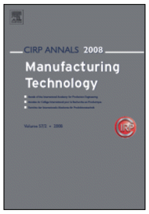
Contents lists available at ScienceDirect

CIRP Annals
Manufacturing Technology
Journal homepage: www.elsevier.com/locate/cirp



A system for the detailed scheduling of wind farm maintenance

András Kovács[1], Gábor Erdős[1], Zsolt János Viharos[1], László Monostori[1,2] (1)
[1] Fraunhofer Project Center for Prod. Mgmt. and Inf., Computer and Automation Research Institute, Budapest, Hungary
[2] Department of Manufacturing Science and Technology, Budapest University of Technology and Economics, Hungary

As the share of wind energy increases on the global energy market, the efficient operation of wind farms gains an ever growing significance. Among operational decisions, the planning and scheduling of maintenance operations are crucial for the availability of turbines, as well as for the operational costs. The paper introduces a system that performs the detailed scheduling of maintenance operations at a set of wind farms maintained by common personnel. The scheduling problem is modeled and solved as a mixed-integer linear program. The system constitutes a module of an integrated framework for condition monitoring, diagnosis, and maintenance of wind turbines.

Maintenance, Scheduling, Wind Energy

1 Introduction

Wind energy industry has experienced an extensive and world-wide growth during the past years. Certain forecasts indicate that the share of wind in Europe's energy production will reach up to 20% in the close future [1]. The efficient operation of installed turbines has an increasing significance. Among operational decisions, the planning and scheduling of maintenance tasks is decisive regarding both turbine availability and operational costs. Considering the spread of off-shore installations and the fact that their operational costs can be estimated to be 50% higher than that of the onshore farms [2], maintenance scheduling will receive even more emphasis.

Maintenance scheduling is not only an important, but also a complex problem. The scheduler must consider the availability of various resources, spare parts, and appropriate skilled personnel, while minimizing the disruptions caused in production. Moreover, it has to respond quickly to new events in a rapidly changing environment. Hence, from the maintenance scheduling aspect, a wind farm is quite similar to a manufacturing system [3], nevertheless, a number of differences stem from the different operating conditions, including the dependence on weather conditions.

Mathematical models and optimization methods for maintenance planning and scheduling have been widely studied for various application areas in manufacturing and in the service industry [4]. For instance, Perron [5] proposed a decomposition approach to a problem of scheduling teams of skilled workers for tasks to be performed at different locations. The problem is divided into a planning part (the formation of teams), solved by mixed-integer programming, and a detailed scheduling part (fixing the execution time of the tasks), solved by constraint programming.

A current research trend is the integration of maintenance and production planning in manufacturing systems. Kaihara et al. [6] present a Lagrangian decomposition coordination method for the simultaneous scheduling of production and maintenance activities in a re-entrant flow shop environment. Iung et al. [3] propose an opportunistic approach to finding the most suitable timing of preventive maintenance by balancing between the two conflicting criteria of functional performance and reliability. The opportunistic maintenance concept is extended to multi-component systems in [7] by considering the proximity of components and the resulting benefits of maintaining multiple components under one production stop.

An approach to scheduling the maintenance tasks in a semiconductor fabrication plant is presented in [8]. The model captures the variance of production level over time, as well as the different skills and availability of technicians. It considers multiple optimization criteria, including the leveled load of technicians, the minimal disruption caused in production, and a quality measure of the timing of the individual maintenance tasks. De Boer et al. [9] introduce a decision support system for maintenance capacity planning and detailed scheduling in a naval vessel repair shop. The detailed scheduling problem is modeled as a resource-constrained project scheduling problem, where the repair of each ship is modeled as a project consisting of multiple jobs, and projects last several months, typically.

The role of maintenance from the perspective of product life cycle management has been investigated by Takata et al. [10]. The authors argue that in a sustainable society, where the goal of manufacturing is not to produce goods efficiently, but to provide the needed functions to the society, maintenance is an essential means of life cycle management. They introduce a maintenance framework that covers all decision problems related to maintenance, including maintenance planning, and within this, the detailed scheduling of maintenance tasks.

At the same time, the literature of planning and scheduling maintenance specifically for wind turbines is rather scarce. While the technological and economic questions related to applying condition-based maintenance to wind turbines have received significant attention recently (see [11],[12]), the authors of the paper are not aware of any detailed scheduling system that covers all the relevant aspects of wind turbine maintenance.

In the paper the transfer of the maintenance-related results of production management into the field of wind energy production is attempted, while taking the specifics of the latter into account. The detailed scheduling problem of wind farm maintenance is formulated as a mixed-integer program (MIP). The developed maintenance scheduler system constitutes a module of a framework for condition monitoring, diagnosis, and maintenance of wind turbines. A short report is given on the results of the experimental implementation. For confidentiality reasons, the numeric examples presented in the paper do not coincide with real-life data.

2 An Integrated Framework for Monitoring, Diagnosis and Maintenance

The framework performs failure detection and prognosis on quasi-online data from the SCADA supervisory system. In case a failure is detected or prognosed, it assists human experts in initiating the corresponding corrective or predictive maintenance tasks—the available digitized knowledge on mapping failures to tasks is not reliable enough to completely automate this step. Other planned tasks, such as preventive maintenance or retrofitting originate from the ERP system. The developed system schedules the maintenance tasks on a short term horizon so as to minimize production loss due to failures and maintenance. The execution of maintenance tasks is tracked, during which technicians provide valuable detailed information on the nature of the failure, the failed component, and the actual execution of the task, such as its duration and the usage of spare parts (Fig. 1).

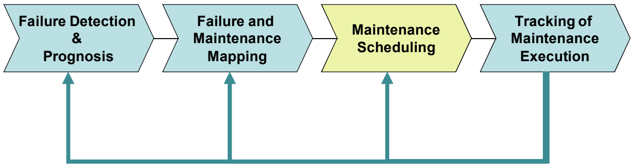


Figure 1. Key functionalities and the workflow in the system.

The integrated handling of failures, maintenance, and execution makes it possible to feed back the acquired knowledge in order to improve failure detection and prognosis models, the mapping of failures to maintenance tasks, the definition of the maintenance tasks, and through component reliability statistics, even the turbine design. Therefore, the system not only supports the daily operation of the turbines, but it is also a key element for achieving the long-term digitization objectives of the wind farm owner and maintenance service provider companies. Hence, this system represents a significant step towards the practical implementation of the vision stated in [10] that maintenance should be a key element of the life cycle management of the products.

3 The Maintenance Scheduling Problem

The maintenance processes at wind farms, as well as the resulting requirements for an automated maintenance scheduler are presented in detail below. While wind farm operator and maintenance service provider companies are typically large multinational enterprises, maintenance is executed by local staff. Namely, technicians are assigned to so-called *zones*, each consisting of 1–5 nearby wind farms. The scheduling problems of different zones can be considered to be independent. A detailed maintenance schedule is prepared for a short-term horizon of 3–7 days, on a rolling horizon basis. The schedule is updated every morning, which implies that usually only the tasks of the first day are executed as planned. Despite the obvious uncertainties in the scheduling problem, all parameters—including weather conditions and spare part availability—are assumed to be deterministic within the day.

3.1 Maintenance Tasks

The scheduling of so-called field maintenance tasks are investigated, i.e., all maintenance operations to be executed at the wind farm, either on a turbine, on the electric substation, or on another element of the wind farm infrastructure. In the paper, it is assumed that tasks are related to turbines, but exactly the same model applies to tasks related to elements of the infrastructure, too. Tasks may include the troubleshooting of wind turbines, replacement of components, as well as inspection, cleaning, or other types of servicing. According to their origin, maintenance tasks can be classified into the following main categories:

- Corrective maintenance, released for scheduling upon the localization of a failure in a turbine;
- Predictive (or condition-based) maintenance, triggered by a prognosed failure;
- Preventive maintenance, which can be foreseen and planned well before the task becomes timely;
- Retrofitting activities released by high-level decisions.

The proposed model captures tasks of any of the above origin. The typical duration of a maintenance task is between 30 minutes (minor repairs, e.g., a filter change) and 2 hours (major repairs, e.g., a converter change).

3.2 Required resources

Maintenance tasks require different kinds of resources, such as skilled personnel, various spare parts, and special equipment. Below, each of these requirements will be reviewed in detail. The tasks are executed by technicians, working in teams of two people. Maintenance teams are dispatched to farms and turbines based on the maintenance schedule. A team can execute only one task at a time, and it must finish the task before moving to the location of the next task. Traveling from one farm to another one takes a given amount of travel time, whereas the travel from one turbine to another one within the farm is neglected. Although technicians may have different qualifications, the overwhelming majority of the tasks may be assigned to any team. Special tasks can be handled by forbidden task-team assignments.

Some tasks require appropriate spare parts as well. While some parts are immediately available—e.g., if they are stocked in the wind farm warehouse or carried in the team's van—, other ones must be ordered from a central warehouse. Hence, expected material arrival times imply release times for the tasks. In addition, some complicated tasks require special equipment, such as cranes or trucks, which must be hired from service suppliers. In such a case, maintenance planners negotiate the service availability interval via personal communication, and the negotiated interval defines a time window for the corresponding task.

An interesting and highly domain specific feature of the scheduling problem in question is the dependence of maintenance tasks on weather conditions, such as wind speed or temperature. For instance, tasks requiring an outer crane can be executed in calm winds only. There might be a minimum and maximum value of each weather parameter assigned to every task, depending on the type of work to be done, as well as the local safety regulations.

Finally, pairs of tasks may interfere beyond competition for common resources as well. Namely, some tasks are executable only when the turbine is put into a special state, such as “Disconnection from network”, “Hydraulic pump presses”, or “Hydraulic pump does not press”. Multiple tasks can be executed on the same turbine in parallel only if their required states are compatible. An example of an incompatible pair of states is the above two conditions of the hydraulic system.

3.3 Performance Measures

In order to quantify the importance of individual maintenance tasks, the production loss due to the corresponding (present or future) failure must be estimated. However, the loss cannot be modeled as constant over time: it largely depends on the wind speed, as the production of the turbine is cubically proportional to this weather parameter. A simplified model with two different profiles of production loss is applied:

- General degradation, which reduces the power output of the turbine by a given percent in any operating condition, compared to the production of a healthy turbine;
- Peak degradation, which decreases the peak production of the turbine by a given percent at high winds, but does not affect production that can be achieved during low winds.

In both cases the production loss is assumed to last from the occurrence of the failure until the completion of the related maintenance task, when production returns to normal (see Fig. 2).

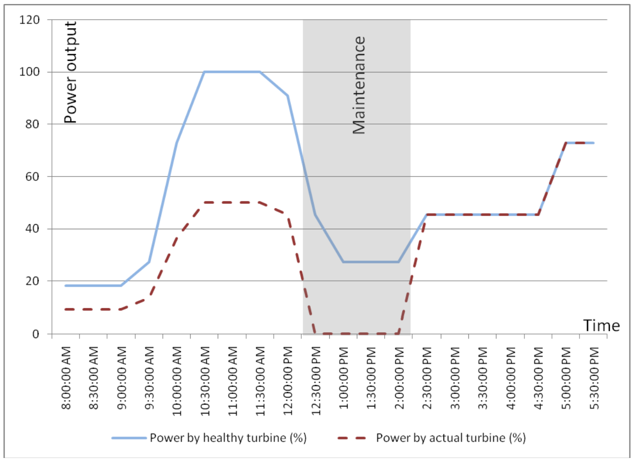


Figure 2. Power output of a defective turbine over time, in percent of the nominal power. The upper, continuous line corresponds to the expected production of a healthy turbine over time, given the forecasted wind speed. The lower, dashed line shows the expected production given the current failure and the maintenance schedule. Production is degraded by 50% until 12:30 when the turbine is stopped for maintenance, at the end of which it is restored into the healthy state.

Note that two or more failures may affect the same turbine at the same time. In such a case, it is assumed that the expected production is the minimum of the values calculated with each of the individual failures.

Periodic and preventive tasks are planned and released well before they become timely. Maintenance planners assign time windows to these tasks, in which the date of execution can be chosen according to the actual circumstances, e.g., the load of technicians or the weather conditions. The relative importance of these tasks is captured by assigning a virtual loss percent to them, which gradually increases from zero at the beginning of their time window up to 100% at the end of the window.

In addition to failures, production loss is caused by the maintenance tasks themselves, since turbines may have to be stopped during the maintenance. An interesting feature of this problem domain is that the maintenance of one turbine may stop other turbines as well; since several turbines are connected serially to the grid, the complete disconnection of one turbine stops its posterior ones as well. For each task, the set of affected turbines can be determined based on the states required by the given task.

Scheduling consists in determining the set of tasks that should be executed within the scheduling horizon and assigning a team and a start time to them, so as to minimize the total production loss of the turbines. The objective function contains both loss due to failures and loss due to maintenance. Note that from the scheduling point of view, this optimization criterion belongs to the class of irregular criteria, which is an atypical and difficult-to-handle class. This means that it may be worth postponing certain tasks, e.g., from a period with high winds to a later period with low winds, even if all resources are available to execute it earlier.

3.4 A Sample Task

The characteristics of maintenance tasks differ fundamentally depending on the nature of the work to be executed within the task. An example of a minor repair task is the replacement of the yaw brake pads. These parts are components of the brake system that stabilizes the orientation of the nacelle in the upwind direction. This task can be executed by a team of two technicians, and it takes 40 minutes. The task requires two sets of yaw brake pads with a given part identifier. Since these parts can be carried by the technicians, the task does not require a crane or any other special equipment. The maximum wind speed allowed is 12 meter per second, and the turbine must be stopped for the complete duration of the maintenance. The yaw system chapter of the electronic maintenance manual is also linked to this task, and it can be accessed in the developed prototype system as well.

4 A Mathematical Programming Solution Approach

The problem of finding an optimal maintenance schedule that fulfills all the above requirement has been encoded as a MIP. The model uses a discrete time scale representation where the scheduling horizon is subdivided into a series of identical-length time periods. In applications the length of the time period may be, e.g., half an hour, while task durations and travel times must be the integer multiples of this length. This representation enabled us to use a so-called time-indexed MIP formulation, frequently used in operations research to encode scheduling problems. The notation used in this model is summarized in Table 1.

Table 1. Notation used in the mathematical model

Dimensions	
N	Number of tasks
J	Number of turbines
K	Number of maintenance teams
T	Number of time periods
Indices	
i	Task
j	Turbine
k	Maintenance team
f	Farm
t	Time period
Parameters	
p_i	Processing time of task i
Z_i	Set of services required for task i
$F(i)$	Farm where task i is to be executed
$w^0_{i,j,t}$	Production loss on turbine j at time t if task i is not completed until that time period
$w^1_{i,j,t}$	Production loss on turbine j at time t if task i is under execution at that time period
$d_{f,f'}$	Travel time between farms f and f'
$S_{s,f,t}$	Capacity of service s available at farm f at time t
$V_{i,i'}$	Indicates whether tasks i and i' are incompatible
$\Theta_{i,k,t}$	Indicates whether task i can be started by team k at time t
δ_i	Cost of postponing the task i
Variables	
$x_{i,k,t}$	Indicates whether task i is started by team k at time t (binary)
y_i	Indicates whether task i is postponed (binary)
$z_{j,t}$	Production loss on turbine j in time period t
$a_{k,f,t}$	Indicates whether team k is located at farm f at time t (binary)

In an instance of this scheduling problem, N maintenance tasks are to be executed on a set of J turbines by K maintenance teams on a horizon of T discrete time periods. Each task i is characterized by its processing time p_i, the farm where it has to be executed $F(i)$, and requires exactly one team and one unit of each of the hired services in set Z_i. Flag $V_{i,i'}$ indicates whether tasks i and i' are incompatible.

It is assumed that a forecast of the production loss caused by each failure is known for each (usually one, but potentially more) turbine and each time period. If task i is not completed until time t, then a loss of $w^0_{i,j,t}$ is incurred on turbine j at this time period. If task i is under execution at time t, then the loss on turbine j is $w^1_{i,j,t}$. Finally, the production loss must be estimated for the tasks that cannot be executed within the scheduling horizon. For tasks like this, a lower bound estimation equal to the total production loss throughout the scheduling horizon is given:

$$\delta_i = \sum_{t=1}^{T}\sum_{j=1}^{J} w^0_{i,j,t}$$

The further requirements of task i, such as material requirements, weather conditions, as well as the availability of maintenance teams are pre-processed and encoded to binary parameters $\Theta_{i,k,t}$. Parameter $\Theta_{i,k,t}$ indicates whether task i can be started by team k at time t, which is true if and only if all the following conditions hold:

- all required parts are available at time t;
- the weather conditions are suitable throughout interval $[t, t+p_i-1]$;
- team k is able to execute task i;
- team k is available throughout interval $[t, t+p_i-1]$.

By using the above defined notations, the MIP model of the maintenance scheduling problem can be stated as follows:

Minimize

$$\sum_{j=1}^{J}\sum_{t=1}^{T} z_{j,t} + \sum_{i=1}^{N} \delta_i y_i \qquad (1)$$

subject to

$$\sum_{k=1}^{K}\sum_{t=1}^{T} x_{i,k,t} + y_i = 1 \qquad \forall i \qquad (2)$$

$$x_{i,k,t} = 0 \qquad \forall i,j,k : \neg\Theta_{i,j,k} \qquad (3)$$

$$\sum_{i=1}^{N}\sum_{t'=t-p_i+1}^{t} x_{i,k,t'} \le 1 \qquad \forall k,t \qquad (4)$$

$$z_{j,t} \ge (1 - \sum_{k=1}^{K}\sum_{t'=1}^{t-p_i} x_{i,k,t}) w^0_{i,j,t} \qquad \forall i,j,t \qquad (5)$$

$$z_{j,t} \ge \sum_{k=1}^{K}\sum_{t'=t-p_i+1}^{t} x_{i,k,t} w^1_{i,j,t} \qquad \forall i,t,j \qquad (6)$$

$$x_{i,k,t} \le a_{k,f,t'} \qquad \forall i,k,t,t' : t \le t' < t + p_i \qquad (7)$$

$$a_{k,f,t} + \sum_{f' : d_{f,f'} > t'-t} a_{k,f',t'} \le 1 \qquad \forall k,t,t',f : t' \ge t \qquad (8)$$

$$\sum_{i:\, s \in Z_i \wedge F(i)=f}\ \sum_{k=1}^{K}\sum_{t'=t-p_i+1}^{t} x_{i,k,t'} \le S_{s,f,t} \qquad \forall s,f,t \qquad (9)$$

$$\sum_{k=1}^{K}\sum_{t'=t-p_i+1}^{t} x_{i,k,t'} + \sum_{k=1}^{K} x_{i',k,t} \le 1 \qquad \forall i,i' : V_{i,i'} \qquad (10)$$

$$x_{i,k,t} \in \{0,1\} \qquad \forall i,k,t \qquad (11)$$

$$0 \le y_i, b_{k,t} \le 1, \quad 0 \le z_{j,t} \qquad \forall i,j,k,t \qquad (12)$$

Objective function (1) describes that the total expected production loss (or its lower bound estimation for the tasks that cannot be scheduled) has to be minimized. Constraints (2) describe that a task is either performed exactly once (and then it is not postponed, $y_i = 0$), or it is not performed (then it is postponed, $y_i = 1$). Equations (3) eliminate the infeasible team and start time assignments. Inequalities (4) state that no two jobs can be executed in parallel by the same team. Constraints (5) and (6) encode the production loss due to failures and maintenance, respectively. Inequalities (7) describe that the assigned team must be present for the complete duration of the maintenance task, whereas constraints (8) state that travel from one farm to another one requires a given travel time. Line (9) encodes the capacity constraint on the services. Inequality (10) ensures that incompatible pairs of tasks are not processed in parallel. Finally, constraints (11) describe the integrality condition for variables $x_{i,k,t}$ and inequalities (12) define the range of the other variables. Integrality is implied for variables y_i and $a_{k,f,t}$. Note that in an actual implementation it is sufficient to use variables $x_{i,j,k}$ for indices such that $\Theta_{i,j,k}$ holds, thus reducing the size of the MIP.

5 Validation of the Results

The developed system has been validated by using data originating from a European wind turbine manufacturer, covering ca. 100 turbines in 3 wind farms maintained by the manufacturer under warranty. The data set includes historical SCADA measurements, as well as detailed definitions of ca. 50 failure modes, 25 different maintenance tasks, and all resources required by these tasks. The soundness of the implemented models and algorithms has been verified involving industrial experts.

Furthermore, the computational efficiency of the proposed maintenance scheduling approach has been evaluated on a set of randomly generated problem instances. A problem generator has been implemented in such a way that problem size could be varied, but parameters simulate real-life scenarios. In the experiments below instances with number of tasks $N \in \{10,20,...,50\}$ and number of farms $F \in \{3,5,7\}$ have been considered, and five instances have been generated for each combination of *N* and *F*. For solving the scheduling problems, the system uses the ILOG Cplex 11.2 commercial MIP solver package and its default branch and bound algorithm. The experiments were run on a 2.66GHz Intel Core 2 Duo computer, using 600 seconds as the time limit. Table 2 displays a summary of the experimental results. Each cell contains combined results for a given combination of *N* and *F*, namely, the number of instances solved to proven optimality out of five, the average solution time in seconds, and the average relative gap when optimality could not be proven. The relative gap is computed as *(UB-LB)/UB*, where *UB* and *LB* stand for the upper and lower bounds, respectively, and the values are displayed in *ppm* (10^{-6}).

Table 2. Experimental results

	F=3			5			7		
	Opt	Time *(s)*	Gap *(ppm)*	Opt	Time *(s)*	Gap *(ppm)*	Opt	Time *(s)*	Gap *(ppm)*
N=10	5	0.18	-	5	0.12	-	5	0.13	-
20	5	1.96	-	5	1.26	-	5	0.55	-
30	5	6.39	-	5	11.40	-	5	3.36	-
40	5	51.40	-	5	85.31	-	5	123.35	-
50	3	439.48	259	3	311.74	280	5	25.35	-

The results indicate that the scheduling problems are solvable by the proposed approach with up to 50 tasks in reasonable time. Moreover, even when the solver found sub-optimal solutions, the relative gap was in the order of magnitude of 0.01%, which is insignificant. In a real application, problem instances with at most 30 tasks and 3-5 farms are expected, and hence, the developed mathematical model satisfies the computational requirements in that application.

6 Conclusions and Future Research

The paper investigated maintenance scheduling at wind farm operators. A detailed presentation of the scheduling problem was given, and a mathematical programming model was defined. To the best of our knowledge, this is the first mathematical model that captures all the discussed important aspects of automated scheduling of wind farm maintenance. The maintenance scheduler constitutes a module of a framework for the integrated monitoring, diagnosis and maintenance of wind turbines. It is emphasized that this system does not only support the daily operation of the turbines, but also helps to achieve the long term digitization objectives of the related parties.

Future research will address different variants and extensions of the current scheduling model. On the one hand, the case when maintenance is executed and scheduled by an external service provider company, different from the wind farm owner is investigated. Service contracts in the wind industry usually specify a target availability value for wind turbines, i.e., the portion of time that the turbine must spend running or ready to run. Hence, the economic goal of the service provider—often, the service department of the manufacturer—is to maximize the availability, instead of minimizing production loss. On the other hand, our long term objective is to extend the model to offshore wind farms, an application where the proper maintenance of turbines is even more critical.

Acknowledgements

The authors acknowledge the support of the EU FP7 grant ReliaWind No. 212966, the Hungarian Scientific Research Fund (OTKA) grant “Production Structures as Complex Adaptive Systems” T-73376, and the National Office for Research and Technology (NKTH) grant “Digital, real-time enterprises and networks”, OMFB-01638/2009.

References

[1] Blanco, M.I., 2009, The Economics of Wind Energy, Renewable and Sustainable Energy Reviews, 13:1372–1382.

[2] Markard, J., Petersen, R., 2009, The Offshore Trend: Structural Changes in the Wind Power Sector, Energy Policy, 37/3545–3556.

[3] Iung, B., Levrat, E., Thomas, E., 2007, ‘Odds Algorithm’-based Opportunistic Maintenance Task Execution for Preserving Product Conditions, CIRP Annals - Manufacturing Technology, 57/1:13–16.

[4] Budai, G., Dekker, R., Nicolai, R.P., 2008, Maintenance and Production: A Review of Planning Models. In D.N.P. Murthy and K.A.H. Kobbacy (eds.), Complex System Maintenance Handbook, 13:321–344, Springer.

[5] Perron, L., 2010, Planning and Scheduling Teams of Skilled Workers, J. of Intelligent Manufacturing, 21/1:155–164.

[6] Kaihara, T., Fujii, N., Tsujibe, A., Nonaka, Y., 2010, Proactive Maintenance Scheduling in a Re-entrant Flow Shop Using Lagrangian Decomposition Coordination Method, CIRP Annals - Manufacturing Technology, 59/1:453–456.

[7] Derigent, W., Thomas, E., Levrat, E., Iung, B., 2009, Opportunistic Maintenance Based on Fuzzy Modelling of Component Proximity, CIRP Annals - Manufacturing Technology, 58/1:29–32.

[8] Davenport, A., 2010, Integrated Maintenance Scheduling for Semiconductor Manufacturing, in Proc. of CPAIOR'2010 (Springer LNCS 6140), 92–96.

[9] de Boer, R., Schutten, J.M.J., Zijm, W.H.M., 1997, A Decision Support System for Ship Maintenance Capacity Planning, CIRP Annals - Manufacturing Technology, 47/1:391–396.

[10] Takata, S., Kimura, F., Van Houten, F.J.A.M., Westkämper, E., Shpitalni, M., Ceglarek, D., Lee, J., 2004, Maintenance: Changing Role in Life Cycle Management, CIRP Annals - Manufacturing Technology, 53/2:643–656.

[11] Nilsson, J. Bertling, L., 2007, Maintenance Management of Wind Power Systems Using Condition Monitoring Systems–Life Cycle Cost Analysis for Two Case Studies, IEEE Transactions on Energy Conversion, 22/1:223–229.

[12] Nielsen, J.J., Sorensen, J.D., 2011, On Risk-based Operation and Maintenance of Offshore Wind Turbine Components, Reliability Engineering & System Safety, 96/1:218–229.