ESReDA Conference 2012
42nd ESReDA Seminar on Risk and Reliability for Wind Energy and other Renewable Sources
15-16 May 2012, Glasgow, Scotland

Enabling Multi-Agent-Systems for wind turbine maintenance optimization through a common database

Khalid Rafik[1] , Stefan Faulstich[1], Sebastian Pfaffel[1], Paul Kühn[1]
[1]Fraunhofer IWES, Kassel, Germany
Khalid.rafik@iwes.fraunhofer.de

Abstract

Maintenance management for wind turbines (WT) aims on the one hand at reducing the overall maintenance cost and on the other hand at improving the availability. Although modern onshore WT attain high technical availability of up to 98 %, the evaluation of maintenance work in previous projects shows, that high WT availability requires additional maintenance work and costs. There is a considerable scope for optimizing reliability and maintenance procedures. A possibility therefore is to systematically make use of available knowledge and past experience. Thus, necessary steps have to be introduced for operation and maintenance of wind turbines to bring several readings together and to use them for improvements. At this point, information coming from databases, statistical methods as well as sound statements is essential. The consideration of several conditions e.g. weather conditions, power prognostics, stock keeping etc. are essential for optimal decisions. However, due to this enormous amount of information sophisticated tools are needed. This paper is going to show the possible application of high-performance computing methodologies, which may help wind farm operators (WFO) examining optimal maintenance strategies. The so called Multi-Agent-System (MAS) which is a new discipline in the world of Artificial Intelligence (AI) and the Data Mining (DM), which is a high-performance computing methodology used to observe and deduce hidden knowledge and logical dependencies of a great amount of data using several appropriate algorithms, should be investigated and a methodology for the use of AI in WT maintenance is proposed.

Keywords – Maintenance, Optimization, Artificial Intelligence, AI, Multi-Agent-Systems, MAS, Failure Database, Reliability, Availability, Data Mining, O&M

I. Introduction

The efficiency of WTs has been substantially improved in the past two decades in technical and economic view. The continuous development of wind power use permits purposeful advancements of the system technology in order to increase both efficiency and performance of the turbines However, earlier intensive and broad analyses in research projects [1], [2] show that the efficiency of modern WTs and their equipment units are not obligatory proportional to their reliability. However, today's organization of operating supervision and maintenance makes it still difficult to use the various experiences from the operating and historic data purposefully for future improvements of maintenance activities.

Up to now maintenance planning is usually still accomplished individually and intuitively by the WFO, although a multiplicity of different aspects (e.g. energy yield, availability, weather condition, personnel employment, material costs etc.) with partly opposite effects on availability and costs should be taken into account (Fig. 1) [3]. At present the WFO can't consider these different interests of the various aspects to the necessary extent for making sound decisions. There is a lack of tools that help to manage all those aspects simultaneously.

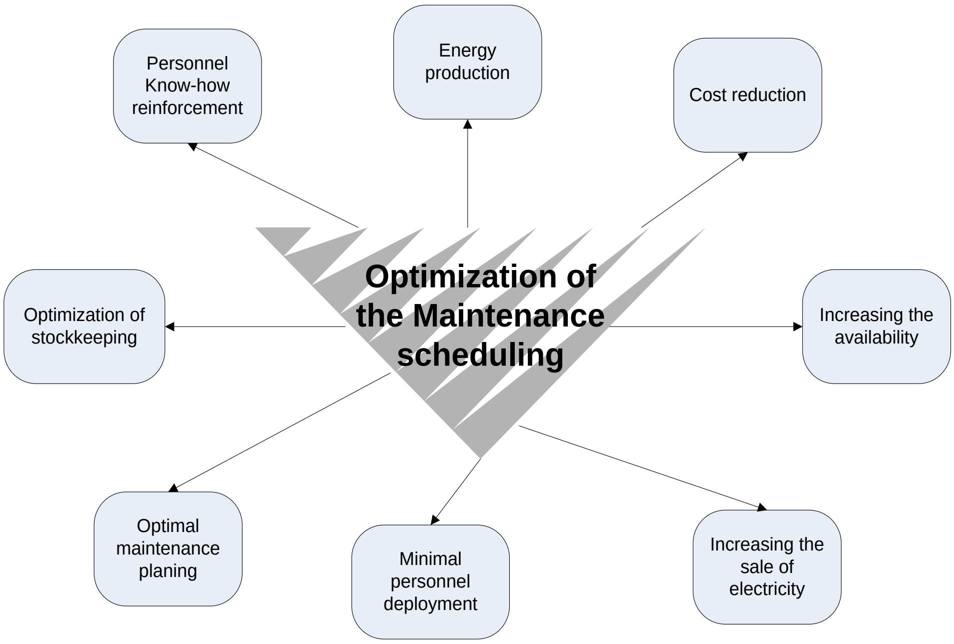

Figure 1: Competitive interests

In the past, only little focus was put in the use of methods and models of AI within the area of maintenance planning. The so called Multi-Agent-System (MAS), also known as Agent-Based-Modelling and Simulation (ABMS) can model the competitive aspects in such a way that the Agents negotiate quasi among themselves, which interests to be considered in decision-making [4]. Thereby each aspect is represented by an Agent. These Agents are programmed to cooperate with each other in order to determine an optimal total conception. As a result of the Agents communication either a particular or several optimal alternative solutions can be suggested.

The project MAS-ZIH 'Use of Multi-Agent-Systems as Support for Reliability-Based Maintenance', which is it funded by the German Federal Ministry of Environment, Nature Conservation and Nuclear Safety, is going to investigate the possibility of using AI in WT maintenance. The project duration is three years, starting last October 2011. Therefore, the findings presented here, represent the first steps in the field and will give an overview about the methodology and expected results.

II. Common (Failure) Database

A. *The WMEP failure database*

In the period from 1989 to 2006 a monitoring campaign, the scientific measurement and evaluation programme (WMEP), was conducted by ISET. During these 17 years 193.000 monthly reports of operation and 64.000 maintenance & repair reports from 1,500 WTs were collected and analysed [5]. The database of this programme contains a quantity of detailed information about reliability and availability of WTs and subassemblies, the preventive maintenance and repair costs, the failure causes, the failure effect and the removal of the malfunction. This provides one of the most comprehensive studies of the long-term behaviour of WTs worldwide.

Taking into account that activities are often carried out simultaneously for more than one subassembly (e.g. many replacements or many preventive tasks at the same time), will increase the amount of information concerning the maintenance tasks regarding a certain subassembly.

B. *Parameters diversity*

As described in [7] there are many parameters influencing the reliability characteristics of WTs e.g. the technical concepts, the external conditions, the power class of the WT, etc. For detailed analyses all these parameters must be taken into account. Fig. 2 shows the parameter diversity. One can see that even with a broad database like the WMEP failure database, with a breakdown in different groups a certain point is reached, where the statistical basis is getting insufficient. By the example shown the need for a broader database is getting clear.

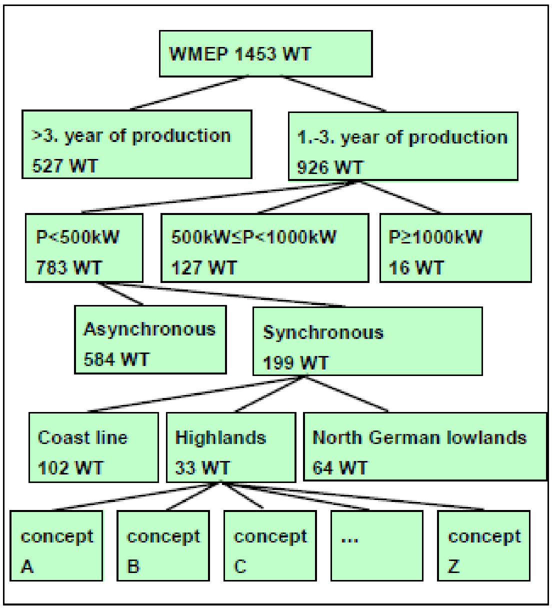

Figure 2 Parameters diversity

C. *Research projects 'Improving Availability of WTs' and 'Offshore-WMEP'*

In the research project 'Improving reliability of WTs' a consortium of owners, WFOs, services-providers and researchers exploit experience with WT operation more intensively. The focus of the project is on proposals for standardising data acquisition, data transmission and on a reliability characteristics library [6]. The project aims at improving reliability and as consequence availability and maintenance effort by the sub-goals:

- Standardising information structures
- Developing efficient management tools
- Improving strategies
- Optimising maintenance processes

Especially the standardising of information structures is fundamental for the use of experience gained.

Similar works in the offshore field is done in the project Offshore~OWMEP, where on the one hand fundamental questions concerning the use of offshore wind energy shall be answered by a general monitoring, and on the other hand operating experience shall be collected and analysed systematically in collaboration with operators and manufacturers. Gathering data will generate a large database which will contribute to political decision-making processes and facilitate further technological progress. The generation of a common database will also, due to its size, enable statistically reliable predictions concerning the success of operational concepts

III. Methodology of Artificial Intelligence

The reliability-oriented maintenance of WTs relies particularly on the management and the evaluation of operating and maintenance data [2]. However, today's organization of data acquisition and data management by the WFO doesn’t permit the easily use of experiences [8]. Additionally WFOs/service companies are missing tools and necessary information (e.g. failure statistics, weather forecasts, staff disposition, etc.), instructions and recommendations needed for their maintenance decisions.

A. *Artificial Intelligence*

By estimation of failure probabilities, remaining useful life and early recognizing of possible damages and errors as well as by using wind and power prognosis, maintenance tasks and procuring of spare parts could be better planned and unexpected stops could also be avoided. For an efficient maintenance planning the economic boundary conditions e.g. spare part and personnel costs or the temporal development of the fluctuating electricity tariff at the electricity market are to be considered. For the support of a foresighted maintenance strategy a MAS is to be developed, which uses the reliability characteristics and the cost information from WFO and weighs the competitive interests of the different aspects for the studied case and then suggests favoured maintenance measures for the decision-maker.

A schematic representation of the research within the work is shown in fig. 3, where different Agents manage different tasks. Some of them have the task to analyse the failure rates, while others regard weather and power forecasting, and the third category considers the question of cost of the whole maintenance process. A main goal thereby is to submit the WFO with an arranged list of requirements and proposals, on how the next maintenance should look like.

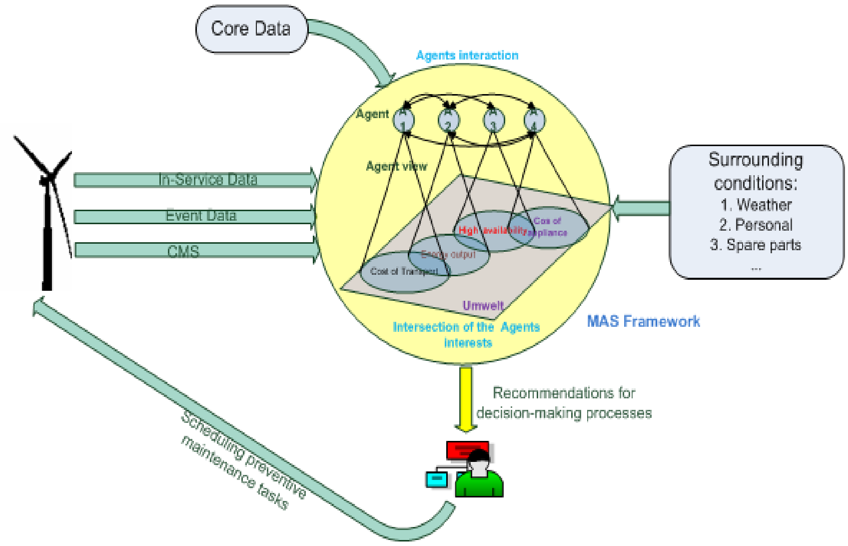

Figure 3: Use of MAS for improving the maintenance decisions

B. *Hybrid approach of MAS and Data Mining*

This approach consists of using the advantages of both technologies MAS and Data Mining. Before modeling the MAS-Model, some knowledge will be deduced by applying the Data Mining for the historic data of the WFO. This allows the Agents having some initial states, which they need in order to make sound simulation.

Data Mining

To understand the dependencies of historic preventive and repair maintenance, professional Data Mining Tools are used for this task. Such dependencies could identify the components that failed mostly and simultaneously with a given analyzed subcomponent or also possible cluster populations regarding the behavior of the subassemblies concerning the factors that play a dominant role on the failure of the analyzed component e.g. failure causes or downtimes etc. Fig. 4 shows an example for an extract of the Tree view that analyses the behavior and dependencies of the subassembly ‘electric converter’ for a WT type in the coast region of Germany. The figure shows that when this subassembly failed because of an ‘Unscheduled repair after malfunction’, and when the ‘electric generator’ was also affected at the same time and the whole downtime takes less than four hours, then the cause of this failure is usually ‘malfunction of control system’ otherwise it was ‘other causes’ and so on.

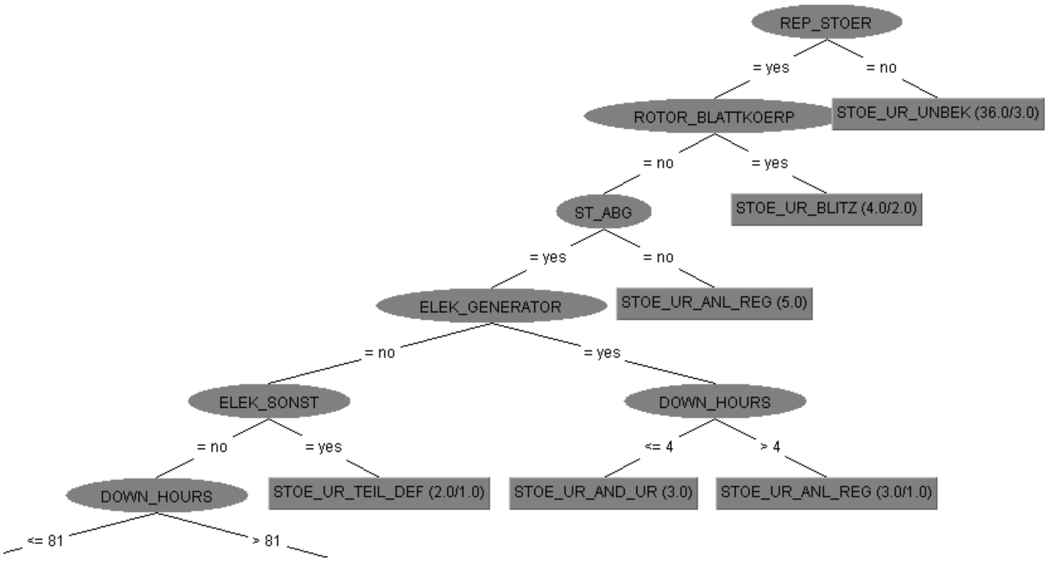

Figure 4: Extract of the Tree view ‘electric converter’

Fig. 5 shows the distribution of failure downtimes in function of failure causes for the same subassembly (‘electric converter’). The most frequent failure cause for failure with short downtimes duration between 0.5 and 79 hours (see the first bar in the x-axis; occurred 286 times) are ‘component wear’ (blue), ‘malfunction of control system’ (red) and ‘cause unknown’ (dark green). For failure with long downtimes duration in the interval [79h, 157h] (occurred 12 times) the first cause is ‘storm’ followed by ‘component wear’ and then ‘other causes’.
Identifying those dependencies for every subassembly will be decisive for improving the Agents intelligence as we will see later.

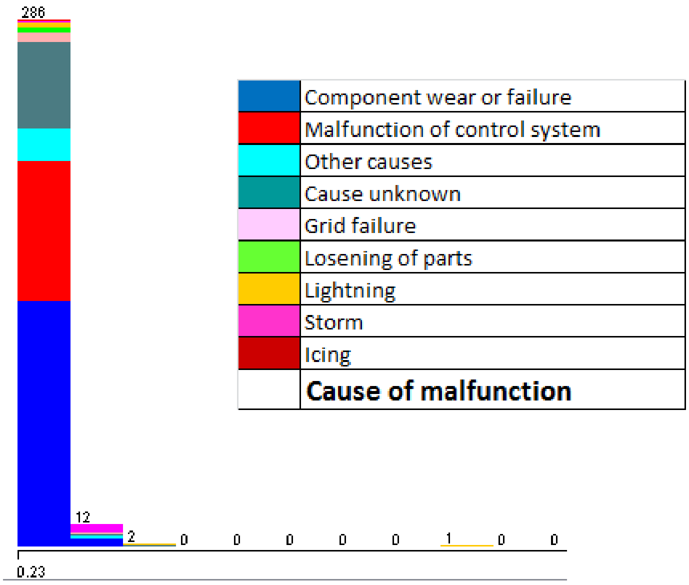

**Figure 5: Distribution of failure downtimes in function of the failure cause for the subassembly ‘electric converter ’.
X-axis: downtime duration intervals**

MAS

The approach of the dynamic modelling and simulation using MAS can make an important contribution in the area of maintenance of WT. In the past the analysis systems have integrated the reliability and maintenance aspects more and more in their evaluation. Several proven techniques already obtain considerably successes i.e. [13]. The existing methods for the modelling of availability/reliability can be divided into two groups: static and dynamic methods. [9].

Static methods require less information about the system characteristics than dynamic methods. A logical consequence of this decreased information requirement is their application in the early phases of a project. Although this knowledge base can be quite limited, static methods achieve good estimations for expected future availability and reliability of the object regarded [9]. In addition they are generally more intuitive and simpler in their application and attain faster results than their dynamic counterparts. The main impairment is their inability to treat time-based changes. Since the temporal sequences cannot be represented with static methods, they are generally less suitable for the modelling of maintenance activities, where maintenance planning and maintenance strategies are based mainly on time management [9].

Quite contrary to the static methods the strength of the dynamic methods lies in their ability to combine the temporal effects and the system developments. This characteristic makes the representation for system aging as well as the maintenance scheduling possible. Well-known examples of these dynamic methods are Markov Chains and Dynamic Fault Tree Analysis (FTA), which was already used successfully in the past [10]. Nevertheless these two techniques have large deficits, e.g. the Markov chains suffer an inevitable „condition explosion“, if they are used at large-scale systems and with mass data [1], while FTA already reach their borders, if the system models contain complex feedback loops [12].

Many investigations have been done in the area of dynamic methods using AI for optimizing the maintenance. Z. Tian, Y. Ding and F. Ding [1] review the current research status of maintenance of wind turbine systems, discus the application of Artificial Neural Networks (ANN) based health prediction tools in that field, and develop a CBM approach for wind power generation systems to address maintenance planning issues.

E. Byon [14] examines the optimal repair strategies for wind turbines operated under stochastic weather conditions and lengthy lead times with the objective to minimize the expected average cost over an infinite horizon. He formulated the problem as an observed Markov decision process for these goals.

MAS is seen as an adequate technology for seeking out unknown and unexpected behavior of complex systems as well as for filtering the most important knowledge, those the WFO needs later for his maintenance planning [1]. Figure 6 illustrates a MAS platform with several modules. The Agents representing many objects (components, subassemblies, weather, spare parts stock keeping etc.) interact with each other, in order to find the optimal „solution” for a given problem. The optimal replacement interval for a certain component or the best scenario of the team employment for tasks shared at different wind parks are examples for those solutions. The MAS regards several concepts in its analysis. It assigns Agents to analyse the so called Look-back database, in order to examine the past experiences, other Agents are assigned to analyse the Look-Ahead database for information and prognostics (e.g. the electricity tariffs of the next hour or days or also the weather prognostics as well as information concerning the stock keeping or to Team disposition).

C. *MAS modules*

An entire model based on the idea of categorizing the maintenance activities and the failed maintenance tasks in quality levels (Perfect, Imperfect, Minimal, Worse and Worst) introduced by [15] (see also [16] and [17]), where a Perfect maintenance task is a total replacement of wear out components or subassemblies, the Imperfect maintenance tasks are e.g. greasing, oiling, adjusting etc., and the Minimal maintenance task is reuse of old existing spare parts in another WT. These maintenance activity levels have an obvious impact not only on the health and useful life of the components and subassemblies but also on future maintenance strategies. The whole model is created by taking into account the several factors i.e. financial, weather conditions and staff disposition (see Figure 6). It consists of five closely interconnected modules, which are the modules for: Failure-Rates, Production, Logistic aspects, Weather and Cost. This separation provides the option of using different simulation methods as well as an easy extension.

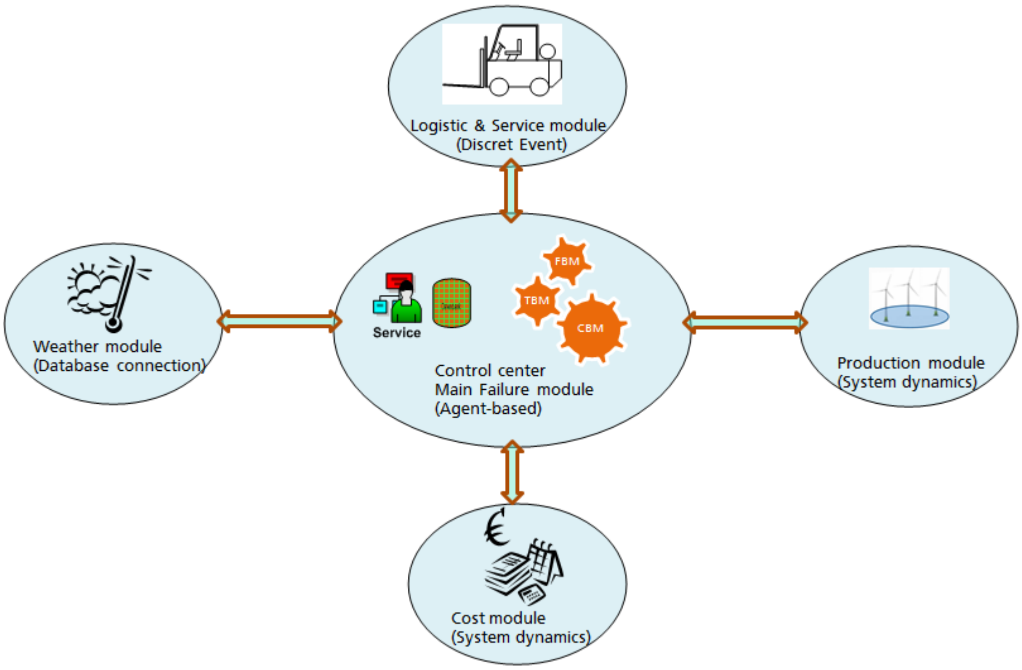

Figure 6: MAS Modules

The systems and their subassemblies will be represented by appropriate Agents, which have their own parameters and methods that enable them to act and react with their environment. Each one of those systems will represent an environment of its subassemblies (e.g. Generator-environment). All systems of the WT are in turn part of their own environment named WT-types-environment. The WTs at last are housed in the Farm-environment (see figure 7). This interconnected scheme makes the communication for homogeneous Agents inside an environment easier; the Agent is therefore more autonomous and self-directed, more flexible and possesses the ability to learn and to adapt its behaviours based on experience.

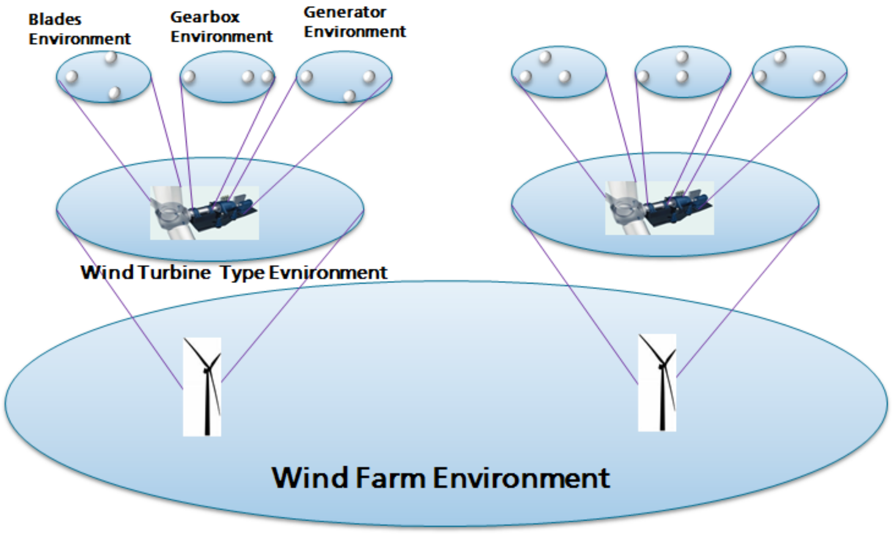

Figure 7: Interconnected Environment architecture

Based on the idea of characterizing the maintenance activities with quality levels, the Failure-Rate module triggers the interruptions in the Production module by message passing and calculates therefore the preventive maintenance and repair costs for the actual activity. The failure rates are calculated and updated after each maintenance activity using a developed algorithm, thus it provides the Agents with the necessary updated input parameters over the failure behaviour and failure frequency of the WT and their subcomponents continuously. For this first step, sources and information of the WMEP failure database are explored and analysed on their applicability for a showcase.

The Production module supplies the Agents with crucial information regarding the energy output and negotiate the best times of a maintenance measure based on power forecasts and SCADA data. The reliability-relevant SCADA operational data are prepared and analyzed on their applicability in a first step. Subsequently, the power forecasts are sighted, selected and forwarded as input parameters for the appropriate Agents. It provides the Logistic module with the needed information.

The development of the Weather module has the purpose to introduce weather conditions on basis of weather forecasts into maintenance planning. After identifying and evaluating existing meteorological aspects and their influence as well as relevant parameter for the maintenance, the results of the weather forecasts are made available as input data for the appropriate Agents.

Costs play a vital role in the maintenance organization; with the help of the Cost module it is to be demonstrated, how the cost can be considered during the reliability-oriented maintenance. Based on a commercial tool and several cost methods e.g. the methodologies of the 'Total Replacement Models' and the 'Partial Replacement Models' [218], which give an estimation of the optimal interval point to make a replacement with minimal costs, taken into account the labour costs, components costs and crane costs etc., all relevant cost parameters will be prepared as inputs for the appropriate Agents.

The consideration of logistics factors is indispensable for the optimization of maintenance strategies for WTs. The Logistic module will be interconnected with the Production module in order to manage the whole maintenance scheduling. Inside this module many input data (e.g. Spare parts stock keeping, components costs, transport cost etc.) will be available for the appropriate Agents, helping them suggesting optimal decisions.

IV. Conclusions & Conclusion

The necessity of building a common failure database as a basic condition for using Artificial Intelligence has been described in the contribution. Sophisticated Tools using AI are able to improve operating maintenance activities and help the WFO managing their task planning, taking into account several surrounding conditions in the analysis. For doing so a methodology has to be developed which was briefly described in this paper. The following points should be kept in mind when investigating the use of AI in WT maintenance:

- Establishing a common failure database is essential to achieve a suitable statistical basis for thorough analyses.
- Such a common failure database enables sophisticated approaches by analysing the history of the subassemblies in order to deduce and to forecast the failure behaviour of different subassemblies e.g. by using AI.
- Data mining and MAS are promising technologies in the field of maintenance of WT, but using them separately has some impairments. The use of a hybrid methodology to analyse dependencies between failure rates, weather conditions, logistics etc. is proposed.
- Using several cost optimization methods/algorithms will help by making the optimal decision in both reducing costs and improving availability.
- A balance between economic, reliability, availability and organisation issues needs to be achieved by the model developed.

V. Outlook

The use of MAS, which is based on a common failure database, is a part of the project MAS-ZIH funded by the German Ministry BMU. The five modules described in (3.3) will be combined and interconnected in this project to get a broad and comprehensive view of the several aspects of the maintenance process. This will help the WFO understanding the failure rates, costs, logistics, power outputs and weather dependencies and thereby to reach a decision for maintenance planning based on profound knowledge.
The project is now in the stage of developing the first main module; the Failure Rates module.

VI. Acknowledgements

The project MAS-ZIH 'Use of Multi-Agent-Systems as Support for Reliability-Based Maintenance' is it funded by the German Federal Ministry of Environment, Nature Conservation and Nuclear Safety.

References

[1] ISET, Wissenschaftliches Mess- und Evaluierungsprogramm WMEP 1989-2006.

[2] Fraunhofer IWES, Verbundprojekt zur Erhöhung der Verfügbarkeit von Windkraftanlagen EVW, 2007-2009 (www.evw-wind.de).

[3] K. Rafik , IT-basierte zuverlässigkeitsorientierte Instandhaltung von Windenergieanlagen, FhG IWES, 4. ETG-Fachtagung IT-Solutions in der Elektrizitätserzeugung, Stuttgart, 17.-18. November 2009.

[4] Michel North, Charles M. Macal, Managing Business Complexity: Discovering Strategic Solutions with Agent-Based Modeling and Simulation, Oxford University Press, USA; 1st edition, 2007.

[5] Faulstich, S. et al.: 'Windenergie Report Deutschland 2011', Kassel, 2011

[6] Hahn, B.; Jung, H.: 'Improving wind turbine availability by reliability based maintenance', DEWEK 2006, Bremen

[7] S. Faulstich, B. Hahn, H. Jung, K. Rafik, A. Ringhandt, Appropriate failure statistics and reliability characteristics, 2009.*

[8] S. Faulstich, B. Hahn, IWES, Ausfallverhalten von Windenergieanlagen und Konsequenzen für die Offshore-Windenergienutzung, RAMS/LCC-Expertenforum, Dresden, 31. Mai -01. Juni 2010.

[9] Ralf Moser, Business Architecture. A handbook for modeling complex organizations and business: A handbook for modeling complex organizations and business processes, Meidenbauer, 1. November 2007.

[10] Francois Besnard, Lina Bertling, On Optimal Maintenance Management of Wind Power Systems, Vindforsk, November 2009.

[11] John A. Sokolowski, Catherine M. Banks, Modeling and Simulation for Analyzing Global Events, John Wiley & Sons, 1. Auflage, 30. Juli 2009.

[12] A.V. Ramesh, An integrated reliability modeling environment. Reliability Engineering and System Safety IEEE, 17. September 1998.

[13] Z. Tian, Y. Ding and F. Ding 2011 Maintenance Optimization of Wind Turbine Systems Based on Intelligent Prediction Tools. Innovative Computing Methods and their Applications to Engeneering Problems. Springer Verlag.

[14] E. Byon 2010, Optimal Maintenance Strategies for Wind Turbine Systems Under Stochastic Weather Conditins. IEEE TRANSACTIONS ON RELIABILITY, VOL. 59, NO. 2, JUNE 2010 393.

[15] S. El-Ferik, M. Ben-Daya, Age based hybrid model for imperfect preventive maintenance, IIE Transactions 38 (2006) 365–375.

[16] R.I. Zequeira, C. Bérenguer, Periodic imperfect preventive maintenance with two categories of competing failure modes, Reliability Engineering and System Safety 91 (2006) 460–468.

[17] M. Ben-Daya, S.O. Duffuaa, A. Raouf, Maintenance Modeling and Optimization, Kluwer Academic Publisher, Massachusetts, 2000.

[18] Adolfo Crespo Márquez. The Maintenance Management Framework, Springer Verlag 2007

[19] Bussel, G. v.: 'Offshore Wind Energy, The Reliability Dilemma', EWEC 2001, Madrid

[20] Hongzhou Wang, Hoang Pham, Reliability and Optimal Meinatenance. Springer Verlag 2006.