Simulation of Health and Safety Aspects during the Maintenance of Offshore Wind Farms

Philipp Kuenz[1]; Lucian Constantin Ungureanu, Ph.D.[2]; Timo Hartmann, Ph.D., M.ASCE[3]; and Thorsten Albers, Ph.D.[4]

[1]Civil Systems Engineering, Institute for Civil Engineering, TU Berlin, Gustav-Meyer-Allee 25 13355, Berlin, Germany. E-mail: kuenz@mail.de
[2]Civil Systems Engineering, Institute for Civil Engineering, TU Berlin, Gustav-Meyer-Allee 25 13355, Berlin, Germany. E-mail: l.ungureanu@tu-berlin.de
[3]Civil Systems Engineering, Institute for Civil Engineering, TU Berlin, Gustav-Meyer-Allee 25 13355, Berlin, Germany. E-mail: timo.hartmann@tu-berlin.de
[4]Ostfalia Univ. of Applied Sciences, Herbert-Meyer-St. 7 29556, Suderburg, Germany. E-mail: t.albers@ostfalia.de

ABSTRACT

Operations as well as health and safety aspects during the maintenance of off-shore wind farms are connected within a complex process that is highly dependent on environmental conditions and the chosen maintenance strategy. Health and safety restrictions must be carefully balanced with economic performance parameters and local environmental conditions. To explore this balance, we developed a simulation model for different operation and maintenance strategies that provides information about accessibility of wind turbines, technical availability of the wind farm, and the mean time to repair. The model represents the maintenance process using discrete events steered by stochastic environmental and process related input parameters. It is built upon the abundance on existing maintenance simulation models for off-shore wind farm and can therefore be considered as stable enough to explore the specific effects of health and safety modeling aspects. The model implements health and safety aspects using a rule-based decision system that defines certain thresholds beyond which maintenance processes will not be carried out. These thresholds are based on existing health and safety standards for off-shore windfarm maintenance routines. To illustrate the model, we implemented it for a fictional offshore wind farm. Initial simulation experiments show that the model allows to quickly understand the effects of different choices on several key performance indicators.

INTRODUCTION

Maintenance activities for infrastructure often need to be conducted in harsh environmental conditions. Therefore, strict health and safety constraints have been developed for maintenance activities that must be strictly followed to ensure the well-being of the maintenance engineers. Already in the procurement phase, construction firms need to provide a sound health and safety approach that more and more becomes an important factor in the bidding process prior to the construction phase. Further, the effective and safe allocation of human resources is an important aspect for an economically successful operation of an off-shore wind farm. As these constraints are specific to different available work routines, possible for a maintenance task and because each of these routines vary in their efficiency to provide the maintenance task, deciding on a maintenance strategy is a complex task. For example, during the corrective maintenance of off-shore wind farms, repair workers can be transported to wind turbines using different means, ranging from sea vessels to helicopters. Each of these choices underly different health and safety regulations that depend on weather conditions and, at the same time, influence the speed maintenance engineers can be transported to a defect turbine. Choosing the adequate transport mean, one of the main cost drivers to be considered during strategic maintenance planning, is therefore not an easy task.

This paper hypothesizes that stochastic discrete event simulations can help maintenance planners to support these complex decisions as they allow to simulate the various work routines under different environmental conditions. To support our hypothesis, we built an exemplary discrete event simulation model that we thoroughly base on the many available models to simulate off-shore windfarm maintenance tasks. This model simulates the effect of choosing different means of transportation for the maintenance of off-shore wind-farms under varying weather conditions accounting for health and safety constraints. Initial simulation experiments show that the model allows to quickly understand the effects of different choices on a number of key performance indicators for assessing the effect of maintenance strategies, such as accessibility of wind turbines, overall operation availability of turbines, or mean time to repair a specific turbine in case of defects.

The next section of this paper briefly introduces the concept of discrete event simulations (DEVS) and reviews research into its applicability to model maintenance tasks and to include health and safety constraints. The paper then briefly introduces the approach followed to showcase the applicability of DEVS for maintenance planning and then describes the developed DEVS model in detail. Before concluding, we analyze several initial experimentation results based on their utility to support strategic maintenance decisions.

DEVS SIMULATION OF HEALTH AND SAFETY CONSTRAINTS

DEVS models allow to represent work processes as discrete sequence of tasks, each with a specific stochastically distributed duration. DEVS allows for the study of a system behavior within the boundaries of a given set of observed elements and conditions (Wainer, p35, 2009). This technique allows for the modeling of real systems by using a hierarchical systemic decomposition into atomic and coupled components (Wainer, p36, 2009). While atomic DEVS models allow for the behavior study of the simple system components, coupled DEVS models allow for the composition of various atomic and coupled sub-models at a higher hierarchical level (Wainer, p36, 2009). The formal specification of a DEVS model requires a set of input events, a set of output events, a set of sequential states, an external state transition function, an internal state transition function, an output function and a time advance function (Wainer, p35-36, 2009). A DEVS model can then use the state function to define states, such as operational or failed for wind turbines. A simulation then moves a system to a new state such as failed, under repair or repaired, according to the state function and the time advance function The model outputs a specific event and information related to it as defined by the output function that in turn can again trigger new state changes.

Because of its simplicity and descriptive power, there is a long history of using the DEVS formalism to model processes and to understand resource usage of construction work (Halpin, 1992). Recent examples of the application of DEVS are for example to understand the process of off-site construction (Hsu et al. 2018), optimize crane usage (Peng et al. 2018), or understand the environmental impacts of construction work (González & Echaveguren, 2018). DEVS has also been applied to model and simulate different health and safety related aspects of construction work activities, such as understanding the effect of different ergonomic aspects on worker productivity (Golabchi et al., 2018), or understanding lighting requirements during night work (Nasser, 2008).

Table 1 – Transportation modes - constraint based reasoning patterns based on weather conditions

Parameter	Transport modes							
	CTV Catamaran boat landing		CTV SWAT boat landing		CTV/SOV platform access	HLV lifting limits	Helicopter winching	
wind speed	< 18m/s	<18m/s	<18m/s	< 18m/s	< 18m/s	< 10m/s	< 4m/s	<20m/s
cloud coverage	-	-	-	-	-	-	< 7	< 7
waves height	<1m	<2m	<1.5m	< 2.5m	< 3m	< 2m	-	-
waves period	-	< 3/s	-	< 3/s	-	-	-	-
wave direction*	-	< 40˚	-	< 40˚	-	-	-	-
wind direction*	-	-	-	-	-	-	-	< 40˚

*wind and wave direction are measured based on access location of the wind turbine

Recent research has also shown the applicability to represent safety rules using case-based reasoning approaches to model strategies for safety performance on construction projects (Pereira et al. 2018). This capability to formally represent safety rules combined with the possibility to stochastically model environment conditions (Jung et al. 2016) makes DEVS simulations potentially applicable to strategically plan infrastructure maintenance tasks under harsh conditions. This paper sets out to explore this utility by building and evaluating a DEVS model of the maintenance tasks for off-shore wind-farms, a maintenance task that is subjected to extremely harsh environmental conditions. Furthermore, off-shore wind farms lend themselves well to this study as researchers have suggested an abundance of DEVS models that can be used to develop a relatively stable baseline model to which H&S modeling aspects can be added. The next section described briefly the approach we took in building and evaluating this DEVS model.

RESEARCH METHOD AND MODEL BUILDING

Recent years have seen an increasing interest in developing models for simulating the off-shore maintenance process and several DEVS based models have been developed to understand the most effective maintenance strategies as well as very detailed aspects of the process itself (König et al. 2015) and the environmental conditions affecting the process (Hagen 2013). Drawing on this previous work, the case of off-shore wind farm maintenance lends itself well to build and evaluate a simulation model that integrates the aspects of health and safety constraints and environmental conditions.

To make use of the existing modelling experience, we started our model building effort with a literature review to identify detailed information about failure modes of wind turbines, different possibilities to transport service engineers to the turbines, and different environmental conditions that effect the maintenance process. We reviewed existing DEVS models and policy documents to build a model that stands on a solid basis. In particular, the abundance of existing DEVS models of off-shore wind farm maintenance activities were helpful to explore the aspects of H&S (Santos et al. 2015; Joschko et al. 2013; Joschko et al. 2014). Based on this literature review we identified the main influencing drivers of the maintenance process as input factors for building our DEVS model. These factors include information about the characteristics of the off-shore wind farm, such as the number of turbines, or the distance of the turbines from the respective service harbor, different choices for the means of transportation of maintenance engineers (smaller crew transfer vessels, larger service operating vessel, large service operating vessel with compensating gangway access systems, helicopters), and the environmental conditions influencing the maintenance process (wind speed and direction, wave height and direction, cloud coverage). Next to identifying the parameters for building the DEVS model, we also identified major key performance indicators for the strategic maintenance process of off-shore wind. The chosen indicators are accessibility of the turbines during maintenance, long-term availability of turbines for energy production, and mean time to repair a defective turbine. Additionally, for each of the selected transportation vessels we identified the existing safety requirements based on different weather conditions and formalized them within constrained based reasoning patterns (Table 1). Finally, common failure modes and failure patterns for off-shore wind turbines were identified and stochastically formalized (Table 2). Afterwards, we validated the identified parameters and key performance indicators together with three selected experts with experience in planning and controlling off-shore wind farm maintenance operations.

Table 2 - Off-shore wind turbines failure modes and requirements

	minor failure	major failure	inspection
probability distribution function	Poisson	Poisson	Poisson
expected number of occurrences – λ (turbine /year)	8.793	0.685	1
required transportation means	CTV* helicopter	HLV**	CTV helicopter
required number of service engineers	3	5	3
repair time	7	21	7

*CTV-Crew Transfer Vessel
**HLV – Heavy Lift Vessel

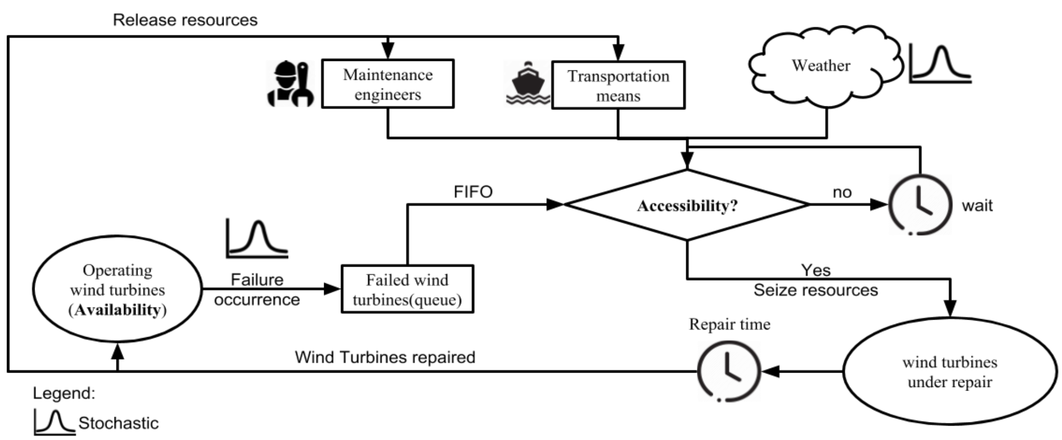

Figure 1 - DEVS framework

The final DEVS framework is represented in **Figure 1**. To illustrate the applicability of the DEVS simulation model to support health and safety informed decisions about maintenance activities we experimented with the model using different input scenarios as summarized in Table 3. The results of the experiments are discussed in the next section.

In detail, at every time step representing a normal work day of seven hours, the model simulated whether some of the turbines require maintenance based on the stochastic distribution of the failure probability and moves defective turbines to a repair queue. A specific working shift, operating under a certain operating strategy, repairs turbines from this queue using a first in-first out release pattern according to the specific capacity. This capacity depends on the probabilistic distribution of repair time and takes different weather constraints into account that are sampled for the specific time step from the probabilistic distribution of the weather factors. The model accounts for the number of maintenance engineers that can be transported to the off-shore wind-farm calculating the number of turbines that can be repaired during each time step. The duration of each repair activity is based on the travel and repair time accounting for the severity of the defect, the speed of the selected transportation means, and the distance to the off-shore farm. The entire model was implemented using the AnyLogic simulation platform.

Table 3 - DEVS setup and simulation scenarios input

1. Model Description				
	Simulation Time	*Simulation Resolution*	*Weather data resolution*	*Simulation Runs*
	3 years	1hour	24hours	150 times
2. Wind Farm Description				
	No. of turbines	*Distance base to windfarm*	*Location*	*Wind and wave data*
	80	50Km	North Sea	FINO1-weather station Helgoland
3. Transportation means				
	No. of vessels	*Vessel's speed*	*Capacity workers*	*Max. offshore time*
CTV	2	46Km/h(25kn)	12	1 shift
HLV	1	20Km/h(10kn)	60	unlimited
helicopter	1	300Km/h	4	1 shift
4. Repair workers				
	No. available	*Working shift*	*No. of daily shifts*	*Days of sick leave*
	20/shift	12 hours; 7 days/week	1	10/year

To illustrate the potential to inform decision making about maintenance procedure including health and safety constraints, we then conducted 150 simulation experiments. Each of the experiments simulated the maintenance activities for an exemplary off-shore wind farm in the North Sea with 80 wind turbines. For the experiments we assumed that 20 maintenance engineers are available for each maintenance shift. We chose to simulate the maintenance activities of the wind farm varying the choices for transportation mode over a period of three years, in time steps of one hour. We used weather data from the FINO1 weather station in Helgoland Germany. The set used for this experiment contain data collected between 2014 and 2016 and a sampling length of 30 minutes. Out of the entire collection we selected the parameters considered when making decisions about transportation means (Table 1) and chose custom probabilistic distributions for each. The next section discusses the outcomes of the experiments.

SIMULATION EXPERIMENTS TO UNDERSTAND HEALTH AND SAFETY RELATED ASPECTS

Figure 2 summarizes the outcomes of the experiments. Based on the simulation results, the largest accessibility to turbines for maintenance tasks (89.2%) can be guaranteed with a large transportation vessel in combination with a compensating gang way. Access by helicopter and large vessel without compensating gang way was only simulated at around 67%. Both values were surprisingly similar for the specific weather condition simulated. It seems as if cloud coverage conditions that are mainly influencing accessibility values for helicopters are compensated by wave conditions that influence the possibility for large vessels to access turbines for maintenance. The lowest accessibility was simulated for small catamaran vessels that only could access turbines in less than 50% of the cases.

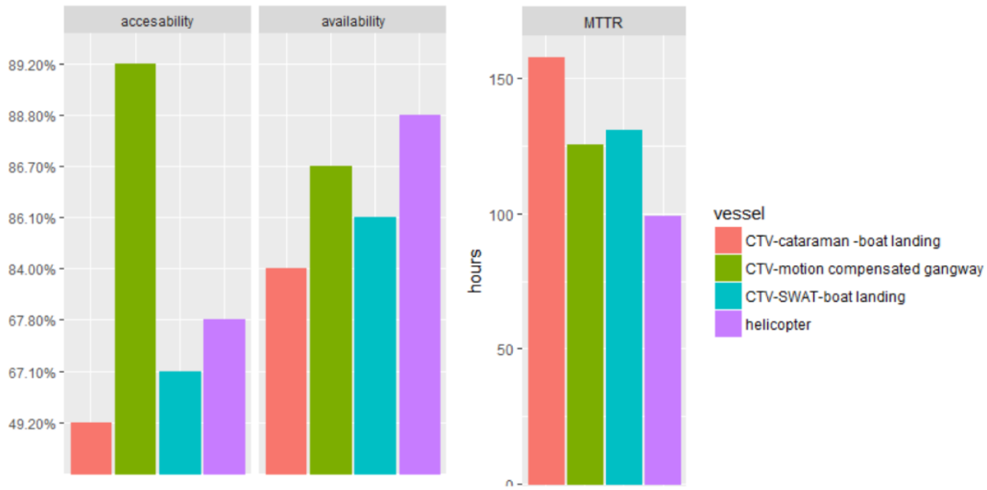

Figure 2- Mean values of the simulation outcomes according to the different KPIs

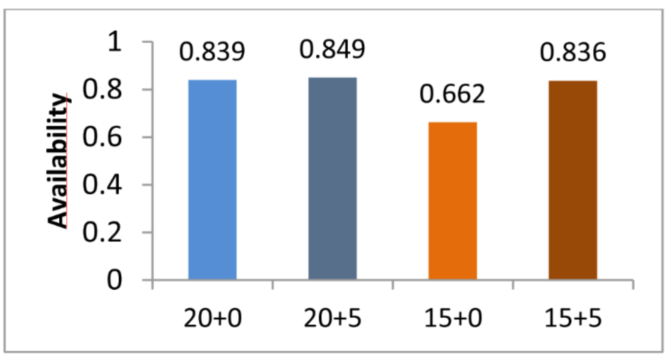

Figure 3 - Effect of number of regular workers and optional workers on the availability

Surprisingly, the simulation results for availability do not reflect the results obtained for accessibility. According to the simulation results, the highest availability of wind turbines within this condition can be achieved by organizing maintenance with helicopters, followed by large vessels with compensating gang ways, by large vessels without compensating gangways, by small catamaran-based vessels. Important here is to realize that the values for the simulation period of three years between the different transportation means do not vary much and all lie around 85%. This result would probably point towards choosing the economically most optimal solution among the four transportation means.

Finally, the results for mean time to repair show that crews that are transported by helicopter can repair defect wind turbines the quickest, followed by large vessels with a compensating gang-way, followed by large vessels without a compensating gang-way, small catamaran-based vessels. Again, these results are surprising and suggest that a provision of smaller vehicles would allow to reduce the required amount of service engineers.

Accordingly, we used the model to evaluate if it is reasonable to increase the number of workers temporarily in case of service bottlenecks. Figure 3 summarizes the results. It could be observed that those bottlenecks increase the mean time to repair. An optional team of five workers was implemented and the need for this team was checked on a daily basis. If positively checked the optional team was added next day to the regular team. If the regular team consists of 20 workers, an optional team of five workers results in a minor improvement of the availability, in average on 19 days per year. If the regular team consists of 15 workers, an optional team of five workers results in a major improvement of the availability, in average on 115 days per year. Generally, a high availability can only be increased with large effort. But, a flexible coverage of peaks in personnel requirements, in form of optional teams, can further improve the availability.

All in all, at times counter intuitive results of the simulation experiments show the potential of discrete event simulation to support strategic maintenance planning decision making tasks under consideration of harsh weather conditions and health and safety constraints. The above presented results would allow decision makers to choose the best transportation option for maintaining the specific wind farm we simulated. While making these decisions, the maintenance managers would be able to carefully balance their decisions accounting for different key performance indicators – in this case accessibility, availability, and mean time to repair. This potential for decision support that we illustrated could be probably further increased by the implementation of structured sensitivity analysis at the local input parameter level and at the global simulation level. The presented simulation itself could also be improved by further detail within the simulated processes and its relation to possible weather effect. These possibilities should be explored by future research studies.

CONCLUSION

This paper introduced a study which shows the potential of supporting the strategic maintenance decision making for infrastructure that is operated in harsh conditions under the consideration of health and safety constraints. Our study explored this potential at the example of off-shore wind farms by building a discrete event simulation and discussing simulation experiment results for an exemplary off-shore wind farm in the North Sea. The discrete event simulation was built drawing on a literature review and was validated by experts to increase the illustrative power of the research. All in all, the experimentation results show the potential to significantly support decision making tasks for infrastructure managers. Several rather counter intuitive results were found with the simulation that would have probably not been considered during normal maintenance planning.

REFERENCES

Golabchi, Alireza, SangUk Han, and Simaan AbouRizk. "A simulation and visualization-based framework of labor efficiency and safety analysis for prevention through design and planning." Automation in Construction 96 (2018): 310-323.

González, Vicente, and Tomás Echaveguren. "Exploring the environmental modeling of road construction operations using discrete-event simulation." Automation in Construction 24 (2012): 100-110.

Hagen, B., Simonsen, I., Hofmann, M., & Muskulus, M. (2013). A multivariate Markov weather model for O&M simulation of offshore wind parks. Energy Procedia, 35, 137-147.

Halpin, Daniel W., and Leland S. Riggs (1992). Planning and analysis of construction

operations. John Wiley & Sons.
Hsu, Pei-Yuan, Panagiotis Angeloudis, and Marco Aurisicchio. "Optimal logistics planning for modular construction using two-stage stochastic programming." Automation in Construction 94 (2018): 47-61.
Joschko, P & Widok, Andi & Page, Bernd. (2013). A Simulation Tool for Maintenance Processes of Offshore Wind Farms. 15th International Conference on Harbor, Maritime & Multimodal Logistic Modelling and Simulation, At Athens, Greece
Joschko, Philip & Widok, Andi & Appel, Susanne & Greiner, Saskia & Albers, Henning & Page, Bernd. (2014). Modeling and simulation of offshore wind farm O&M processes. Environmental Impact Assessment Review. 52. 10.1016/j.eiar.2014.09.009.
Jung, M., Park, M., Lee, H. S., & Kim, H. (2016). Weather-delay simulation model based on vertical weather profile for high-rise building construction. Journal of Construction Engineering and Management, 142(6).
König, M., Düster, A., González, D. F., & Abdel-Maksoud, M. (2015). Simulation of Safety-Relevant Situations Regarding the Interaction of Service Ships With Offshore Wind Turbine Plants. In ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering (pp. V007T06A044-V007T06A044). American Society of Mechanical Engineers.
Nassar, Khaled. "Integrating discrete event and lighting simulation for analyzing construction work zones lighting plans." Automation in Construction 17.5 (2008): 561-572.
Santos, Fernando & Teixeira, A & Guedes Soares, Carlos. (2015). Modelling and simulation of the operation and maintenance of offshore wind turbines. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability. 229. 10.1177/1748006X15589209.
Peng, Bo, Forest Lee Flager, and Jiaao Wu. "A method to optimize mobile crane and crew interactions to minimize construction cost and time." Automation in Construction 95 (2018): 10-19.
Pereira, Estacio, SangUk Han, and Simaan AbouRizk. "Integrating Case-Based Reasoning and Simulation Modeling for Testing Strategies to Control Safety Performance." Journal of Computing in Civil Engineering 32.6 (2018): 04018047.
Wainer, G. A. (2009). Discrete-event modeling and simulation: a practitioner's approach. CRC press.