

ARTIFICIAL INTELLIGENCE APPLICATIONS FOR MAINTENANCE ORIENTED HEALTH MONITORING OF WIND TURBINES

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Abstract: *The paper describes the result of the research in the fields of supervision, failure detection and prognosis, control, maintenance planning and decision support performed for ensuring high level availability of wind turbines and wind farms. This activity is realized in the frame of the EU 7th Framework project ReliaWind: Reliability focused research on optimizing Wind Energy systems design, operation and maintenance: Tools, proof of concepts, guidelines & methodologies for a new generation. Wind turbines are relatively complex electro-mechanical systems, their smooth functioning is an important economical factor. The handling of this complexity is supported by various, applied artificial intelligence techniques and solutions as described in the paper.*

Keywords: *artificial intelligence, wind energy, maintenance, supervision*

1. INTRODUCTION

Wind energy is one of the most promising branches today, e.g. in 2008 the market growth of this sector was above 20% [12]. Forecasts show that in Europe the share of wind energy will be between 5% and 20% of the total demand by the time [2][6][12], while, e.g., currently the share of offshore electricity is around 1.3% representing that the growth of this sector is above the linear trend, it is nearly exponential [1]. This economical trend involve dramatic technical developments, and as result, e.g. today, a wind turbine produces 180 times more electricity, at less than half the cost per kWh than its equivalent type 20 years ago [2] and it decreases with 10% every time the total capacity is doubled. However 80% of the total costs is fix and arise then establishing the wind turbine generator (WTG), flexible cost, like operating and maintenance of wind farms pays more and more importance, especially when considering offshore turbines that have around 50% more preparation cost and far higher risk in operation than onshore [12] turbines. One of the most important challenges in comparison of cost at various producers and operators is the lack of universally agreed set of cost categories [12], however, some cost models are presented in [18].

Beyond the investment analysis one can identify that cost is only a factor among further important features listed here and analysed in [4] to compare the effects of different renewable energy sources: price of energy produced; greenhouse gas emission during full life cycle of the technology; availability of renewable sources; efficiency of energy conversion; land requirements; water consumption; social impacts.

Taking the same weights for these evaluation aspects wind and hydro energies were found as best solutions. Various aspects are to be found at players of the value chain of wind energy, too [12]: Project developers which focus on planning and realization of wind farms;

electric utility companies on buying and selling the electricity produced, while; grid operators on balancing and re-allocation of electricity in the electric net; manufacturers concentrate on technological developments.

The increasing market share and growing number of wind farms in energy production, the growing rate of offshore installations having higher investment cost and risks and the variety of viewpoints when evaluating this branch indicates especial importance of maintenance and reliability of wind farms.

Wind turbine generators are data intensive information sources because they incorporate various sensors similar to other branches, e.g. like manufacturing [19]. This allows real condition monitoring and supervision of wind turbines and wind farms also from different locations and supports the preparation of reliability models with statistical information, too [5]. There are also some differences, e.g., wind turbines are operating in continuously changing environmental conditions with sometimes extreme circumstances [17] that is not typical e.g. in production system because they try to ensure stable and unchanging operation. This variety in environmental effects gives a great difficulty for handling changing conditions but it has also positive side: for statistical and further Artificial Intelligence (AI) analysis and modelling it can ensure a data set collected in various conditions. From the other side the data intensity requires sophisticated data processing techniques and knowledge related to them [9][20][21].

Various condition monitoring and sensing techniques, ordered to different WTG components extended by some fault detection solutions with AI methodologies are enumerated and compared in [6][14] similar to [3] that explains the relation of condition monitoring to reliability modelling as a tool for handling the changes at the right/wearing out side of a bath curve. Combinations of turbine components and monitoring techniques are highlighted in [3], hybrid statistical modelling is introduced in [11] for special problem domains however one can find the lack of a comprehensive framework for handling orderings of turbine components, failure modes, detecting sensors, appropriate data processing and monitoring, field specific limits, failure detection and prognosis tools, efficient control modifications, and appropriate maintenance and repair actions to each-other. Even the internal structures of these components are not clearly defined up to now. The establishment of such a framework is one of the main targets of the ReliaWind project.

The paper is organised as follows: After introducing the project goals reported in the paper the description of its condition monitoring and artificial intelligence related work package is described. The introduction of the novel logical architecture of an advanced wind turbine generator health monitoring system is followed with the description of its harmonisation with the recent standard series on communications for monitoring and control of wind power plants. For putting concrete content to the defined architecture SCADA data collection and analysis were performed applying artificial intelligence methods serving with failure detection and prognosis tools, generating maintenance assignments described in the next paragraph. Scheduling of the maintenance tasks is introduced before summarizing the scientific result achieved.

2. RELIAWIND – EU 7TH R&D PROJECT: GOALS AND MEASURE

ReliaWind: Reliability focused research on optimizing Wind Energy systems design, operation and maintenance: Tools, proof of concepts, guidelines & methodologies for a new generation [16]. ReliaWind project's main goal is to usher in a new generation of more efficient and reliable wind turbines, providing practical results to be used in wind turbine design, operations and maintenance. The project aims to achieve better efficiency for wind turbines, through the deployment of new systems with reduced maintenance requirements and

increased availability. To this end, the project proposes architecture directed at a modular design more immune to environmental conditions, permitting the replacement of components simply and quickly; to improve monitoring systems for components and thus achieve more accurate diagnosis; and to develop preventive maintenance algorithms for failure anticipation. These new technologies will be integrated in future generations of wind turbine components, wind turbines and wind farms.

Ten partners are taking part in this ambitious project, each of them leaders in technical and operational disciplines in the wind power generation value chain. This includes the Wind Industry itself, Gamesa and Alstom Ecotecnia are wind turbine producers, LM Glasfiber is producer of blades, Hansen Transmissions of gearboxes, ABB of generators and SKF of bearings for the turbine. Technology experts are Garrad Hassan as an engineering consulting firm and Relex Reliability Software and Services serving with a software and reliability modeling knowledge. Academia is represented by Durham University, UK and SZTAKI, the Computer and Automation Research Institute of the Hungarian Academy of Sciences.

Further the operative project members, a “Reliability Panel” has been established in order to interact with top-level experts in reliability worldwide, not necessarily from the wind energy sector, such as aerospace and other sectors where reliability is paramount. Its mission is to share conclusions, establish guidelines, etc. The first invitation to join the “Reliability panel” has been issued to NREL, the US National Laboratory. A “Users Working Group” has also been established in order to interact with top wind farm owners worldwide. Its mission will be to share experiences in wind farm operation and maintenance, providing feedback on “best practice”. The first invitations to potential members will be issued shortly.

The project results improve the reliability of wind turbines and wind farms and have enhancement effect directly on Mean Time Between Failures (MTBF) and on Mean Time to Repair (MTTR) resulting improved availability of facilities of energy production. Finally the relative cost of energy by kWh is decreased. All of the target measures are differentiated whether considering onshore or offshore installations.

3. LOGICAL ARCHITECTURE OF AN ADVANCED WTG HEALTH MONITORING SYSTEM

An important part of the ReliaWind project is the WP3 that is targeting to develop the Logical Architecture of an Advanced Wind Turbine Generator (WTG) Health Monitoring System (AWTGHMS). It is not only an architecture design but active also in the field of idea approval. The Fig. 1 shows the architecture of the AWTGHMS. The different components of the system are developed in consecutive tasks comprehend by the Task 3.0 for guaranteeing the overall consistency of the monitoring architecture. Logical architecture definition of required hierarchical system breakdown guarantees a common WTG & Wind farm level integration from a diagnosis, prognosis & health monitoring point of view.

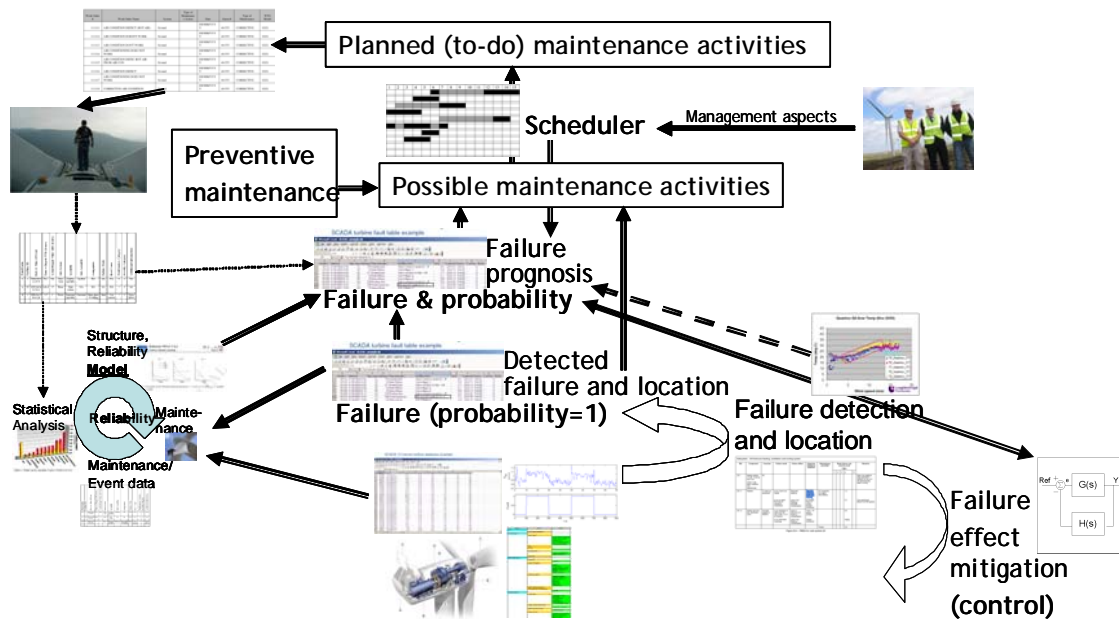


Fig.1. The architecture of an Advanced Wind Turbine Generator (WTG) Health Monitoring System (AWHMS)

Improvements in the cost-effectiveness of wind turbines will drive designers towards more ‘intelligent’ control algorithms inside the Task 3.1 which play an important part in actively improving the reliability of components and sub-systems. Advanced controllers which receive multiple inputs and make use of this information for regulation of structural loads and vibrations as well as for maximization of energy output are already under development, test and, in some cases in commercial operation. The objective of the work to be conducted in this task is to investigate the extent to which such advanced control algorithms might be extended to address reliability issues. The purpose of the Task 3.2 is to develop agents for the detection of specific incipient failure modes in the whole turbine. The purpose of the Task 3.3 is to develop agents for the location of specific incipient failure modes identified before, integrated with the knowledge developed in failure effect mitigation and failure detection. The mission of these algorithms is to locate which turbine system has progressed from a nominal to a malfunction condition. The aim of Task 3.4 is to develop algorithms which can provide a prognosis for the incipient failure modes detected and located before. The purpose of the Task 3.5 is to generate maintenance activities based on the repair prognosis for the faults detected and located to effect improvements to the availability of the wind turbine. Having a list of maintenance assignments is to plan maintenance activities based on the repair prognosis for the faults detected and located from and the maintenance activities generated. This Task 3.6 gives maintenance operators the work plan of maintenance activities. The feedback of operators and also the reliability model developed in the previous Work Package for design for reliability and understand failures and their mechanisms are also included among the inputs of the AWHMS realizing a closed loop for high system availability. Task 3.7 extends the AWHMS with a decision support framework.

4. HARMONIZATION OF THE LOGICAL ARCHITECTURE OF AN AWTGHMS WITH THE RECENT STANDARD SERIES ON COMMUNICATIONS FOR MONITORING AND CONTROL OF WIND POWER PLANTS

Typically, any wind power plant component, which needs to exchange information with other components and actors, is equipped with a so-called intelligent electronic device (IED), which can send data to external receivers and receive data from external senders. Therefore the information exchange is already implement in currently working WTG systems, but these information models are proprietary and cannot be used in a research project like ReliaWind. To overcome the problems of the proprietary data models a standard data model is proposed to use, which is based on the IEC 61400-25 [7] standard.

This standard defines a communication model for monitoring and control of wind power plants. The communication model comprises three separately defined areas of the information model, information exchange model and the mapping of the information model and the information exchange model to standard communication profiles. The information exchange model and the mapping to standard communication profiles are concerned when a standard interface is implemented in the WTG system.

Unfortunately the IEC 61400-25 series leaves it open how and in which physical device the server is to be implemented in practice. The objective of IEC 61400-25 series is that the information associated with single wind power plant component is accessible through a standardized interface. This implies that the information model defined rather generally and in a way that supports the information exchange interface smoothly. If the standard is implemented in a specific WTG system it is the responsibility of the device owner to map their internal (and proprietary) data structure to the standardized information model [10][13]. This mapping is required only because of technical reasons, namely to define the information exchange function.

The information model defined in IEC 61400-25 series - and because this standard is heavily relies on the IEC 61850 [8] standard this two standard is concerned later on – provides a list of well organized named information. These pieces of named information are our main interest, since this gives us a way to define and communicate algorithms in a non-proprietary format even if the algorithms are developed on proprietary data sets. The following process is planned to implement in the project:

- Develop the algorithms based on field data or other proprietary data
- Map the data to the information model of IEC 61400-25 series
- If the map is not possible extend the data model
- Deliver the developed algorithms using the standard naming strategies

The IEC 61400-25 series utilises the concept of object modelling to represent the systems and components of a wind power plants to communicate with. This means that all of the components in the real world are identified as objects that have data such as analogue values, binary status, commands and set points and these objects and data are mapped into generic, logical representations of the real world components as a wind power plant information model (see in Fig. 2).

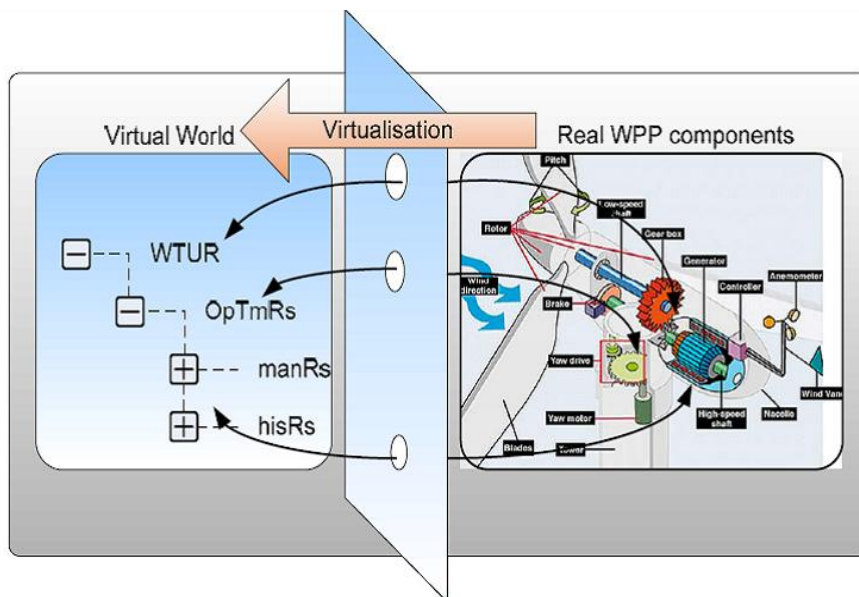


Fig.2. Mapping components to information model

The information model is principally a tree structured model that captures the assembly-subassembly- ...- part structure of the real WTG system. The structure of this hierarchical tree is defined in the IEC 61850 standard. The name of the concept is Abstract Communication Service Interface (ACSI) and the basic conceptual class model of ACSI is displayed in Fig 2. The class model is described in [8].

5. COLLECTION AND ANALYSIS OF MONITORING DATA

In order to prepare the ground a data cleaning is implemented to provide high quality data for the forthcoming data analysis. The field data currently available for the analysis came from two sources:

- Work orders (some thousand records)
- SCADA data from central databases

The work orders store the repair works performed on the wind turbines. The SCADA data is available in 3 delimited text files. The data are available for the same wind turbines that were referenced in the Work Orders file. The three files contain the following information

- Alarm information (some ten thousand records)
- Wind information (some million records)
- Energy information (some million records)

The work orders are edited by hand; therefore, it is highly possible that small syntax errors might occur during the editing phase. Automatic filtering is realized applying AI technique called Porter's stemming and a clustering algorithm [15] in order to clean the data analysed.

At the beginning of the data analysis phase clustering of the work orders was carried out. This analysis is a very simple way to find out dependencies between failures. Since every work order corresponds to a failure mode, therefore, the work orders clustering is equivalent of the failure modes clustering. In order to visualize the dependencies first the work orders are clustered into dependency groups. Dependency groups mean a set of work orders that have some connections between them. The dependency groups are determined in this analysis based on date stamps. Two work orders are considered dependent if they occurred on the same turbine and the difference of the two date stamps is less than some days. In other words

if two failure modes occurrence is close to each-other frequently they probably influence each other, e.g. they may be dependent. All work order pairs – or failure mode pairs – in a dependency group represent an edge in a dependency graph (Fig. 3.). Visualizing these dependencies might immediately reveal some real – which means here accepted that by experts – dependencies between the different failure modes.

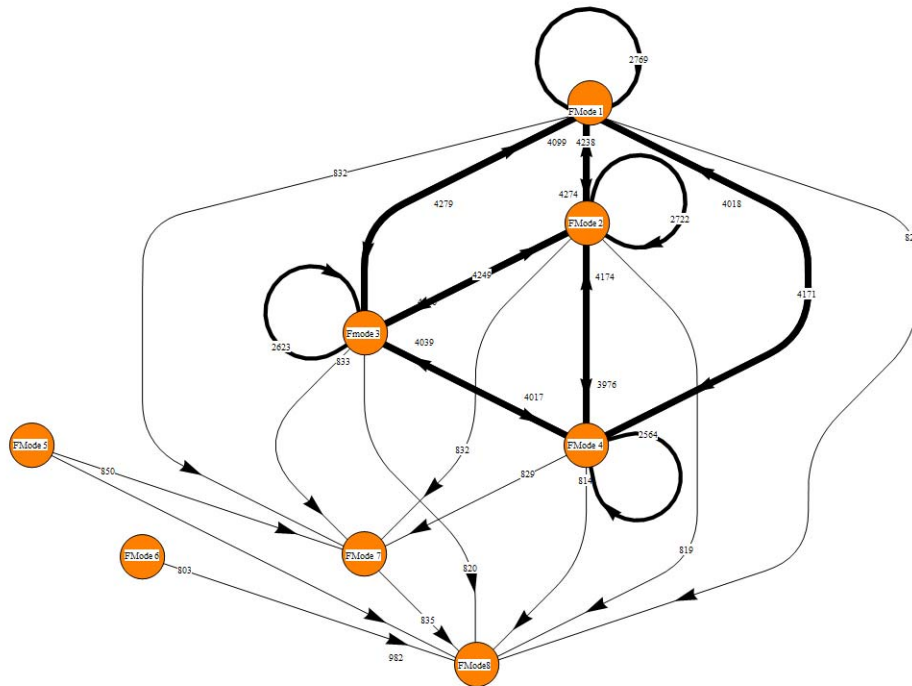


Fig.3. Failure modes dependency graph

The development of the most frequent failure modes can be investigated from the available signals too. This analysis is started with supervised learning, where the failure mode development is investigated together with experts. Experts can help understand the failure evolution and determine the signals, which might indicate the development of a failure (Fig 4). This analysis is a basis for an automatic health monitoring system that is under development, which is capable to automatically detect failure modes.

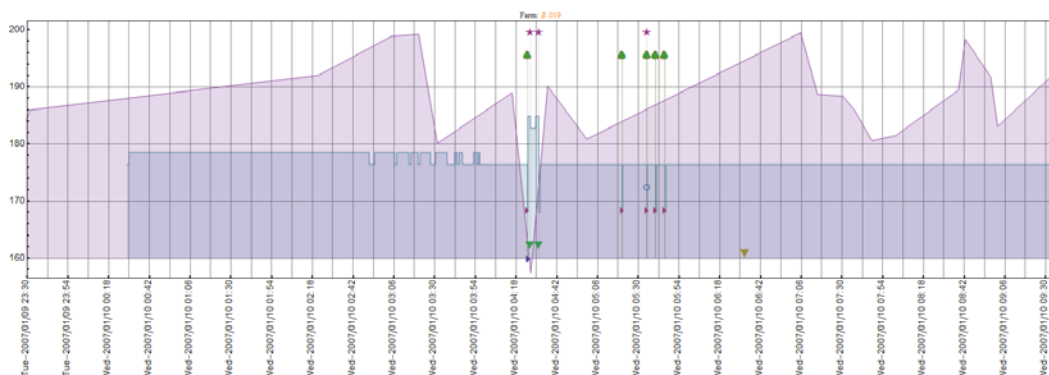


Fig.4. Alarms (icons), status (discrete values) and one relevant measured signal (continuous value) of a failure mode

6. MAINTENANCE SCHEDULING

The final stage of the failure related workflow addressed in the project is the automated generation of short-term maintenance schedules. The resources and decision responsibilities related to maintenance are assigned to so-called regional offices of wind turbine operators, each in charge of up to 3 wind farms, i.e., at most 150 wind turbines. Accordingly, scheduling is performed on the regional office level. Schedules are prepared for a horizon of three days on a rolling horizon basis: they are updated frequently upon the arrival of new requests, and only the first tasks are actually executed as planned. Maintenance requests may originate from various sources:

- Corrective maintenance requests, which are released for scheduling upon the localization of a new failure event
- Preventive maintenance requests of failure event prognoses, triggered by failure prognosis
- Periodic maintenance requests, which become schedulable when they reach the start of their so-called opportunity windows, typically, a week before their nominal due dates
- Retrofitting activities released by higher-level decisions

For each of the above maintenance requests, the scheduler must make a series of interrelated decision: it has to select the maintenance mode to apply, assign the maintenance task to resources, and determine a suggested execution time or decide to postpone the task. During this, the scheduler must consider a rich set of constraints and objectives as follows.

There is a set of candidate maintenance modes that can serve a request. Typical maintenance modes are repairing the affected part, replacing the part, or replacing a higher level assembly. Each maintenance mode defines one maintenance task, which comes with resource and part requirements defined a priori. Namely, the execution of a task requires the presence of a maintenance teams for a given duration. The skills of maintenance personnel are not modelled in detail, because any team can execute the majority of the tasks, whereas tasks requiring special skills will be assigned to teams manually. Some tasks may require additional resources, such as an outer crane, which is available for hire in certain time periods only. Tasks can be executed after the arrival of the required spare parts to the turbine. The stock amounts are specified for each part and each of the different warehouses, and it is also possible to order parts from the supplier with given lead times. The time required for the maintenance team to get from one turbine to the other needs to be considered, too.

An interesting and highly domain specific feature of the scheduling problem is the dependence of maintenance tasks on weather conditions, especially wind speed. Suitable weather conditions are defined for each task, e.g., the tasks requiring an outer crane can be executed in calm winds only. Furthermore, the power output of the turbine depends on wind speed. Since a failure may stop the turbine or reduce its power output, and turbines may have to be stopped for the time of maintenance as well, there is a difficult non-linear interrelation between the timing of maintenance tasks and the resulting production loss.

After all, the objective of the scheduler is to minimize the total failure and maintenance related cost, which is made up of the following components:

- Production loss due to failures
- Production loss due to maintenance
- Cost of leaving a failure unrepaired in the short-term horizon
- Maintenance costs, including spare parts, hired services, and labour cost

We have applied a two-stage decomposition approach to solving the above scheduling problem. As a first step, a maintenance mode is selected for each request based on cost analysis. The analysis considers all the above presented constraints and objectives, but assumes that no resource conflict will arise with other—yet unknown—tasks. A regret-based strategy is applied, i.e., the maintenance task with the highest difference between the cost of the cheapest and the second cheapest mode is investigated first. Note that the commitment to a given mode decreases the stock levels of the required parts, and consequently, may affect the mode costs related to other requests.

The selected maintenance modes and the corresponding maintenance tasks serve as input to the detailed scheduler. The problem of assigning the known tasks to resources and start times has been modelled as a mixed-integer linear program (MIP) using a classical time-indexed formulation. The MIP problem is solved by a commercial software tool called ILOG Cplex. In preliminary experiments the prototype solver was able to solve sample problem instances of moderate sizes. Ongoing research addresses the composition of realistic problem instances, as well as the evaluation and potential enhancement of the computational efficiency of the scheduler.

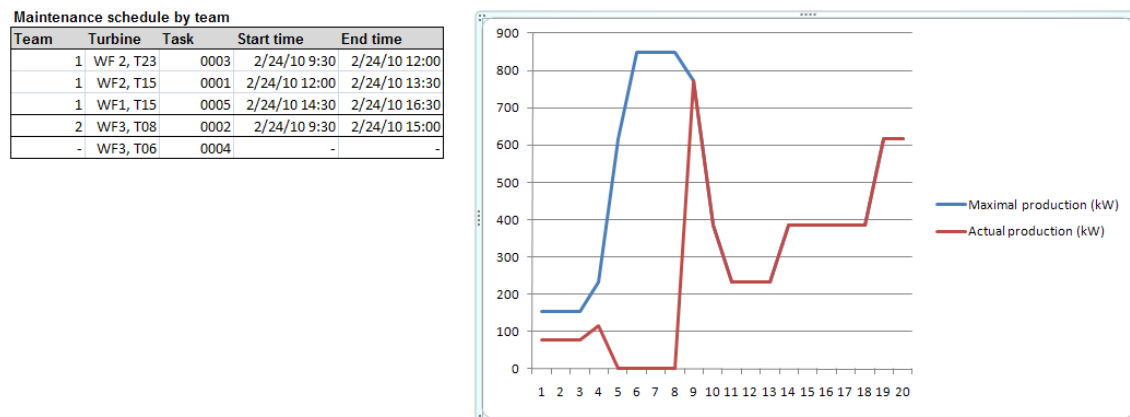


Fig.5. A small sample schedule (left) and the predicted power output of a turbine (right) if this schedule is applied. The upper line in the diagram represents the maximum production assuming a healthy turbine, whereas the lower line stands for the actual production. Degradation is due to failure in periods 1-4 and stopping the turbine for maintenance in periods 5-8.

7. CONCLUSION

The environmental effects of wind power are relatively minor, compared to those of more traditional energy sources. Among the renewable energy arts wind energy plays a significant role and, as forecasted its ratio within the total energy production will rapidly increase. Wind turbines are relatively complex electro-mechanical systems, their smooth functioning is an important economical factor. This is why monitoring and diagnosis of wind turbines and wind farms gained extreme importance in the past years. The ReliaWind EU 7th Framework Research project has set up ambitious goals, namely, optimizing wind energy systems design, operation and maintenance. Concentrating on monitoring, diagnosis and maintenance issues the novel logical architecture of an advanced wind turbine health monitoring system harmonized with the recent standard series on communications for monitoring and control of wind power plants was introduced. Wind turbines have several built-in sensors measuring various physical characteristics during the operation and SCADA systems serve with huge amount of data. This allows applying artificial intelligence

techniques for analysing the dependencies among data. Similar to other branches, e.g., to manufacturing [20], exploration of this new knowledge the necessary models for condition monitoring can be set up ensuring a part of the content for the introduced advanced wind turbine health monitoring system.

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