items are stored in the company Data Base (DB). All the scenario processed are stored in DB Scenario in order to collect a historical set of analysis performed (useful for future research).
In order to have the better interaction with the users the authors develop three different kind of output reports: a customer report (it is possible to send it directly to the customer), a pre-customer report (these reports need to be checked by the user before sending them), and a user-report (to control if the results are consistent with the related scenario).
Due to the high computational workload related to this very complex model, it was decided to implement it in C++ allowing to run optimization process within reasonable time (i.e. few minutes for simple case/partial optimization, few hours for complex scenarios); at the same the authors are used to consider the automatic optimization not as a stand alone solution, but as a procedure to be run by decision makers interactively while they test new hypotheses and ideas; in fact changing some hypotheses on exogenous factors the best solution change and the decision makers need to compare the results and evaluate the reliability of data and evaluation provided by experts.
So in order to guarantee an easy access to simulation and optimization results as well as en effective analysis tool the LAPIS report are post processed and handled by a module implemented using MS Office Suite, while FUSE model provides additional capabilities in evaluating the solutions.
By using the report carried out by the combined use of LAPIS and FUSE the decision makers are able to quickly evaluate, accept, modify or reject alternative proposed solutions.
The authors worked on optimization and simulation of pooling strategies for managing several power plants with different spare parts; therefore due to complexity of the system it was critical to guarantee an effective interface to make the use of the program easy for decision makers and to support all the functions provided by LAPIS.
LAPIS VV&A (Verification, Validation and Accreditation) was extensively applied even in term of dynamic analysis of simulation/optimizer over several complex scenarios. Several month of work, desktop review and dynamic testing in cooperation

with Subject Matter Experts (SME); in particular power plant service experts (i.e. project managers, supply chain management team member, planners) supported the validation phase. Several Statistical Test Technique was applied to LAPIS models such as Analysis of Variance (ANOVA), Mean Square pure Error (MSpE), Confidence Band, Statistical Comparison and Sensitivity Analysis (as presented in figure 4).

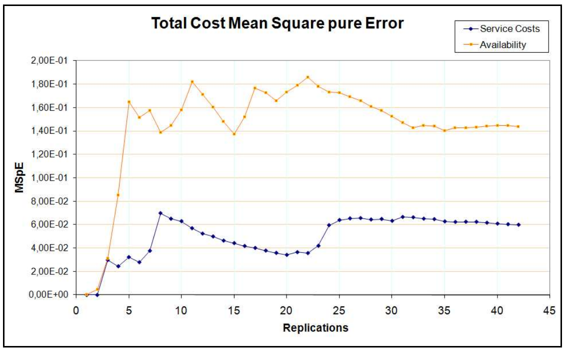

Figure 4 – LAPIS Verification and Validation

In the paper the results of sensitivity analysis based on Design of Experiments (DOE) are proposed as VV&A; the analysis allows to quantify the effects and the contrasts of selected parameters on the target functions as well as their interaction.

The case proposed for this analysis and optimization is related to a realistic scenario involving a collaborative service provided to nine different combined units (steam turbine plus gas turbine) located over different sites.

The aim of this analysis is to identify what, and in which way (direct or inverse proportionally), a controlled variable impact on a target function (i.e. availability of the pool and the overall cost); in similar way all the combined effect of different variable are estimate, in fact due to the high degree of not linearity of the problem under analysis the high level order effects are usually significant and cannot be neglected .

In the paper the analysis is focalized on some of the main parameters, according to the SME suggestions:

- Parameter A: Number of kits of Gas Turbine blades available (condition tested over the values: 3 kits or 6 kits).
- Parameter B: Enable or disabled the Cannibalization of new kits of blades.
- Parameter C: Scraping Percentage, that indicate the percentage of damaged blades that can’t be refurbished at each step (based on company historical data and SME: from 1% to 5%)
- Parameter D: Computing/Neglecting the Residual Value of the item mounted in the machines at the end of the contract in the overall service cost KPI; this parameter is important because permit to consider the residual value of the material in the plants (especially if the customer don’t renovate the contract).

As shows in Figure 5, considering the availability of the power plants the sensitivity analysis shows how, in all the scenario tested, the residual value of the plants don’t affect the availability of the plants.

Analyzing the contrast the graph shows that the scraping impact on the availability of the plants in inverted proportional way; unfortunately the scraping is not easy to control, in general sense scraping should be considered as an exogenous factor that evolves with the time, usually positively due to new technological material developments and operational experience; so this variable is able to produce future benefits that are estimated by LAPIS, but it is not subjected to a direct control by users or service providers.

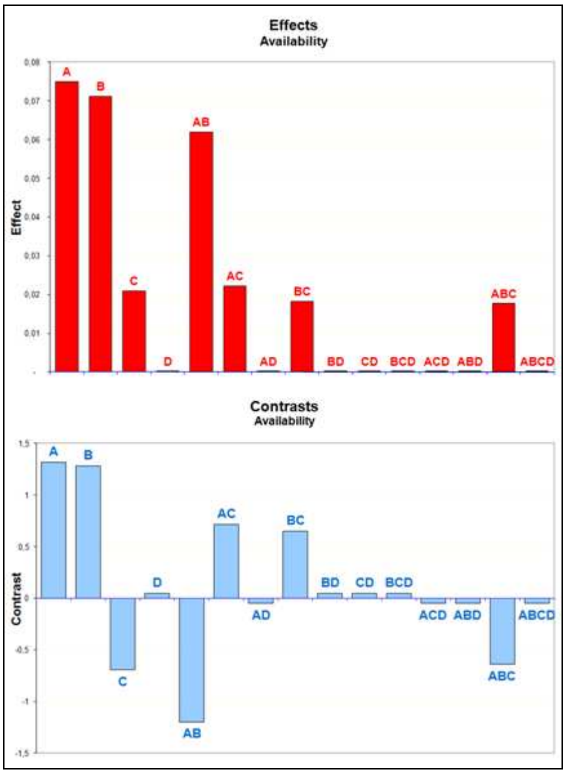

Figure 5 – Sensitivity Analysis Availability

Trough the analysis of Figure 6 related to a different target function (overall service costs) is possible to identify a particular behavior where the combination of 2 variable (A and B) is very big; in fact the influence on the related target function is

much more than the impact of the individual parameters if considered separately (please note that the scale is logarithmic); this is a classical confirmation of the complexity of the phenomena generating a very not-linear behavior.
In fact the possibility to cannibalize the new kits permits to optimize the maintenance operation and then to reduce total cost (as contrast shows).

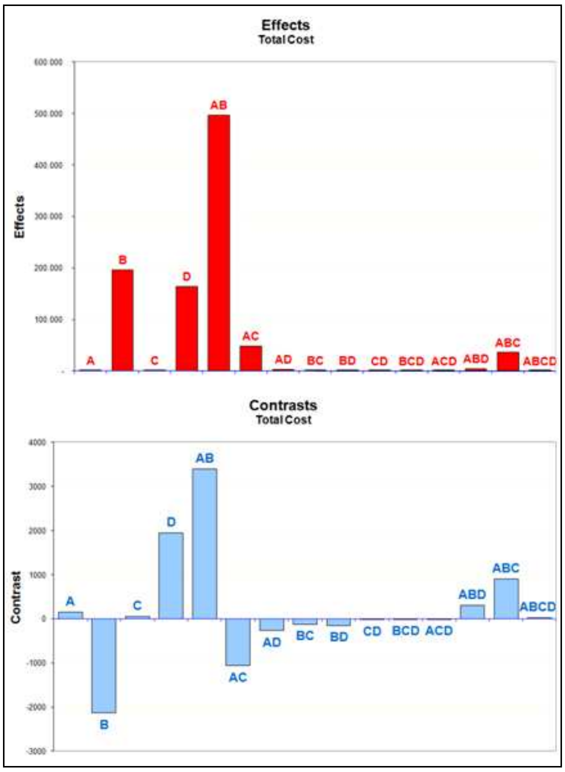

Figure 6 – Sensitivity Analysis Total Cost

The obtained results support to development of robust solutions able to consider inventory costs, stop costs, availability, contractual term respect and constraints in fact the simulator driven by the to genetic algorithms is able to provide useful service management solutions.

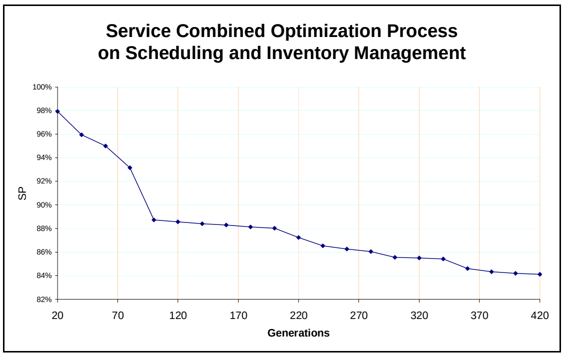

Figure 7 Lapis Optimisation Evolution

Figure 7 propose the evolution of the optimization process during an optimization; it is evident the significant saving and benefits provided by the integrated use of simulation and GAs.

CONCLUSIONS

The architecture of the model resulted very reliable and robust even when applied to pretty complex scenarios; currently this approach is proposed by the author to support decision making in terms of service and maintenance in system-of-systems service for major companies .
The evaluation of the profitability combined with availability related to the market prices represent an example of how it could be possible to redirect the service management to most efficient approaches by properly evaluating the overall effectiveness and efficiency; in power industry for instance this aspect have a growing impact and the use of such models could guarantee significant improvements and high level of competitiveness both for service providers as well as for users; in fact a major benefit of introducing these advanced models in the service of complex systems it is related to the sharing among providers and users of a common understanding of the scenario with possibility to achieve much better results and lean decision making process both in management and acquisition of service contracts. the introduction of this innovative approach in power plant service allows to define pooling management strategies able to evaluate more properly the real performances and to change the scheduling criteria for inspections/revisions as well as the policies in use (inventory management, safety stock, refurbishment services).
Due to its effectiveness LAPIS was effectively used to be integrated in the company decision making process for supporting complex power plant's service and maintenance.

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