Project title	Optimal maintenance of wind power plants
Project number	TG5-21
Organisation	Chalmers University of Technology, Applied Mathematics and Statistics
Project leader	Michael Patriksson
Other participants	Quanjiang Yu (PhD student)
Report for	2016-07-01 – 2018-09-30
Participating companies	Greenbyte, Göteborg Energi, NCC Sverige, Rabbalshede Kraft, Röbergsfjället Vind, Stena Renewable

Project description

Climate change now affects every country on every continent. It disrupts national and personal economies, affects lives, communities and countries, today and even more tomorrow. To address climate change 195 countries have signed the Paris Agreement, agreeing to work towards limiting global temperature rise to well below 2 degrees centigrade, and given the grave risks, to strive for a minimal raise from 1.5 degrees centigrade. Climate change mitigation generally involves dramatic reductions in human-induced emissions of greenhouse gases. Wind power as a clean energy is available in abundance, it's renewable, and it produces almost no greenhouse gas emissions during operation. The area of wind turbine operations & maintenance represents a growing segment and business opportunity in the wind energy industry.

The goal for Quanjiang Yu in the project Optimal maintenance of wind power plants (July 2016–) is to develop an app, which uses maintenance data (corrective maintenance (CM) costs, preventive maintenance (PM) costs, survival functions, logistic costs, etc.) as input, and generates a short-term maintenance schedule which will indicate to the maintenance staff, who are on site, those components which have the highest probabilities of failing within a short time span. The app should also connect to the SCADA system, so it can change inputs like survival functions based on the data gathered from the SCADA system.

We also develop a program which can generate a long-term maintenance schedule. It allows wind turbine owners to have a long-term plan, to give them some leverage on bargaining how much they should pay for a 5-years maintenance contract, estimate how many spare parts they should purchase, and so on.

Results

For the short-time maintenance schedule, a new optimization model – called STPMP (short-term preventive maintenance problem) – has been built.

The basic idea is: for a wind farm contain a certain number of wind turbines, we want to minimize the maintenance cost. For different components, they have different survival function which indict how often that component break down. Based on the survival function and the costs to perform maintenance, we calculate the average corrective maintenance cost and preventative maintenance cost and pick the lowest one.

Figure 1 below shows a case study for a gear box. From the left figure, we can see that at the beginning, the cost of choosing to perform PM is really high, due to the low risk of the component failing. After a while, the cost of performing PM becomes lower than performing CM, and if we consider the time steps 20–80, represented in the right figure, we can see that around month 53 we get the best solution, which following the PM maintenance schedule yields a cost which is around half the cost of the CM schedule; it is a huge difference.

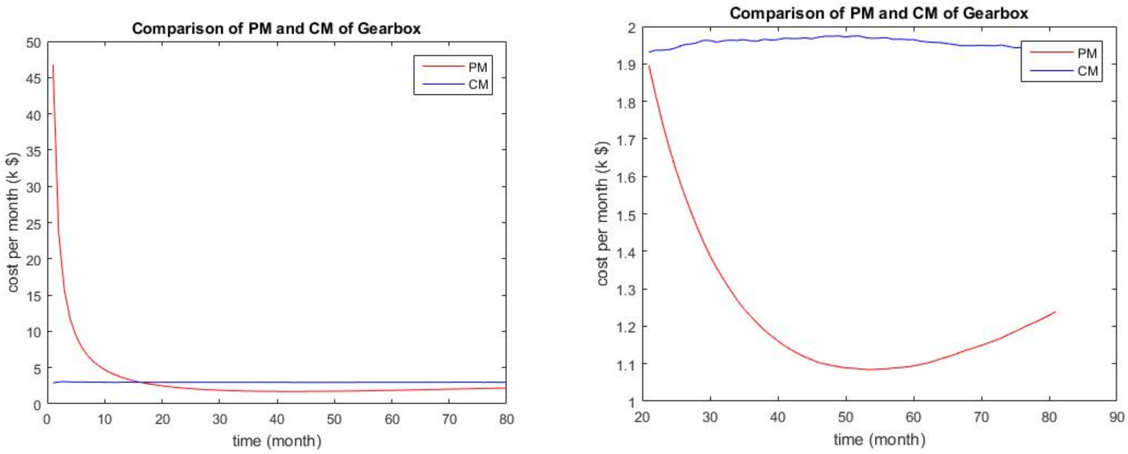

Figure 1 A case study for a gear box

After building the new optimization model STPMP, we performed a comparison between STPMP and PMSPIC. The solution time is composed by two parts: first the calculation of the parameters of the models, and then the time to actually solve them. From Table 1 we can see the time to solve the models; STPMP is much faster than PMSPIC, especially for small time steps. The results also show that STPMP provides equally good results as PMSPIC:

	Two optimization models	Solution time (Matlab + CPLEX)		Results
		Calculate the parameters with Matlab	Solve the model with CPLEX	
Time step length **1 month**	STPMP	49.19 sec	0.018 sec	5.06(k $) per month
	PMSPIC	51.12 sec	113.08 sec	5.01(k $) per month
Time step length **3 days**	STPMP	442 sec	0.094 sec	0.506(k $) per 3 days
	PMSPIC	514 sec	Over 5 hours	

Table 1 A comparison between STPMP and PMSPIC

From this model, based on different weights on cost and risk, we can generate a series of maintenance models, by playing with the CM cost. If the wind turbine owners want the reliability to be really high, we can make the CM cost higher. If the wind turbine owners want the components work as long as possible, we can make the CM cost lower.

To make the model more accurate, we connect the model with the condition monitoring system or SCADA system. We developed a method which incorporates elements from stochastic modeling with time-dependent covariates to represent the uncertainty of component lives; those covariates are calculated from the condition monitoring systems or SCADA system. We can combine the short-term model with the data we receive from the condition monitoring system or SCADA system. To do so, the first step is to incorporate historical alarms. We developed a model describing how the parameters of the Weibull distribution depend on the covariates (i.e, alarms). We choose log-linear models for both parameters, i.e., models of the form $\log k = a + bx$, where b and x are vectors and k is one of the parameters of the Weibull distribution; we choose x as the number of alarms (up to time t). Maximum likelihood is used to estimate the parameters a and b, which in turn determine the parameters of the Weibull distribution. The alarms enter according to a point process in time, which are time-updated covariates. In the end, we can make predictions on the remaining life of components. To do so, we can use the stored information about the past and update the distribution as new alarms enter. So, every time a new alarm enters, the Weibull distribution will be changed.

This method can also be used to look at other kinds of data, like the gearbox bearing temperature and gearbox oil temperature. By analyzing this data, we can have a better estimate on the survival function, and hence generate a better maintenance schedule.

Solving STPMP is really fast, so it can be used to generate a short-term schedule, and even be implemented in an app. For long-term scheduling, or if the wind turbine owner wants to look at the whole picture, we can use PMSPIC. Its complexity implies the need for longer time steps and a numerical termination criterion, based on lower and upper bounds on the optimal objective function value.

During this period, we also supervised a candidate project: Experiments on optimal maintenance operations with emphasis on end-of-contract constraints. This project focused on what will happen if we don't plan to perform maintenance at the end of the contract period, or at the end of the wind turbines' life time. From the results obtained, we can see that the shape of the PM schedule is still the same – we just move it to some earlier time steps.

Fulfilment of SWPTC's goals

This project contributes to the fulfilment of several of the Centre's goals, in particular to the profitability of wind power. It tries simultaneously to increase the reliability of wind turbines and decrease the cost of maintenance. The aim is to develop a tool, which can indicate to the maintenance personnel what they should do next, more specifically when and which component they should maintain.

Deviations from project plan
We are rather a lot behind the anticipated schedule, regarding the collection and analysis of the condition data from the member companies.

Publications
The manuscript "The short-term preventive maintenance problem" by Quanjiang Yu and Michael Patriksson will be sent to *European Journal of Operational Research* this month. (EJOR announced a call for papers on applied combinatorial optimization.) The second paper – a study on the PMSPIC – is planned to be submitted later this year.

External activities
Quanjiang participated and presented this project in Vind2016, in Oct. 2016-10, in Stockholm.
Quanjiang participated in a winter school: optimization and operations research, in Jun. 2017, in Zinal.
Quanjiang participated in Seventh GIGAWIND Symposium, in Mar. 2017, in Hannover,
Quanjiang participated in Energy Transition 2017, in Mar. 2017, in Trondheim.
Quanjiang participated and presented this project in Wind Energy Science Conference, Jun. 2017, in DTU Lyngby.
Quanjiang presented this project at the conference SOAK 2017, 19–20 October, in Linköping, Sweden.