A MAS Model Approach to a Wind Farm Maintenance Strategy

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Keywords: Cost Optimization, Decision Support Systems, Maintenance Strategy, MAS, O&M.

Abstract: The aim of this work is to propose a new method of analysis and optimization of maintenance strategy for wind farms. The objective is to help wind farm operator to carry out the optimization of the maintenance costs through profitability analysis of the wind farm according to failures, planned shutdown situations and maintenance budgets. Such approach has the advantage of combining the O&M (optimization and maintenance) technical vision and the financial vision within the meaning of profitability. The platform model is based on multi-agent systems. It aims to realize the calculation and optimization of scenarios. Agents have been identified from the knowledge of the windfarm O&M domain thanks to the wind farm operator's point of view. The platform we're developing is named PROMEEO, a French acronym for O&M onshore wind farms rationalization and optimization's platform.

1 INTRODUCTION

The maintenance of the equipment represents an important issue in all industries. In wind energy's case where the exploitation of the wind farm is strongly impacted by maintenance policies management. A wind farm is established for an approximate lifetime from 20 to 25 years. During this period, the owner sets up various operations intended to guarantee the availability of the wind turbines and their good performance.

For most industrial owners, the optimization of maintenance is firstly focused on the maintained equipment (a wind farm for the wind power operator). Most industrial owners thus focus themselves on the equipment's state to maximize its operating time.

Consequently, the preventive or corrective policies of maintenance are prioritized to guarantee the availability of the wind farm, which is the major indicator of maintenance analysis; it is calculated by (1):

$$\mathrm{D}\ \% = \frac{\text{Operating time}}{\text{total time}} * 100 \qquad (1)$$

The temporal availability allows to know the ratio corresponding to the operating time of the wind turbine regarding the total time. It is the ability of an equipment to be able to perform a given function under given conditions at a given instant or during a given interval of time, if the provision of external means is assured. The percentage of availability makes it possible to deduct the associated overall loss of production.

The first objective of the wind farmer is to maximize availability. Maintenance plays a strategic role regardless the type of industry. In wind energy industry, it represents a significant cost; it has a major impact on the cost of operating the wind farms. As it has been said, each wind turbine is built for an approximate service life of 20 to 25 years. During this period, the operator shall put in place various maintenance operations to ensure the availability and operation of the wind turbines. This availability is determined upstream in the operating contract. It is located between 80 and 95% according to farms.

According to the AWE (American Wind Energy), the cost of O&M is not negligible throughout the life cycle of a wind farm (Ribrant, 2006). At the end of life, this cost can reach up to 25% of the total cost of kWh. Reducing O&M costs by 0.18% would result in a 3% reduction in the total cost of a kWh.

Availability implies a maintenance cost that cannot be minimized without degrading the availability rate; then the operators adapt each maintenance contract to the windfarm's characteristics and to the availability objectives (Piana, 2016). However, the final priority of an

Kpakpo, M., Itmi, M. and Cardon, A.
A MAS Model Approach to a Wind Farm Maintenance Strategy.
DOI: 10.5220/0006554501590167
In *Proceedings of the 10th International Conference on Agents and Artificial Intelligence (ICAART 2018) - Volume 1*, pages 159-167
ISBN: 978-989-758-275-2

operator is to opt for the maintenance strategy that would enable a better profitability of the windfarm. Our method is focused on this priority. Indeed, the vision of financial profitability, reinforces the technical vision of maintenance while usually profitability is often separated from the financial sector. Availability is no longer the only criterion of maintenance analysis because the wind farm's profitability accentuates this analysis.

Our approach uses a model based on MAS theory to realize wind farm profitability scenarios based on available budget forecasts and information on breakdowns that would occur. The main objective is to evaluate different scenarios and their profitability providing financial indicators for one or many failures list to choose the scenario that suits the operator's requirements.

1.1 The Problem of Maintenance in Wind Energy Sector

There are several types of maintenance that are used in wind energy sector:

Preventive maintenance: it aims to reduce the breakdowns by anticipating them. The interventions are carried out after a well-defined duration (annual, semi-annual etc…) or after a signal appearance following the failure or the going beyond a threshold. This type of maintenance aims to reduce the possible risk of breakdown. It corresponds to a logic of the breakdowns prevention and maximization of the availability. Ideally for a wind farm, this type of maintenance is carried out during the periods of low wind to ensure availability during the periods of strong winds.

Curative maintenance: used in a single way, curative maintenance certainly reduced well the maintenance costs, but it can quickly exceed the forecasts and causes important disadvantages related to the production. As the wind farm ages, the number of corrective increases and generates indirect costs which it is difficult to estimate before the breakdowns.

Corrective maintenance: it's a type of maintenance made after a diagnosis of breakdown. Its goal is to set back an element in operating condition (Hajej and Rezg, 2012). It's a strategy which results in an unquestionable advantage relating to the maximum use of the wind turbine's components; in fact, the equipment is replaced or repaired only in the event of breakdown. It's also called the "breakdown" strategy. In the case of a wind turbine, the failures often occur during period of strong wind. However, it is in this period that the wind turbine must be available to the production. The wind turbine's stop throughout corrective maintenance thus involves a consequent production loss. The single advantage of a corrective maintenance is that it makes it possible to use the equipment until exhaustion.

Hybrid maintenance: it is the most current type of maintenance. It combines the two types of maintenance: preventive and corrective. It consists in anticipating some breakdowns by the means of preventive interventions and being reactive for the corrective O&M operations when the breakdowns occur.

Several maintenance tools were developed by research laboratories and companies. Each one of these tools adopts an angle of analysis of maintenance. It can be oriented to some maintenance fields like spares management or to the whole O&M field including: spares management, human resources, installation etc…). For example:

1. SINBAD (Guillon, 2015): is a tool which main objective is to predict the behaviour of a wind turbine at any moment. This project was born from a recommendation of a Franco-British partnership dedicated to the offshore oil rig to create a digital tool allowing the visualization of the tree structure of wind turbines offshore oil rigs.
2. The OMCE (Operation and Maintenance Cost Estimator) (Rademakers et al., 2009): it is one of the most complete models of simulation, marketed since 2004. The project was initiated by a consortium including Vestas, Shell Wind Energy, DTU and ECN (Energy Research of the Netherlands). It combines three strategies of maintenance: corrective, preventive and predictive to predict the annual cost of the maintenance actions of wind farms. (Onshore and Offshores) (van de Pieterman et al., 2011). As inputs, the tool records the components reliabilities, maintainer information and the operation to provide maintenance costs.

From the maintenance operator's point of view, the problems consist in finding the "optimal" cost of maintenance that represents balance between an expected production of the wind farm and a budget associated with a series of breakdowns planned during the period. To optimize maintenance, we thus must optimize the budget of maintenance (subcontracts and spares) on the wind farms because it represents the most important owner's growth drivers.

1.2 Strategy of Maintenance over One-Year Duration and Financial Indicators

An efficient maintenance strategy is measured by the reactivity of the team of maintenance, the capacity to control the costs of parts and the additional costs and profitability of the wind farm at the end of a period. In our approach, the final profitability of a wind farm, over a consequent period of operation, is expressed by a customized EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortization) indicator. This indicator is called "Function Cost": FC (2)

$$\text{FC} = \text{Theoretical turnover} - \text{Production losses} - \text{O\&M Costs} \tag{2}$$

$$\text{FC} = \text{ThT} - \text{PL} - \text{O\&M Costs}$$

The theoretical production (3) of a wind turbine is equivalent to its production with an availability to 100% i.e. no downtime ago over the period. Over a chosen period, we can obtain a theoretical production of the wind turbine starting from the variables of entry which are the data of wind measured on the wind farm and the curve of real power.

Data of wind: they represent the speeds of wind measured by the anemometer-nacelle of the wind turbine. In the event of unavailability, they are recovered on the anemometer of the nearest wind turbine. If no data is provided on the wind turbines, it will take the data of the mast of measurement which is located near to the windfarm.

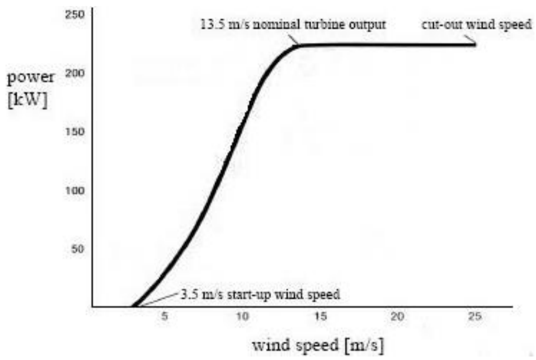

Figure 1: A power curve diagram.

$$\text{ThT} = [\Sigma(\text{Vd}) * \text{Pd}(\text{PC})] * \text{kWhPrice}(€) \tag{3}$$

Where:

- ThT: theoretical turnover
- Vd: Wind measurement with the period in m/s
- Pd: power curve measure
- PC: power curve measures kWh

The production loss is defined as a production which should have been realized for the period when the wind turbine was stopped; it's deduced in a theoretical way. The production loss represents a shortfall which is calculated by the same formula as the theoretical turnover but over the duration of production loss (PL). In this case, we use the same formula as in (3).

The O&M Cost is related to all maintenance cost. (4). It can be divided in two parts: spares et subcontract costs.

$$\text{O\&M Cost}(€) = \sum \text{Spares Costs}(€) + \text{Subcontract cost}(€) \tag{4}$$

Subcontract cost (€): this cost is related to the company receiving benefits and which is responsible for the wind farm maintenance. This company has an availability rate to reach fixed by contract. In the facts, the company in charge of maintenance subcontract is a dissociated company of the farm owner. The later delegates all the ordinary maintenance actions.

Spares cost (€): this is the cost of all the parts used during maintenance operations. This cost is valued at the end of the stock.

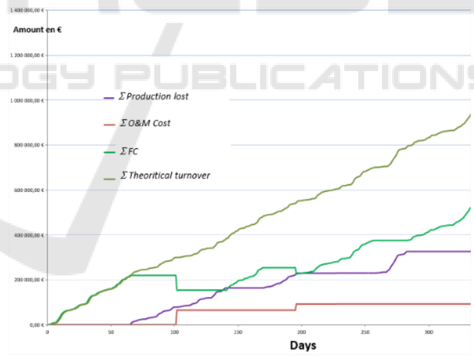

Figure 2: A scenario of the evolution of the indicators in relation to a series of breakdowns and O&M costs.

Operator estimates maintenance budget at the beginning period: O&M Cost $_{\text{estimated}}$ of period; it may be different at the end of the period O&M Cost $_{\text{real}}$. In the present case, three situations may arise at the end of the period:

1. The forecast of cost is higher than the real maintenance costs; then maintenance is overpaid compared to the work completed on the stops: O&M Cost $_{\text{estimated}}$ > O&M Cost$_{\text{real}}$.
2. The expected O&M cost is lower than the final real cost of maintenance. We suppose then, all

other things being equal, that O&M $Cost_{estimated}$ < O&M $Cost_{real.}$

3. The ideal situation where the operator has properly estimated its O & M budget in relation to the operation of the farm: O&M $Cost_{estimated}$ = O&M $Cost_{real.}$

The evaluation consists of analysing the activity of the wind farm during the period of operation through the evolution of the O&M indicators over time (Figure 2).

We will construct this evaluation thanks to several scenarios that will help the operator in the choice of his strategy.

1.3 State of Art Discussion and Problem Definition

The tools for current maintenance are focused on the wind turbine or the windfarm. These tools can predict equipment failure that does not allow to project on the income that can be derived from the equipment itself.

In our case, at the "Compagnie du Vent", a company that manages several wind farms, there exist a tool named PROMEEO (Platform of Rationalization and optimization of the maintenance of the Onshore wind farms). We've made a comparison between the state of art's tools and PROMEEO.

Table 1: Comparison of state of art's tools and our tool PROMEEO.

Tools	State of art's tools	PROMEEO
Strengths	Tools focused on turbines, their operation. Operational vision for maintenance Complete maintenance indicators on the probabilities of failures occurrences.	Financial maintenance-focused tool Corresponds to a management vision of maintenance
Shortcomings	Incompatibility with the operation of a wind farm operator because of several models of different turbines in a territory. There is no modularity to follow the business evolution and the context of the wind farm operator.	Management of simulation input parameters: O&M subcontractor's time of maintenance reactivity. Improvement of the prevention of failures from alerts Prevention of defaults on large components by analysing the alarms that precede these defaults.

We set the problem upside down by optimizing the wind farm production compared to the maintenance that can be budgeted.

1.4 The System Agentification

With O&M Multiagent system we can evaluate the indicators of current and future situations of a wind farm in real-time with the management of the evolution of knowledge. The system performs the simulation of the indicators from the validated input data (failures list and wind measurements over the year for theoretical production). We proposed a scenario calculation which is the expression of a management of failures over a significant period. Thus, a one-year (for example) scenario using the history on-line gives the state of the fleet, the actual cost of providing maintenance and its profitability. (figure 3). A scenario S for year n is described by:

$$Sn = List\ Pn \wedge O\&M\ Cost\ n \wedge ThT \wedge FP\ n$$

Where:

- List P_n: This list of failures is either recovered from the year n chosen or constructed fictitiously from the forecasts of stops.
- ThT Theoretical Turnover: Theoretical production forecast during the analysed period.
- Subcontract cost: budget for the period for maintenance providers.
- FC: Function cost (windfarm profitability).
- FP: «financial performance» ratio of performance of the costs compared to the theoretical turnover (5).

$$FP(n)=FC(n)/ThT(PC,n) \quad (5)$$

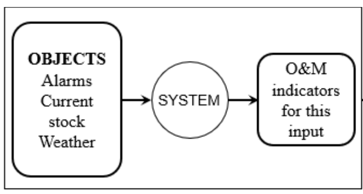

Figure 3: A scenario in PROMEEO.

We compare the various indicators of

profitability according to the various proposals of maintenance contract anything being equal. Several scenarios can be provided for the same list of breakdowns and different subcontract cost. Each scenario is composed by a series of breakdowns. A breakdown (Figure 4) involves a production loss and costs specific to this breakdowns or failures. For each breakdown, the system calculates the real cost of maintenance.

$$\text{O\&M Cost}_{breakdown} = \text{Subcontractor Cost}_{breakdown} + \text{Spares Cost}_{breakdown}$$

The set of O&M costs is the sum of the breakdown costs (Σ Ct O&M Cost). Each scenario expresses a strategy of maintenance of the breakdowns and the results of the wind farm in terms of performance and profitability.

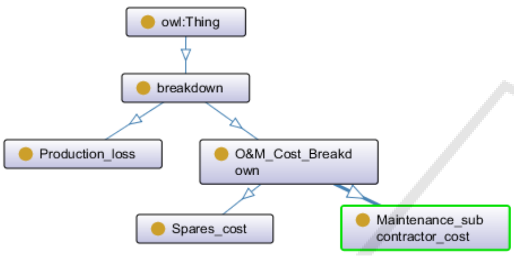

Figure 4: From descriptive ontology extract of a breakdown.

1.5 The Multiagent Model Used to Develop the Different Scenarios

The multiagent approach is an alternative to more conventional approaches to cooperation and problem solving. In general, it can deal with a problem by decomposing it into simpler sub problems, so that agents must focus on only one subtask at a time. In (Ferber and Simonin, 2003), an agent is defined as an entity driven by a set of trends (satisfaction's function to optimize or goals to reach) which has its own resources and has only a partial representation of the environment. Its goal is to meet its objectives while considering its skills, its resources, its perception of its environment.

An agent is aware of its decision's capacities and seeks to achieve a precise goal. Another agent's characteristic is its capacity to cooperate with other environment's entities. While conforming to its level of rationality, it can choose to interact, cooperate, negotiate or limit its interaction with the environment. An agent, like an object, encapsulates a state and behaviour but the agent encapsulates its control on its behaviour; an object has control only on its state.

In a system with many agents, the goals to reach can be complementary or contradictory. The agents can be separated according to the type of relation in two categories: the competitive agents and the collaborative agents. A collaborative agent makes decisions and carries out actions in agreement with other agents to achieve their respective goals. This effect of group enables them, consequently, to pool knowledge and to bind their goals. The environment of maintenance is composed of agents as well as objects in the system. The agents present in the environment are in interaction with objects and other agents. Whether they are physical or abstract, they carry out actions to conform to the objectives which are predefined; the objects can interact with databases and provide answers at the requests of other agents.

In our work, an agent has a goal which consists in modifying the object "Breakdown", to modify its state then to share its information with its dealings. The concepts identified in the descriptive ontology give us the objects which compose the field of the O&M. The concepts in the ontology can be at the same time physical or abstracted elements. The concept, when it is a physical entity can be translated in agent if it expresses behaviours, goals. Each agent must be able to express at least one objective to reach. Example: the wind turbine (the equipment) expresses an objective to run with an availability of 100%. Even if it has an objective of operation (Availability ratio =100%), its behaviours are oriented by the O&M indicators values. The wind turbine cannot be proactive on its environment; it expresses a set of states which will be evaluated by indicators. When the concept is a physical entity, it must be able to express at the same time objectives and autonomous behaviours to be declined as an agent.

For example, the indicators are abstract concepts; the indicator "Cost O&M" (the total cost of maintenance), has an objective that is to stay low. The behaviours that it will express will have consequences on the environment composed by failures objects and the other agents.

1.6 The Organization of the MAS According to Environment

Each object "failure" sent in the environment is described by the following attributes expressing knowledge:

- Failure Id
- Turbine Id
- A failure description

- Start and ending date
- O&M failure Cost

The scenarios are built with PROMEEO. The tool is based on eight kinds of agents. For a list of failures given as inputs of the system, the direction of knowledge communication using agents is shown in (Figure 5):

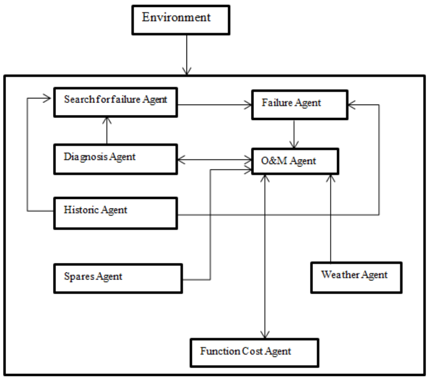

Figure 5: MAS model.

For each agent identified in the system, we will describe its goals and the entities with which it cooperates.

1.6.1 Search for Failure Agent

- Goal: it detects possible failures from alerts and messages based on the history.
- Actions: it sends possible failures as objects to Failure Agent.
  - Proactivity: The search for Failure Agent can be proactive when it detects failure on a wind turbine. It evaluates, and alerts based on the probability of occurrence of failures that have been registered.
  - Communication: With the SCADA (Supervisory Control and Data Acquisition). It retrieves alarms and signals as objects coming from this entity. It sends to Failure Agent the list of failures as objects. In coordination with the Diagnosis Agent, it recovers the causes of failures that had not been identified.

1.6.2 Historic Agent

- Goal: find former O&M operations for O&M agent.
- Actions: it perceives the failures in progress and the potential breakdowns and asks for maintenance operations.
- Proactivity: from the details given by O&M agent, it retrieves the operations that have been performed for the same failure.
- Communication: it provides to the O&M Agent the breakdowns and asks for the execution of maintenance actions. With the Search for failure Agent by receiving information about potential failures.

1.6.3 Failure Agent

- Goal: to close all the breakdowns and to ask for O&M operations.
- Actions: it perceives the breakdowns and failures in progress and the potential breakdowns and asks for the maintenance actions.
- Proactivity: the agent is proactive in sending the breakdowns.
- Communication: with the SCADA: it recovers alarms in progress which describe the stopping of the wind turbine in the event of breakdown. It provides to the O&M Agent the breakdowns/failures and asks for the maintenance actions. It communicates also with the Search for failure Agent by receiving information on potential failures.

1.6.4 Diagnosis Agent

Its identifies the breakdowns and their causes. it perceives the breakdowns, sends the causes and the list of the parts to be used for the interventions. It sends to the Search for Failure Agent the causes of the breakdowns up to that point unknown. It has no proactivity: no proactivity. Communication: It provides to O&M Agent the diagnosis Agent.

1.6.5 O&M Agent

It's equivalent to a maintenance project manager in the company.

- Goal: its main objective is to achieve maintenance operations ASAP while respecting the strategy set by the Function Cost Agent. It provides O&M costs for each failure to the Function Cost.
- Actions: it performs one or more interventions to resolve received failures. Before each operation, it sends the total cost to Function Cost Agent.
- Proactivity: this agent is responsive during the failure management.
- Communication: its communicates with Failure Agent by receiving failures as objects; with Service Provider Agent by receiving their cost

for the failure management; with Diagnosis Agent by receiving the spares that will be used for the operations; with spares Agent: by receiving available spares for operations; with provides cost O&M to the Function Cost Agent that validates the operation.

1.6.6 Service Provider Agent

This agent corresponds to the subcontractor; this agent oversees the operation execution on the site. In the system, it sends the Subcontract cost (€).

- Goal: it must be able to provide a time of intervention and the cost of the service.
- Actions: for each failure or breakdown, it provides a person receiving benefits, the cost of service and the duration of associated intervention.
- Proactivity: it has no proactivity; it only responses to the requests of the O&M Agent.
- Communication: communicate with O&M Agent by sending the provider cost. (It sends the service provider chosen and the subcontractor cost).

1.6.7 Weather Agent

It lists the days with favourable weather for maintenance operations. Proactivity: it responses to the requests coming from the O&M Agent. The agent can be proactive when it detects an alteration (deterioration or improvement) of the weather on the days it has sent.

1.6.8 Function Cost Agent

This agent validates the execution of the maintenance action according to profitability. Within the framework of a calculation, this agent is responsible for analysing and validates each operation. We have modelled this agent for simulations where the system would be constrained by an objective of profitability. According to the owner's strategy based on criteria like the intervention's duration or the importance of the operation's cost (cost O&M), it validates the intervention. It is the most important agent in the system according to the main goal of the system.

- Goal: according to the cost of the intervention, it gives its consent to the execution of the intervention
- Actions: it validates the maintenance operation if it is consistent with the strategy (internal argument).
- Proactivity: it only responds to requests from the O&M Agent.
- Communication: it communicates with the O&M Agent to get the "GO" or "NO GO" for the operation.

1.6.9 Spares Agent

This agent is responsible for spares managements. Its goal is to answers to spare request for operation maintenance and send total spares cost ($\sum Cost_{spares}$ (€)); It communicates with O&M Agent by sending spares costs and supply delays.

1.7 Running the Agents System

We must implement a lot of agents according to the categories we have defined. The agents in our system are not in competition, each one of them expresses a useful state for its dealings. Considering the low number of dealings of each agent, the interaction is direct between the agents. Each agent is defined by its goal, its rules of behaviour and its interactions with the other components within the system. Thus, it has a representation of itself and environment which surrounds it.

A scenario is the result of the operation of the wind farm throughout a given period. This operation considers the possible stops and the estimated forecasts of wind. Three phases were identified for the calculation of scenarios:

Firstly, we have "breakdown" event: this indication gives the state of the wind turbines on the wind farms. They are the system's inputs as objects: ListF (list of failures provided for calculation). Secondly, the treatment of the breakdowns: at this step, the failures are studied to know their costs and effects (lowers availability and production loss) on the productive apparatus; the system calculates for each breakdown the cost of maintenance. Thirdly, the final indicators which give the plan of maintenance and the cost associated with the maintenance actions while making it possible to maximize the profitability of the wind farm (minimum of loss of availability).

For the user, PROMEEO platform provides a set of following scenarios with the data input which is provided. Platform PROMEEO (Platform of Rationalization and optimization of the maintenance of the Onshore wind farms) resulting from this approach is developed for a wind operator ("La Compagnie du Vent"). The platform establishes the scenarios with inputs from several data sources which come from several different applications (figure 6). These applications provide information's to PROMEEO database.

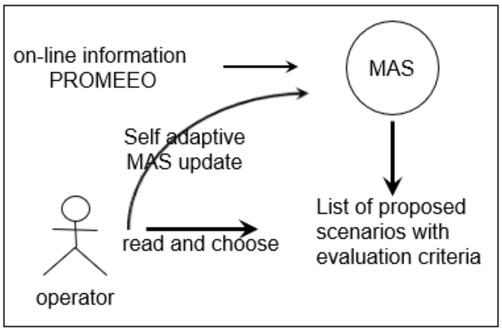

Figure 6: System inputs and outputs.

Presently, we're developing the agents and the treatments for the platform. The data inputs were formatted in a SQL database. The strategies of maintenance of the wind farms are evaluated compared to the results of the indicators. The scenarios depend with time on the relative data to the breakdowns and the results on indicators calculated by the platform. The database schema was designed in UML diagram.

Maintaining industrial equipment doesn't mean any more to keep it in a good condition; it means to achieve goals to maximize the profit which is to get more than a return on investment. It means also to preserve the wind turbines for a long time and at lower costs to amortize the expenses engaged for construction and the exploitation. O&M Budgets and subcontracts costs must be regularly revalued to guarantee efficiency in the wind farms management. To simulate the real costs of service of a wind farm means to know the cost of the reactivity of the maintenance subcontractor. Some questions remain. For example, wow simulate the maintenance subcontractor reactivity while varying the contractual costs within the framework of a forecast?

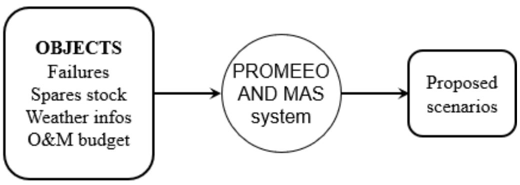

Figure 7: MAS Operating.

Based on the real-time information produced by PROMEEO, the MAS evaluates the various scenarios proposed, improves them, quantifies them by using its history and the old evaluations available and proposes them to the operators. According to the operators' choices, the MAS updates its knowledge (the criteria of good choice for example) to make them operational for any other scenario production action evaluated by the operators (figure 7).

1.8 Conflict Management in the MAS and Results

The agents in the MAS may face conflicts in the system:
On the failure's treatment: for each failure, many indicators are calculated. Their values depend on the failure's day start date and an end date. On each failure, the O&M Agent which validates the failure's end date of the maintenance operation by granting to the "failures object" an end date based on the information at its disposal. The conflicts that may arise if we add a couple of constraints for example: calculate the O&M Cost with a profitability target (6):

$$\begin{gathered} FC = ThT - x - PL \\ x = ThT - FC - PL \end{gathered} \tag{6}$$

ThT: the theoretical production cannot be modified; it represents a fatal data for the operator. The only optimization action that can be applied is related to the failures management and consequently productions loss.

With PL (production loss) which is a function of maintenance support duration; this duration can be mechanically reduced but it depends on subjective criteria such as the responsiveness of the O&M subcontractor company that we are not able to quantify.

2 CONCLUSIONS

To be efficient, we have proposed a MAS model for maintenance that is proactive on the breakdowns, failures and operations on the windfarm to maximize profits. The platform is intended to the wind farms operators. A first prototype is presently under development towards a professional validation and that is our first objective. Our final objective is to produce a MAS system with real-time data and continuous optimization.

ACKNOWLEDGEMENTS

The work presented in this paper was supported by the French Foundation of Technological Research under grant CIFRE N° 2014/0099.

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