Modeling and Simulation of Offshore Wind Farms including the Mapping and Analysis of relevant O&M Processes

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Abstract
This paper describes objectives, approach and preliminary results of the joint-project System Optimization (SystOp) Offshore Wind. It illustrates an outline of relevant maintenance processes required for the operation phase of offshore wind farms as well as on modeling and technical development of a tool that is able to visualize, connect and simulate these processes and combine them with other relevant factors, such as for example stochastic weather generators and other wind farm proprietary aspects.

The complexity of relevant factors for the assessment of the quality of offshore wind farms’ operation only allows for an overview on how to model and assess that quality as a whole. In that regard, this paper will focus on the different stages of depicting and analyzing, from the understanding of relevant players to the interaction between them, the modeling of complex interactions to the visualization in a software and simulation of business processes. In addition, the choices made for different methodologies, such as business process notation BPMN 2.0, or simulation-relevant techniques will be presented, including the given reasons for the choices made.

1. Motivation

Over the past two decades, onshore wind energy technology has seen a ten-fold reduction in cost and is now competitive with fossil and nuclear energy in many areas worldwide (Musial /Butterfield/Ram 2006). The offshore wind energy branch, however, is still in its early stages, especially as long term projections considering the higher costs for maintenance and servicing are only slowly achieving scientific significance. Nonetheless, there is a broad consensus about their key role in achieving the climate policy targets and the associated energy turnaround (at least for Germany). The goal of the German government is to produce approx. 25,000 MW output through offshore wind farms by 2030, which is more than all German nuclear power plants have been producing until recently.

After the successful implementation of initial offshore wind farms such as Alpha Ventus (Germany), Horns Rev (Denmark), and Thanet (UK), numerous offshore wind projects worldwide are either in the planning phase or already at the construction stage (as of March 2013). Yet most of those newly planned offshore wind farms, at least for Germany, will be located much further outwards compared to the “near shore” farms from Denmark. This poses new challenges regarding accessibility and the planning of maintenance. The decisive factor for the success of these and future offshore wind farms is to effectively address the technical challenges and ensure economic feasibility (Klinke/Klarmann/Kodali 2012, 1). One main challenge in that regard is that the standardization of the processes is still in an early stage, compared to other high-end technology sectors, which is also due to the high number of correlating processes and their respective causes or involved parties.

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2. Project SystOp Offshore Wind

2.1 Main Objective

The project SystOp Offshore Wind is a three-year joint project financed by the Federal Ministry of the Environment, Nature Conservation and Nuclear Safety. It is conducted by the University of Applied Science in Bremen, the University of Hamburg, as well as the industrial partners BTC AG, and the IZP Dresden. The main objective of the project is to determine the relevant players and research their interaction, including the capturing of all resulting business processes that have an influence on the continuous smooth running of all needed maintenance activities of offshore wind farms.

Following the description of the processes, they were analyzed in order to deduce critical elements, such as resources or influences on other processes including feedback loops. The main purpose of the processes depiction was to establish an objective basis for communication between the partners that further enabled and evaluated the importance of different stages as well as critical aspects that should be taken under special observation. The different levels of communication and layers of cooperation were thus made more transparent, enabling a higher security level considering long term planning and projections. Furthermore, through the combination with business process simulation (see section 5), it was intended to test the model design and improve the processes in question where possible as well as offer alternative courses of actions, which would present additional possibilities to decision-makers and offer concrete, measurable data depending on the choices made.

2.2 Approach

We contacted several market players from the wind park sector, such as operators, service companies, owners, transport companies, harbors, airports and employment companies. Some of them contractually agreed to give us an insight into their perception of business processes, their resources and their data. We designed a questionnaire including general questions about tasks, resources and typical problems, which provide a substantiated code of practice to describe the project demand for all participants. In successive on-site visits we learned to understand their individual business processes with a focus on interfaces to other stakeholders. This includes reviews processes already depicted with stakeholders during different meetings. We regularly hold workshops, for example with special subject areas, intending bringing together all industry partners to discuss intermediate results.

These models are the basis for reference models, which will be an adequate communication base for all market players. Additionally, these models provide the basis for our risk analysis and simulation experiments. For investigating the dynamic runtime-behavior of the wind farm system we use simulation methodology. For determining critical processes, stakeholders, activities and interactions as well as optimization measures we conducted risk analysis. Simulation allows the comparison of alternative system configurations by means of key figures like process efficiency and process lead times, the detection of modeling errors and critical elements such as deadlocks or resource bottlenecks.

As the offshore wind farm sector is still young and as the standardization of the and components, is yet lacking maturity, there are currently many different approaches as well as different technologies in place: e.g., different structures of platforms naturally also need different processes and related resources to be maintained, which of course has to be reflected by the modeling and the simulation.

On this basis we started with modeling a German offshore wind farm, which means we integrated all relevant and accessible data from the project, such as detailed information of the two different wind turbines in place, including their interior components (at least the data that was made available). In addition to the information considering the technical components, we gathered the data from Fino 1,
which is a research weather station in close proximity to the offshore wind farm Alpha Ventus, as basis for our weather generation model.

3 Offshore Wind Farms

3.1 Stakeholders and their interactions

Offshore wind farms have a high amount of different parties involved, infrastructures, interactions between them and interfaces. Figure 1 depicts the most common dependencies of the operation and maintenance of offshore wind farms. It also provides aspects that are identical for onshore and offshore sections, notably divided through the different background colors. The icons represent the parties involved and infrastructure/resources required. The arrows between them indicate the interfaces on the one hand and for the interactions on the other. The interactions are defined as staff, material, waste, finances and information. Different kinds of parameters, like e.g. lead time, are implied within the interfaces.

Figure 1: The System Offshore Wind Farm operation and maintenance status

The stakeholder analysis focused on the influences of the parties involved and the effects of their operation and maintenance processes. The critical parties involved as well as the secondary stakeholders were identified in detail.
In posters similar to Figure 1 we have marked the interactions in different colors respectively for the different possible interactions of an OWF in maintenance. For each type of interaction, a specific color has been assigned: red refers to personnel, blue to material, purple to waste, green is related to finances and black to information. The interactions can be partitioned into message flows, i.e. the ones between the pools, and sequence flows, the ones within the pools.

### 3.2 O&M Processes

The operation and maintenance processes include all technical and administrative measures that lead to the operation of an offshore wind turbine (OWT) or a respective group of turbines, e.g. a wind farm. They have to take all framework conditions and requirements of the operation phase of an offshore wind farm (OWF) into account and satisfy those to ensure a regular and continuous operation mode.

The internal process operation, operational management, maintenance as well as modification, which are required for a safe and constant operation of the OWF, are included in the operation processes. The maintenance processes ensure a functional condition of the OWT and its auxiliary plants or the return to this state. Operational and maintenance processes generally comprise technical and organizational tasks.

The operation processes considered in the System Offshore Wind Farm are defined as the execution processes: operation, standstill/attendance, maintenance, dangerous situation and operational management.

Out of the operation processes mentioned, the execution process „maintenance“ could be adjusted to the most extent regarding process flows and its optimization. Due to this fact, this process was analyzed more closely within SystOp Offshore Wind.

In the first instance the status “maintenance” of an OWF contains four main processes (DIN 31051 (2003): inspection, maintenance, repair and improvement.

### 4 Modeling Offshore Wind Farm Processes

An on-site recording of the process flows is advisable to survey and to map the processes realistically. During the multiple surveys, which were partially stretched over several days, experts were interviewed, existing process models were discussed, and with help of specifically designed questionnaires several parameters were recorded.

The results generated in this way provide the data basis for the risk analysis and simulation. Up to now the following main processes (among others) were recorded:

- Repair of small-components of an OWT
- Repair of an operation platform
- Annual maintenance and periodic inspection of an OWF
- Maintenance of the foundation structures
- Repair of large components, in particular rotor blades and gears
- Application procedures by federal police and customs duty
- Legal situation and handling with waste from the EEZ (Exclusive Economic Zone)

### 4.1 Process overview

For a standardization of terms, differently detailed levels of the process chain Offshore Wind Farm were defined. In order to classify the processes they were divided in the following groups: execution, main and sub-processes, process steps and elementary processes. (Fischermanns 2012; BTC AG 2010)
Process life-cycles can be ordered hierarchically. Very long running, roughly described project phases contain more detailed cluster processes which consist of main and sub-process, which at least contains short-running, elementary processes which describe concrete human activities. This concerns management, support and execution processes. While management processes control the interaction between and in the processes, the support processes provide all resources required to ensure that execution and management processes can run without interruption. (Allweyer 2007; Hirzel/Kühn/Gaida 2008)

The capturing of the business processes in question is done on different levels (Figure 2) and subsequently in different detail. Level 1 includes the different (project-) phases in the life-cycle of an entire offshore wind park, whereas SystOp Offshore Wind considers the particular case of the operation phase more precisely the execution process of the maintenance. The phases planning, development, production, erection, operation and deconstruction are overlapping each other. All execution processes corresponding to the operation phase are specified in level 2, they are interconnected and interdependent within the accordant phase (IEC/TS 61400-26-1 2011). According to the project objectives, the focus is on defined definitions from DIN 13306 and 31051, including in particular the maintenance (DIN 13306 (2012); DIN 31051 (2003)). This level comprises the cluster processes, which themselves include the management and support processes described above as well as the following execution processes. It should be emphasized that the processes on this level include a lot of back coupling effects and loops for
other project phases. The order of the processes is not to be identified with a time-based logical sequence. The individual processes are closely interlinked and mutually dependent within the associated phase. The next hierarchy of processes is shown in level 3; these are the main processes which are repetitive respectively standardized processes. Their implementation takes place in regular intervals whereby a time interruption of this order is permitted. There is no chronological or logical sequence implied (Bundesministerium des Innern in Zusammenarbeit mit dem Bundesverwaltungsamt 2012; Bundesverband WindEnergie e.V. 2012). Figure 2 shows the main processes of the cluster process ‘maintenance’. On the contrary, the sub-processes in level 4 occur in chronological and causal progression; in case of a maintenance operation these are capturing & evaluation, planning etc. Different subdivisions in further levels below enable a more detailed description of the main and the sub-processes. The main process ‘repair’ in Figure 2 is further divided into the sub-processes, recording and evaluation of OWF information, mission planning, preparation, execution, inclusive outward journey/residence, execution on-site and return journey and post processing. The processes of level 5 are those most interesting for SystOp project, because they describe concrete action and interaction. By means of business process models all parties involved, activities and trans-boundary and sequence flows are defined. Furthermore, this level enables a classification of process-leading and process–supporting steps as well as a prescription of the obligations and responsibilities of the various parties. How these processes can be modeled is shown in section 4.3. Figure 2 shows the elementary processes of the level 4 entity ‘repair/execution’. In case of further subsidiary processes level 6 provides a possible extension which can be recursive repeated in order to visualize of process hierarchies.

The main benefit of this figure is standardization of terms which can be applied for all OWFs. It allows a more precise communication about processes by subdivision into levels and demonstrates the sequentially and logically relation between processes. In this way, it can serve as a basis for work procedures and checklists by provision of process models, and as a basis for process simulations and risk analyses.

4.2 Notation choice: BPMN 2.0

First we had to choose an adequate modeling language which fits our requirements in (semi-)formally defining processes. To document the sequential activities and interactions, we chose the Business Process Model and Notation (BPMN) 2.0, which is a graphical, sufficiently formalized notation for business processes. BPMN 2.0 supports the differentiation of sequence flows which describe activities’ order inside the processes of an organizational unit, and message flows which describe the interaction between processes of distinct organization units, which fits the focus of our project to discover interactions between the stakeholders. These message flows include material, personal, data, communication, waste or cash flows. Additionally, there is a huge set of elements which cover diverse modeling constructs. E.g. there are different kinds of events, particularly attached events, which are able to abort the execution of an activity.

4.3 Modeling results

As a first scenario we recorded the maintenance of small components together with industrial partners and modeled them with BPMN 2.0. In this phase of our project (July 2013) we have determined the corresponding elementary processes recording & evaluation by manufacturer, recording & evaluation by non-manufacturer, mission planning, vessel-preparation, helicopter-preparation, execution-outward journey by vessel and helicopter, execution-on-site, execution-return journey by vessel and helicopter as well as post-processing.
Recording and evaluation is the basis for all maintenance work assignments and has a great impact on expenses and incomes of the offshore wind farm. It covers collection, documentation and evaluation of data and information about the technical components of the wind farm, e.g. SCADA-data or information about previous maintenance activities of each wind turbine. With this background information, decisions about maintenance activities at a wind turbine, which include e.g. working time or decisions about a corrective or preventive component changing, can be taken.

Mission planning covers the best combination of determined work assignments under current requirements, e.g. weather conditions and logistics. This process is the basis for a successful carried out work assignments on-site the wind farm. It also has a great impact on expenses and incomes of the offshore wind farm.

Preparation covers the preparation of wind turbine technicians, material, spare parts and tools as well as logistics processes. Forgotten or damaged material leads to time delay or cancelation of a work assignment. Because of difficult weather conditions with narrow time slots for working and high costs as well as restricted availability of special vessels the preparation has a great impact on expenses and incomes of the offshore wind farm.

Figure 3 shows the process model for the elementary process ‘return journey by personnel transfer vessel’ as one example, because the scope of this paper doesn’t allow presenting all of our results. The three pools represent the different stakeholder operation office, the shipping respectively helicopter companies and an external maintenance company. Furthermore, the pool can be divided in varying departments (called “lanes” in BPMN), like for example the shipping company which is divided in the
vessel crew and the captain. The edges between the pools represent message flows, e.g. the captain updates the operation office about each single step of the operation as there are accessing the OWT, identifying errors, estimated duration, abortive or successful maintenance. While rectangles represent single activities or sub-processes, circles represent events such as a start respectively end occasion, incoming direct messages, broadcast messages, cancelation or compensation.

In conclusion of the discussions based on already existing models, the visualization of the process flows could be used as an excellent, easily comprehensible basis for discussion.

5. Simulation of O&M Processes

Simulation is a methodology for investigating the dynamic runtime-behavior of a system. The stochastic state variation of processes in time is recorded and statistically evaluated. This offers an adequate analysis method for countering the lack of static process definitions. This section describes our approach of tool development and simulation application and the resulting benefits.

5.1 Objectives and Expected Benefits

First of all, simulation can detect modeling errors and assure the logical correctness of static model descriptions. Besides syntactical errors, inactive sequence paths or events can be identified, indicating modeling mistakes. Critical reaction coupling and potential deadlocks will also be detected.

Enhanced with further data on activities’ handling times and probabilities of event occurrences, a large set of key figures for each process can be calculated, e.g. process efficiency, lead times and waiting times. The key figure comparison of alternative process configurations is possible, without having to experiment with the actual system and thus endangering the ongoing enterprise scope. Also a comparison of normal operation and high-pressure tests is advisable. On the basis of resource models, a bottleneck-analysis becomes feasible, targeting at reducing waiting times or optimizing capacity utilization, transport devices, material and human resources. At the end, a comparison of different process strategies, e.g. corrective, preventive or condition-based maintenance, can be conducted when simulating the O&M processes of an offshore wind farm.

The data for the upcoming simulation studies is also based (so far) mainly on different interviews with industrial partners and project partners working in the sector of offshore wind farms. In order to collect the needed parameters for the simulation such as the duration of activities, we also had different sessions with experts considering the probabilities of failure and general approximate values of different components relevant to the simulation.

5.2 Simulation with BPMN 2.0 Models

The BPMN 2.0 doesn’t contain specification for simulation application. Nevertheless, a simulation of BPMN models is possible, if they are modeled according to execution semantics of BPMN specification. In order to achieve this, BPMN models have to be enhanced with further simulation specific information which we call simulation properties (Joschko/Janz/Hann/Page 2012).

The most crucial components regarding the lead time of business processes are the activities. Due to its nature, an activity consumes time while being executed. In most cases, this cannot be modeled deterministically, e.g. the execution time of an operation processed by a human being is always subject to random fluctuations. This aspect is represented by applying stochastic distribution as the duration of an activity.

Events also have a high impact on the lead time of business processes. Some events are created automatically during simulation, such as message receive events or signals. Especially the occurrence of
start, error and escalation events often has to be scheduled stochastically. Thus, their inter-arrival times
results from stochastic distributions that have to be parameterized by the modeler. Every time a start event
is triggered, a new process instance will be created.

At so-called exclusive and inclusive gateways, decisions are necessary for choosing the next
activity of a process. For that reason, conditions have to be defined and assigned to the outgoing sequence
flows of the gateway. This can be easily handled by means of scripting languages like Python. Well-
defined conditions are a requirement for the correct execution and evaluation of O&M processes.

5.3 Tool Development

The main objective of the software suite under development has been to permit the highest possible
flexibility in the creation of the different models needed to pay tribute to the operation of wind farms. One
main challenge has been the combination of different domain layers and thus models, such as BPMN
process models and wind farm models as well as weather models (see section 5.3). In order to create,
delete, edit and manage these models different model editors have been created.

As software-framework we used Empinia which is an open-source plugin-framework specially
designed for rapid component-orientated domain-specific application development (www.empinia.org).
Component-oriented modeling eases coupling of different heterogeneous models like process and weather
models. Empinia is based on .NET Technology and notably C# as programming language. As simulation
engine, a .NET derivate of DESMO-J has been used. DESMO-J is an object-oriented framework targeted
at programmers developing simulation models. We use a specific DESMOI-J extension for simulating
BPMN-models, which can be integrated as Empinia plugin. DESMO-J has also been chosen, because it is
supporting both the process-oriented and the event-oriented modeling style, also known as process-
interaction approach or event-scheduling approach, respectively, which contributed to the different
model/domain types in discrete event simulation.

By integrating the DESMO-J engine as simulation component, and adjusting it to work with the
modeled business processes, we are now able to test critical system sections and deliver information on
running times, waiting periods, identification of non-valid modeling, i.e. errors in the modeling process
itself considering our business processes. It has been very useful in detecting modeling errors and sensitive
parameters so far.

In accordance with OMG specification BPMN processes were saved as XML files, and to ensure the
highest flexibility and compatibility it has been decided to use XML as global persistence layer, i.e. the
models of the wind farms, including the farms themselves, the wind turbines and their respective
components, were also saved in XML files. Results from the simulation can be received in either XML or
HTML format.

5.4 Simulating Wind Operation and Weather Impacts

The O&M processes are certainly exposed to an environment. Their successful execution depends on
weather conditions. It success is depending on the investment return of running wind energy farms. Hence,
we extended our simulation tool with the capability of coupling BPMN process models with weather and
wind farm models.

The modeling of wind farms is done on three different levels, namely its turbines, their respective
components and the aggregation to a wind farm with different turbine types (figure 4, screenshot to the
right). The turbine definition includes modeling of their respective energy output (figure 4, screenshot to
the left) and hence allows the depicting of the energy output of whole wind farms (Joschko/Widok/Page
2013). Most important part of the wind park model, is the occurrence probability of distinct signals,
usually error signals. These signals trigger corresponding signals receive events in the BPMN-based
process models. In the opposite direction, BPMN-processes can affect the state of a wind turbine, such as switching it off, or replacing a component and thus increase its life expectancy. In that way, the workload on O&M processes can be mapped close to reality in a wind farm simulations model.

Another autonomous component is the stochastic weather generator, which is able to analyze data from historic sources and extract distributions from the given data, with the help of various different scientific sources. It permits generating new sets of data in order to supply the simulation with realistic weather data. We developed an Empinia-extension for integrating the CLIMA component into our code base. CLIMA comes with routines to produce synthetic values of the most relevant climate variables (such as precipitation, air temperature and wind speed) from existing weather data. We have access to data from Fino 1 station in the Northern Sea, which provides an excellent data base for the last decade. The interaction with BPMN-models is unidirectional: If the weather conditions don’t allow a work placement on high seas, processes have to be canceled, aborted and compensated. This is carried out by triggering the corresponding event-sub-processes of the BPMN models. In winter, it isn’t sometimes possible to reach single wind turbines for months. This fact has to be considered when planning missions in the summer months.

As next step in our tool development, algorithms for the planning of deployments (aggregations of such) will be integrated and the complete system will be simulated, on order to allow stress tests.

6. Preliminary project results

As the project is still ongoing final conclusions cannot be drawn. However there are already a number of interim results. Some critical and thus especially relevant processes have been defined during the informal feedback loops within our project team and industrial partners. Furthermore, the BTC AG has already published the first version of its GWPPM (German Wind Power Plant Model) as reference process model for the life-cycle of offshore wind farms. In addition to the definition of critical processes and the reference process model we developed a software suite that is able to manage (creation, deletion, edit, etc.) business processes, as well as wind farms and offshore wind farms in particular, and last but not least weather conditions, via stochastic weather generators. In that regard, a software tool has been developed that is able to model most relevant condition concerning the maintenance processes of offshore wind farms. Moreover, the same tool is also able to simulate the outcome of different approaches considering the underlying business processes. In the future, it is planned to simulate for example different approaches on how to maintain offshore wind turbines, which transportation device to use, when to use it, how many people to deploy, for how many days, and many more.

These results have been already discussed on a Stakeholder-Workshop and feedback from the industrial partners has been integrated into further development steps. In the coming months, we aim to
further enhance the completion and integration of our models, to intensify our dialogue with the industrial partners, integrate higher definitions of risk analysis in order to qualify and quantify critical activities during the processes and last but not least intensify the simulation of these relevant processes as well as the total system.

The process maps and business process models, which have been created, are an adequate assistance for technicians in operating processes (e.g. as checklist) or trainings courses. They can support operational management in mission planning. They can act as communication basis for defining interfaces between cooperation partners. They are fundamental for improving those processes and interaction. The simulation tool allows for comparing different maintenance strategies over a whole wind farm life-cycle.

7 Summarization & Outlook

In this paper we outlined how to identify the stakeholders and their relationships (Figure 1), how to define different levels to ease the communication on processes (Figure 2) and how to model the elementary activities and interaction of O&M Process making use of BPMN 2.0 notation (Figure 3). We also showed how we use simulation to detect errors and critical elements in these processes. For that purpose, we developed a domain-specific prototype simulation software. Within the project SystOp Offshore Wind challenges such as high efforts for data collection and in-depth analysis of the processes were encountered. Another ongoing challenge is the lack of full-scale testing for the proposed structures and processes due to shortages of practical experiences in the wind park domain in Germany.

As next steps, the process chain will be investigated in more detail and studied in respect to the usability and benefit generation. We will discuss and validate our preliminary results and business process models within industry workshops, expert interviews and on site-visits. We will quantify ranges for key performance indicator of modeled processes by means of simulation technology. A functional risk analysis for processes will be included. The further modeling steps for risk analysis of business processes are the definition and structuring of required information for process models, the development of a concept of different modeling layers, data collection and annotation and their interactions. These are needed for the determined information and the development of BPMN Meta models for the different modeling layers and annotations similar to the existing simulation extension properties for BPMN 2.0 we are used in this project.

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