Modelling short term decision support tool for O&M of Offshore wind farms

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Abstract

Offshore wind farm managers and schedulers need to manage large numbers of wind turbine visits from day to day: in order to repair minor faults; conduct inspections; and perform scheduled service operations. While major operations - such as gearbox replacements - often have dedicated vessels and technicians booked in advance, the daily schedule forms a choice of which minor maintenance activities to conduct, given the vessels and technicians available. This choice must balance weather conditions, shifts, vessel and technician capabilities, and the impacts of the various maintenance tasks on wind farm profitability. This forms a formidable optimisation problem that today is solved "by hand" by a scheduler.

As part of the Masters research project, work at the Energy Research Centre of The Netherlands (ECN) involved the initial development of a short-term maintenance optimiser, as part of a Dutch research project Daisy4Offshore. This optimiser has been designed to be used each day to determine an optimal maintenance schedule for a given objective which the wind farm manager might be under incentive to deliver. It takes into account the weather forecast, vessel weather window restrictions, shift patterns and the different requirements of the tasks (for both time and technicians).

The problem is solved using a Genetic Algorithm, coupled to a time series evaluation algorithm which determines the objective value for a given order of executing maintenance activities. The tool is planned to be developed further following early testing on a Dutch offshore wind farm in The Netherlands.

Keywords:

Wind farm maintenance, Short-term decision, Modelling, Genetic algorithm, Weather constraints

Introduction

Operations and Maintenance [O&M] costs can be up to 30% of the total project life cycle cost [1]. The effectiveness of O&M impacts directly on the time for which turbine produces power and hence the revenue from the wind farm. With the increase in the size of wind farms, the complexity in O&M also increases non-linearly. Therefore, a priority for the Dutch offshore and global wind farm sector is to maintain and develop its knowledge and experience, to reduce cost and increase energy production or yield by performing maintenance in an optimal way.

Daisy4Offshore project

Several modelling tools for operation and maintenance of offshore wind farm are already commercialized, and some of them are still under development. However, the main focus of these tools is on long term decision making (forthcoming years or lifetime) to strategically reduce overall life cycle cost of the wind farm. A short-term tool doesn't exist to address the problems identified by these long term decision making tool. One of the topics being considered is how to assist the operator in shorter time basis (e.g. daily or weekly), to make the most efficient and beneficial decision.

For this purpose, Daisy4Offshore project was developed. It consists of six project partners out of which ECN is one. Role of ECN is to develop and implement of a support tool for O&M of offshore wind farm [OWF] by prioritizing maintenance activities. The project has a potential end customer in the form of Eneco for implementation in one of their wind farms.

The general objective of this project is to optimize the O&M activities to reduce O&M costs and/or increase the availability. The software is being created as flexible as possible in order to fit the requirements of other wind farm operators or manufacturers. In this master thesis report, the model shall be called as “Farm Manager".

Research aim

The aim of the thesis is to develop a mathematical tool for decision making and prioritizing maintenance activities of offshore wind farms to achieve low cost of O&M and / or higher availability of wind farms.

Type of maintenance

Maintenance activities are broadly classified into to two types; the proactive maintenance and the corrective maintenance. The primary difference between corrective and proactive maintenance is that a problem in the system must exist before corrective maintenance actions are taken, whilst proactive maintenance tasks are intended to prevent occurrence of a problem in the first place

Resources

Irrespective of the type of maintenance, all maintenance activities need resources to perform the intended task. The type of resource might differ depending on the type of maintenance. Offshore wind farm maintenance requires certain general and certain bespoke resources. Resources needed to complete a maintenance activity are as follows.

Access vessel

There are a wide range of equipment and techniques that can be used to ensure that technicians can access wind turbines and other wind farm infrastructure, such as offshore substations.

- Crew transfer vessel (CTV)
- Helicopter
- Service operating vessel

Service support equipment

Service support equipment are used to perform complex maintenance activity or support a large maintenance.

- Nacelle crane
- Jack-up barge
- Diving support vessel
- Cable laying vessel

Technicians

Personnel who perform the maintenance activity on the turbine are termed technicians. In general, technicians with all-round skills could be permanently hired by the OWF, some repairs which do not have to be performed frequently need technicians with special skills and can be hired on a job-to-job basis.

Spare parts

Most of the maintenance activities often need spare parts of different sizes. Transporting spare parts to an offshore wind turbine involves a lot of challenges. Each access vessel or service support equipment has a weight limit of the spare parts it can carry. Hoisting spare parts are subject to wind speed restrictions making the maintenance activity even more complex.

Time to repair

In general, the total time to perform a maintenance activity including the logistics and waiting time is termed **Time to Repair [TTR].** For a corrective maintenance, energy production is hindered from the time of failure until it is fixed, whereas for proactive maintenance energy production is affected only when the actual repair is performed as the turbine keeps producing energy (could be at lower power rating) during other times. [2]

Total cost of maintenance

The total cost of maintenance is the sum of the cost of hiring resources, cost of spare parts and consumables, fuel cost for transportation, inventory holding costs and the costs due to lost revenue. Revenue loss is by far the major contributor to the total O&M costs, followed by renting of equipment or resources. Thus in order to reduce the cost of O&M, these two factors must be addressed.

Wind farm related KPIs

Wind farms typically use cost and availability as key performance indicators. The EU has defined a single overarching KPI to be adopted and developed for the wind industry. This is the Levelized Cost of Electricity (LCOE) produced by wind power, expressed in €/MWh. [20]

$$LCOE = \frac{(C + O)}{E}$$

Where $LCOE$ (€/MWh): The levelized cost of generating electricity
C $(€/y)$: Levelised investment
O (€/y): Annualised operation and
E (MWh/y): Annualised energy production.

Windfarms across the world follow two availabilities defined by IEC standards.

Production based availability can be calculated using following formula [3].

$$\text{Production based availability} = 1 - \frac{\text{Lost production}}{\text{Potential energy production}}$$

Time based availability can be calculated using following formula. [4]

$$\text{Time based availability} = 1 - \frac{\text{Unavailable time}}{\text{Available time} + \text{Unavailable time}}$$

Opportunity for optimization

Operation and maintenance of OWF has a huge potential for improvement, in terms of both cost reduction and reducing delays of repair. The existing tools are focused on long-term evaluation which help a wind farm operator to understand the reasons for higher cost or lower availability. As the OWF industry is still growing faster and bigger, there is a need for a comprehensive tool that can assist maintenance managers and planners to decide on maintenance strategy on a daily basis. Web-based DSS (Decision Support System) is a solution for OWF in the future, helping the managers, operators, and planners to make decisions. To achieve long-term targets day-to-day activities of wind farm O&M should also be aligned with the same. Since it forms a complex problem involving various resources, weather, factor of subsidies / electricity prices, etc. wind farm manager has to be assisted to perform O&M optimally.

Problem definition and modelling

In its most general form, the resource-constrained scheduling problem is defined as follows [5]:

Given a set of:

- activities that must be executed;
- resources with which to perform the activities;
- constraints which must be satisfied, and
- objectives with which to judge a schedule's performance.

what is the best way to assign the resources to the activities at specific times such that all of the constraints are satisfied and the best objective measures are produced? Maintenance tasks are the activities and the resources are explained in the previous sections.

Constraints

Assigning maintenance activity is subject to hard and soft constraints. Hard constraints are those which "have" to be satisfied, whereas soft constraints may not be satisfied but involve a change of the objective function, i.e. a higher or lower cost.

- Accessibility is limited by significant wave height and has to be met for each vessel/equipment used.

- Each activity is assigned only if the exact number of technicians with required skill are available.
- Each technician and vessel can be assigned to only one activity at a given time.
- Total number of technicians assigned to a vessel is less than or equal to its carrying capacity.
- The activities can be performed only during the permitted shift time for each season.
- All technicians are assigned task during each day of the planning process.
- Maintenance activities are not scheduled one hour before and after a bad weather window.

Objective

The "Objective" of OWF scheduling problem can be goals like maximizing energy produced, minimizing the cost of maintenance and many more or even combination of such individual goals.

Feasibility and Optimality

A *feasible* schedule satisfies all of the constraints. An *optimal* schedule not only satisfies all of the constraints, but also is at least as good as any other feasible schedule. Goodness is defined by the objective measures.

Solving scheduling problems

Heuristic algorithms, which can produce solutions which are **near-optimal**, that is, reasonably close to the optimal solution, in a reasonable amount of time are used to solve such complex problems. There are a number of common heuristic approaches to algorithms used for addressing schedule-related problems. After research and literature study Genetic Algorithm was finalized to be used an optimization algorithm. [6] [7]

Genetic Algorithm

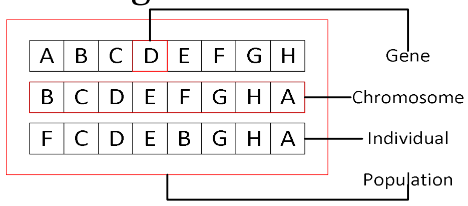


Figure 1 Genetic Algorithm representation

Elements of Genetic Algorithm

A **gene** is the smallest element of an individual / chromosome. Each maintenance activity forms a gene in this case, as Permutation Encoding is used. A **chromosome or an individual** is a set of genes. Since the gene is a maintenance activity, a chromosome is the ordered list of performing maintenance activity of OWF. The set of individuals form the **population**. The size of the population remains constant. This means that in every generation when new individuals are born, either they die or they kill an existing individual in the population to replace them.

Genetic Algorithm Operators

A **selection** operator selects chromosomes in the population for reproduction. This is done by assigning a **fitness** value for each chromosome in the population. The fitter the chromosome, more likely it is to be selected for reproduction. A **crossover** operator produces new offspring by inheriting and mixing genetic information from the selected parents. A **mutation** operator alters the chromosome of a produced offspring to create diversity in the new individuals born. [8] [9]

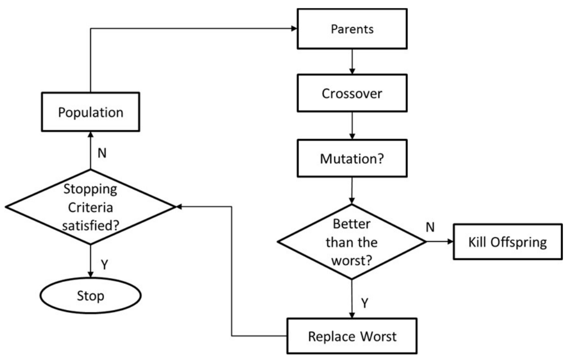


Figure 2 General scheme of evolutionary process [9]

Stopping criteria

A genetic algorithm does not stop autonomously. Stopping criteria has to be provided in order to stop the evolution process. Traditionally 3 kinds of termination conditions are employed [10],

- An upper limit on number of generations is reached.
- An upper limit on the number of evaluations of the fitness function is reached
- The chance of achieving a significant change of fitness value in next generations is excessively low.

Hyper-parameter tuning

Hyper-parameter tuning of a genetic algorithm has to be done with some predefined problem which is similar to the problem being solved. The solution for the test problem has to be known to set the hyper-parameters of the genetic algorithm designed. Since the method used to model genetic algorithm for OWF maintenance scheduling is similar to the method used for optimizing travelling salesman problem [TSP], it was chosen for tuning GA. Tuning was done in two stages.

- Travelling salesman problem with known solution. Where the cities are in a straight line coordinate system making it easy to find the solution using simple formula.
- Travelling salesman problem with unknown solution. Where the cities are randomly spread out making it a real case test problem.

Sensitivity study

Performance of genetic algorithm depends on the selection of the Hyper-parameters. Critical hyper-parameters are **population size, mutation probability and maximum number of generations**.

Trails to set hyper-parameters

Firstly, for a low number of genes trials were conducted for different combination of population size and mutation probability. Each combination has an influence on the number of generations it takes to converge to the optimal solution. The graph below shows the trend.

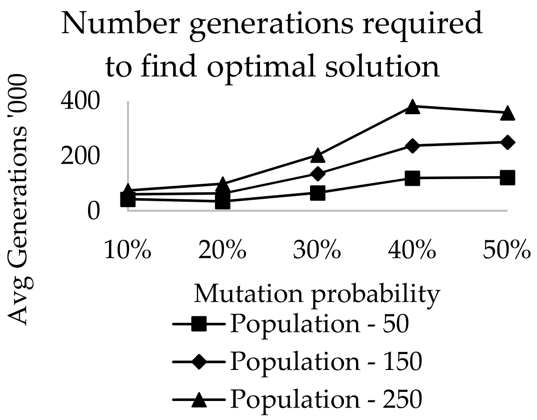


Figure 3 Average number of generations to find optimal solution

Each line in the graph represents a specific population size. Changing mutation probability influences the average number of generations it takes to reach the optimal solution. From the above graph it is clear that low population with low mutation probability tends to converge to the optimal solution faster.

Hence, further trials were conducted for a population around 50 and mutation between 10% and 30% for various gene length.

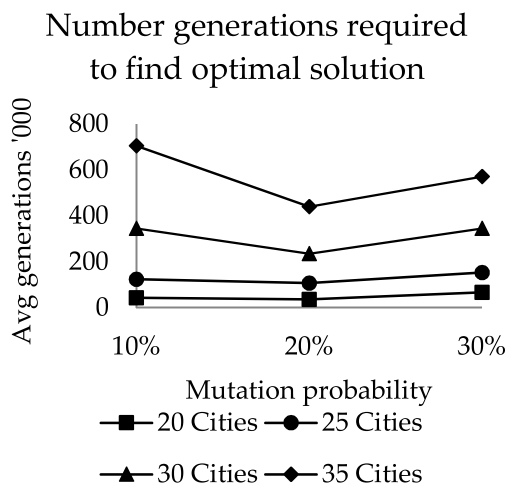
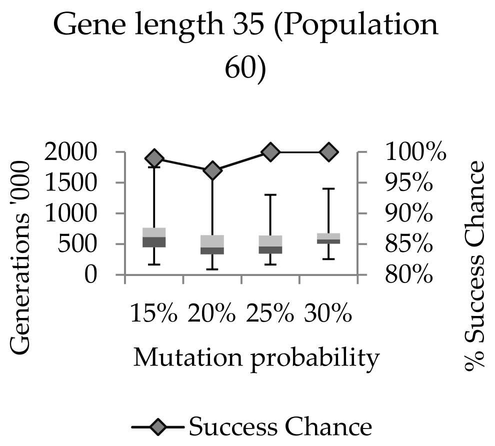


Figure 4 Average number of generations to find optimal solution for different gene length

It can be seen that the mutation probability around 20% perform better especially when the gene length increases. Furthermore, the success chance of converging to the most optimal solution has to be evaluated. Hence more trials were conducted around 20% mutation probability. Graph below shows the spread of number of generations to find the optimal solution, and on the secondary axis the success chance.



For a high number of genes (35), it was found that mutation probability of 25% with population 60 provides better convergence and higher chance to find the optimal solution. This was also true for lower gene length.

Farm Manager Modules

The architecture of the model is shown the figure below.

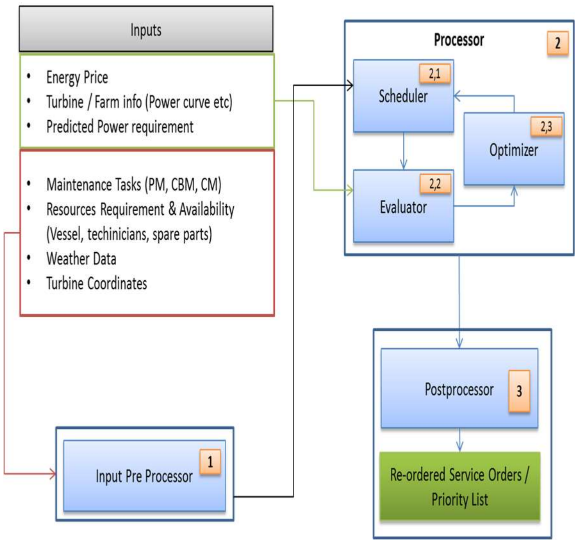


Figure 5 Model architecture

The Farm Manager model building blocks consist of the Input pre-processor, Processor and Post Processor. Master thesis objective was to develop the processor. The processor consists of following modules

- Scheduler
- Evaluator
- Optimizer

Genetic Algorithm which was explained in the previous chapters forms the optimizer.

Scheduler

As the name suggests, the scheduler creates a maintenance schedule. This module checks for the constraints of the problem and defines a feasible maintenance schedule. However, it does not provide any information on how well it satisfies the objective(s) of optimization. Once the constraints are satisfied Scheduler instructs technicians and / or vessels to perform a certain task.

Evaluator

Maintenance schedule generated by the scheduler is rated to check how well it satisfies the objective(s).

Production based availability

Since the goal of the tool focuses on short term the factor that contributes to the production based availability is considered as the objective. From the above formula, it is clear that *lost production* is the only factor which changes the production based availability. Hence the objective of the tool has to be minimization of energy production loss. This can be calculated theoretically using the power curve and the wind speed.

Energy lost by the windfarm can be computed by multiplying the power of each turbine under failure at the given wind speed with the time at that wind speed.

The evaluator takes the input from the scheduler, that is, a time series of performing the maintenance task. For the objective of production based availability it performs the following tasks

- For each service order find the type of maintenance (planned or corrective maintenance)

- For each day find the turbine shut down and restart time of the turbine
- Calculate the energy loss for the given shut down and restart times
- Find the cumulative energy loss for all the maintenance activities in the assigned schedule.

Case study

A case study was conducted to understand how the model functions with an actual windfarm data. Following data was received from the wind farm

Service orders list - It contains the information on when the activity was performed, how many hours it took to complete the activity, how many people performed the task and the type of task.

Transfer plans - Every day, a transfer plan is generated as an order for the technicians and vessel crews to perform the maintenance activities. It is different from the service orders in the sense that, service orders are created for a maintenance activity, whereas transfer plans contain some of these service orders which have to be carried out on a particular day.

Weather forecast and actual weather data were obtained with wind speed and wave height data. The wind speed of forecast was considered at 50m as the hub height of vestas V80 2MW turbine is 60m. In the case of actual weather, the data was obtained from a Metmast. Hence, a transfer function was used.

Considerations for the model

Many assumptions and simplifications had to be made in order to use the data in the Farm Manager model. They are as follows,

- **Technicians** do not have skill requirement (any task can be performed by any technician)
- **Blade repair** was not considered for modelling. It was found that all the resources used for this particular repair was externally hired. Hence it was excluded from the case study.
- **Shift times** were considered constant 7:00 to 16:00 and break time from 12:00 to 12:30
- The **travel time** from the port and between the turbines was considered 30 min
- For planned maintenance it was assumed that the **turbine is shut down and resumes** operation 15 min before and after the maintenance activity respectively.
- **Mobilization time**: It was found from the data receive from the wind farm that the mobilization was carried out half an hour before the shift start time. Hence it was not modelled at this stage.
- **De-mobilization time**: It is assumed all de-mobilization will take place after the shift time (in this case 16:00)
- **Status of turbine:** The type of maintenance is defined by the status of the turbine. They are broadly classified into two categories. **Proactive** (planned / condition based maintenance) - Run & **corrective** maintenance – Stop

Result analysis

Trials were conducted for many different days with the available data.

Scenario 1: 14th of September with 12 available technicians

The schedule which has the earliest completion with least energy loss is presented as optimal schedule. Energy loss for the data provided by the wind farm is was also computed considering the weather on the days when the task as performed. The results are shown in the graphs below.

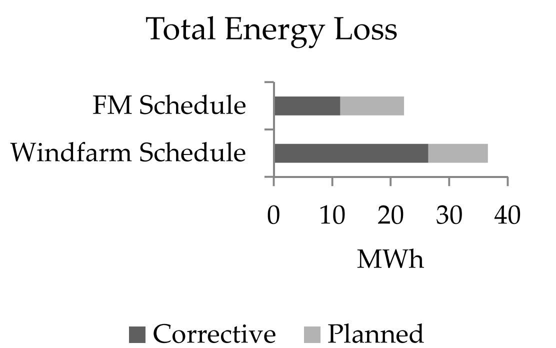


Figure 6 Classification of energy loss on the type of maintenance

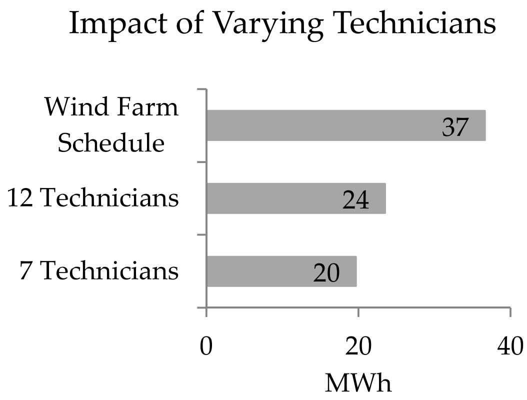
From the two graphs it can be seen that energy loss prediction for FM schedule is less as compared to the predicted energy loss of wind farm. This is mainly due to corrective maintenance.

Turbine no	Turbine status	% task completed after 4 days	
		Wind farm schedule	FM schedule
WTG10	Stop	100% (3:30pm)	100% (1:00 pm)
WTG14	Stop	100% (3:45 pm)	100% (11:30 am)
		100% (1:45 pm)	100% (11 am)
WTG35	Run	100%	100%
WTG28	Run	100%	100%
WTG44	Run	0	100%
WTG13	Run	0	100%
	Run	0	100%
WTG34	Run	0	100%
WTG09	Run	100%	100%
WTG55	Run	100%	100%
WTG24	Run	100%	100%

Even further analysis show that the corrective maintenance activities were completed sooner in the schedule proposed by FM. It also shows that some of the planned maintenance tasks were not even initiated by wind farm operator within the 4-day planning window. The reason for this was hard to comprehend. After a discussion with the wind farm it was concluded that more specific historical data would be required to make further judgment on this, which could not be made available.

Scenario 2: 14th of September with 7 available technicians

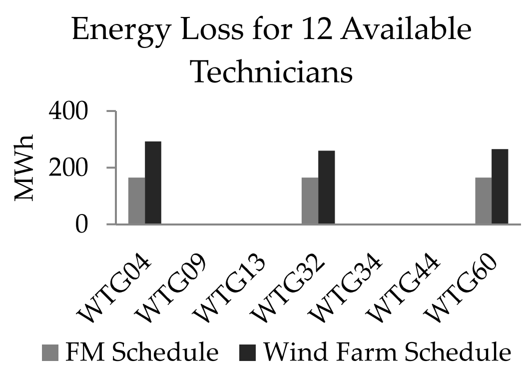
Historical data suggested that not all 12 technicians worked during those 4 days. On an average only 7 technicians worked during those days, hence the total number of available technicians was set to 7 in the model. The results obtained were quite surprising as it still shows that all operations were performed within the 4-day planning window.



The reason for this was, reducing the number of technicians forced some activities to be performed on the 3rd day. During which the wind speed was lower. From the results it cannot be concluded that reducing the technicians results in lower energy loss. The scheduler is currently designed to complete the activities as early as possible with as low energy loss as possible, which is the strategy used by the wind farms during summer. However, the results show that delaying the activities can result in lower energy loss. Delaying the activities and achieving lowest possible energy loss can be strategy for winter and thus it has to be incorporated in the optimization algorithm.

Scenario 3: 16th of August with 12 available technicians

This date was chosen to test the model for an extreme case scenario. During the next few days a jack-up barge was used for replacing generator and the weather did not permit accessibility with normal crew transfer vessels. The following results were obtained from the model.



Turbine no	Turbine status	% task completed after 4 days	
		Wind farm schedule	FM schedule
WTG60	Stop	0%	35%
WTG32	Stop	0%	35%
WTG04	Stop	24%	20%
	Stop	19%	27%
WTG09	Run	0%	0%
WTG13	Run	0%	0%
	Run	0%	0%
WTG44	Run	0%	0%
WTG34	Run	0%	0%

Table 1 Proportion of work completed for pending service orders

As seen from the graph and table, only corrective maintenance activities were performed during the 4-day planning window. The proportion of work completed by FM schedule seems to be higher than that of wind farm. The reason for this is, again, that the wind farm used 7-8 technicians during those 4 days even though a major repair was being performed. The reason for this could not be extracted from the data provided. The wind speed data suggest that the wind turbine was not accessible on 17th and 18th of August. However, work was performed on one of the turbines (WTG04) in reality. It was possible as the jack-up barge was already jacked up and the technicians have possibility to stay on the barge. Farm manager does not yet have the option to include multiple vessels; thus it was not possible to incorporate this in the analysis. Nevertheless, the result shows the FM model also produces schedules where corrective maintenance is given higher priority than planned maintenance.

Learnings from case study

The case study provided several insights:

- Understanding how the model fits into the method of maintenance planning used by operator
- Varying the total number of technicians forms a new variable for optimization.
- Proved that the model performs as intended when critical maintenance activities have to be scheduled before the non-critical planned maintenance activities.
- Season based scheduling has to be incorporated in the scheduler. Thus providing an option for completing the tasks as soon as possible or delaying the tasks in the hope of achieving lower energy loss.
- Understanding extreme case situation like, use of Jack-up barge during a bad weather window.

Conclusion

In this work, a decision support model for O&M in OWF has been modelled and developed. The OWF scheduling problem is similar to a form of resource-constrained scheduling problem, which is common in many industries. Such problems are complex and typically solved by heuristic methods. The tool developed as part of this research is called Farm Manager in the study and optimization is performed using Genetic Algorithm which is coupled to a sophisticated time series evaluation algorithm. The processor was split into three modules: Optimizer, Scheduler and Evaluator.

The Genetic Algorithm, which forms the optimizer, was built in such a way that it can be used by any other project which requires optimization. Hyper-parameter tuning was done by using a travelling salesman problem. A TSP with a unique shortest straight line distance was defined for testing. Results show the performance of the algorithm with up to 35 cities. In the case of 35 cities, to find the unique solutions, the GA is able to find the optimum with on an average 1.8 million evaluations in less than 2 minutes. Increasing the number of genes beyond this increases the computation time significantly.

The functionality of evaluator and scheduler are limited at the moment as the model development was started during the thesis. Further improvements in the model are necessary to make the tool commercial. Nevertheless, a case study was conducted with the existing capability of the model. The results were helpful in understanding the requirements of tool and further work.

Further work

Further work proposed to make the tool commercial are,

Constraints

The constraints that the scheduler solves can be increased further to make the schedule closer to reality. These depend on the requirement of the project and data that is available for the model.

Multiple objective evaluation

In many occasions, achieving one objective has an adverse effect on the other. Thus a rating has to be provided for various objectives so that the optimization can be carried out for a multiple objective function.

Results extension

Results from farm manager can be used to generate other forms of output to assist maintenance manager to achieve the task set by the model. These include,

- Loss of revenue.
- Delay estimation
- Resource utilization

Model integration & implementation

To communicate with the wind farm manager, a GUI has to be developed / the model has to be integrated with the existing GUI the wind farm operates with.

In a situation where a GUI is not developed or available, MS Project can be used to print the output from the model. Maintenance tasks being the main output of the model can be represented in the MS Project as tasks with the given times.

End effect

The cost of not completing tasks with in the given time has to be incorporated in the model. At the same time cost of completing all the tasks with the schedule without looking at the future prospects should also be implemented.

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