Financial assessement and simulation of O&M costs of offshore wind energy projects

João Quirino Rosa Guerreiro

Department of Engineering and Management, Instituto Superior Técnico

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Abstract

The unavailability of land for the installation of onshore wind turbines and size constraints constitute key decision factors for investing in offshore wind farms. However, this type of technology has highly material, installation and operation & maintenance (O&M) costs. The use of larger turbines with higher electrical power and the optimization of the installation, operation and maintenance activities are expected to improve the financial performance of offshore wind projects.

In this context, the aim of the dissertation is to assess the financial performance of an offshore wind energy production project with maintenance costs estimated from Petri net models and Monte Carlo simulation.

First, a typical cost structure of an offshore wind project is defined based on available literature. Then, a Petri net model is developed for the turbine maintenance operations and its cost is evaluated by Monte Carlo simulation, taking into account the uncertainty in the equipment lifetime, maintenance time and other relevant logistics aspects. This more realistic prediction of the maintenance costs is later considered in the financial re-evaluation of the project. The study shows that is possible to obtain positive results for a 5MW capacity project, evaluated through the main financial indicators NPV, IRR and Payback.

Keywords: Project assessment, offshore wind energy, cash-flow, Petri net models, Monte Carlo Simulation, operation and maintenance costs.

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1. Introduction

Renewable energy came from the need to produce electricity in order to surpass certain environmental problems addressed in the Kyoto Protocol. Since then wind energy has been one of the most used renewable energy sources, because wind is an abundant and also inexhaustible resource that allowed great deployments of onshore turbines. The continuous investment in onshore wind power resulted in unavailability of land for the installation of new wind turbines. This together with size constraints of the onshore turbines has given the opportunity to move the technology to offshore (Esteban *et al.*, 2010).

The offshore wind energy has some advantages over onshore. The two main advantages are a larger available area for technology installation, and stronger winds (Da *et al.*, 2011).

However, offshore wind power projects are faced with high capital costs of their technologies, since the turbine and the support structure represent a large part of total costs to the project (Sun *et al.*, 2012).

Despite the dominance of onshore technologies in the European market, major investments in offshore wind power were made over the past decade. Countries like UK, Denmark, Netherlands, Belgium and Germany are responsible for developing this technology. In 2011, an investment of 866 MW in offshore wind energy has been made, representing about 9%

of total annual installed capacity of wind energy (EWEA, 2012).

In Portugal, the first offshore wind turbine was implemented near Póvoa do Varzim. It's a 2 MW Vestas capacity turbine distanced 5 kilometers from the northern coast of Portugal. This turbine has a patented foundation called WindFloat, a floating type structure that was installed in waters deeper than 40 meters (Maciel, 2010).

The main objective of this article is to perform a preliminary study for a possible investment in an offshore wind farm in Portugal, through the investor's perspective. A financial assessment of an offshore wind energy project is carried out first using cost models reported in the literature. Then a Petri net model is developed to simulate the repair needs and the maintenance operations of the offshore wind turbine. The OPEX (OPerational EXpenditure) costs are obtained by Monte Carlo simulation of the Petri net model, and then replaced in the baseline scenario for the calculation of new project financial indicators.

The paper is structured as follows: Section 2 presents relevant literature on the offshore wind energy, offshore wind technology, financial project assessment methods, availability and maintenance concepts and Petri nets models; Section 3 presents the life cycle methodology and costs structure; in Section 4, the Petri nets models are developed to simulate and calculate the maintenance costs; in Section 5 the projects are assessed and the results for the two different scenarios are compared and discussed. Finally, in section 6 some conclusions are presented.

2. Literature review

2.1. Offshore wind energy

The technology in offshore wind structures is subjected to adverse weather conditions, so it needs to be reliable to ensure normal operation of all equipment (Green & Vasilakos, 2011).

In spite of the disadvantage cost of offshore wind energy, when compared to onshore, offshore wind energy has an advantage in scale and also in power generation efficiency (Akimoto *et al.*, 2011).

In order to study the construction of an offshore wind farm is necessary to take into account technical and financial aspects. The main factors to be considered are:

- Turbines;
- Foundations;
- Water depth;
- Distance to the coast;
- Rate Power/ rotor diameter;
- Vessels;
- Electrical Grid;
- CAPEX;
- OPEX;
- Energy production revenues.

Turbines

Responsible for the generation of electrical energy, turbines have to be installed offshore with special cranes. Turbines are divided in HAWT with horizontal axis, VAWT with vertical axis, and FAWT with a floating axis (Akimoto *et al.*, 2011).

This paper is focused on HAWT WindFloat/ Repower since it has a proper foundation for deeper waters and also has the main costs of a Repower 5MW wind turbine for following life cycle cost model.

Foundations

Foundations support the turbine rotor and are composed by the tower and basis. They need to resist to strong wind and strong waves (Sun *et al.*, 2012).

The different designs are Monopiles, Tripods, Jacket, Gravity, and can be built onshore, like the WindFloat (Chen *et al.*, 2011).

Water Depth and Distance to shore

Water depth influences negatively foundation and installation costs. Larger a distance to shore increases installation and electrical costs (Bilgili *et al.*, 2011).

Rate power/Rotor diameter

Increasing rotor size and electric power, increase project costs, but decrease operational, maintenance, installation, and electric grid related costs (Musial & Ram, 2010).

Vessels

Are responsible for the turbine transport, installation, and maintenance for both turbine and foundation. Vessel types are jack-up, self-propelled, semi jack-up and cranes. (Tarelko, 2012)

Electrical Grid

Provides the electric current to the final use and is composed by the cables that conduct electricity. This cables should not be away from the shore, as the distance increases the electric grid costs.

CAPEX

Capital expenditures that aspire the benefit in at least a year, *i.e.* initial investments that compose the project active. They include equipment acquisition costs and technology installation costs (Levitt *et al.*, 2011).

OPEX

Operational costs and maintenance necessary for the project continuity (Levitt *et al.*, 2011).

Energy production revenues

Revenue of the offshore wind energy project from both electrical energy production and green certificates.

2.2 Petri Nets

Petri nets are graphical structures with three basic elements: states, transitions, and directional edges (Figure 1).

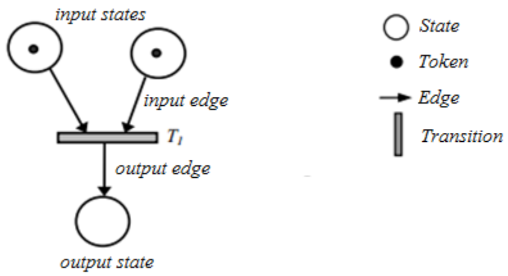

Figure 1 – Elements of a Petri Network (adapted from (Teixeira & Guedes Soares, 2009))

A state represents the system components at a certain moment, transitions are associated with events that change the state, and edges connect a state to a transition and vice-versa. The present state of the system is marked with a token.

Changes in states are acknowledged by a destruction of the token in the input state and a creation of a new token in the output state.

Through Monte Carlo simulation of the Petri model is possible to obtain the system availability, productivity efficiency, and operation and maintenance costs.

3. Cost Model and LCC

To assess the financial performance of an offshore wind energy project it was chosen the *WindFloat*/*REpower* technology of 5 MW and is achieved with the Petri model for the evaluation of maintenance costs through the Monte Carlo simulation.

This project is to be set in the coast of Póvoa do Varzim, in the north of Portugal and, as Table 1 shows, there has been an aggregation of useful data.

Table 1 – Project's main data

Project's Data	Value	Unit
Turbine Power	5	MW
Project Life Cycle	20	Year
Price of Energy	168	€/MWh
Distance to shore	6	km
Water Depth	40 a 50	m

To evaluate the feasibility of an offshore wind energy project one must look for a long term perspective, make comparisons, and choose the best alternative. By calculating the Life Cycle Cost (LCC) is possible to decompose the various stages from the initial phase to the dismantlement of the project. Using the EN 60300 norm is possible to identify five stages:

1) Conception/Design;
2) Construction/Acquisition;
3) Installation;
4) Exploitation;
5) Dismantling.

The total cost of the project is calculated by:

$$CT = C1 + C2 + C3 + C4 + C5$$

Conception/Design Costs – C1

Part of the investment cost, Conception and Design denotes the various impact studies inherited to the project. Is presented by the following formula:

$$C1 = C11 + C12 + C13 + C14 + C15 + C16$$

where:

Table 2 – Conception/Design costs of an offshore wind energy park (BVG Associates, 2010)

Parameter	Cost	Amount (€)
C1	Conception/Design	2 645 250
C11	Environmental studies	48 500
C12	Seashore investigation studies	540 000
C13	Meteorological studies (including station)	1 800 000
C14	Bathymetry studies	144 750
C15	Technical studies of Front End Engineering and Design	12 000
C16	Social impact studies	100 000

Construction and Equipment Acquisition Costs – C2

C2 contains all equipment costs whether they are manufactured or purchased. The detail of these costs of the equipment is broken down according to the price of various materials to the turbine, foundation and electric grid. They are calculated by the formulas:

$$C2 = C21 + C22 + C23$$

$$C21 = C211 + C212 + C213$$

$$C23 = C231 + C232 + C233$$

where:

Table 3 – Project's Equipment Cost Parameters

Parameter	Cost	Amount (€)
C2	Equipment	11 302 000
C21	Turbine	6 011 000
C211	Nacelle	3 000 000
C212	Rotor	1 811 000
C213	Tower	1 200 000
C22	Foundation	3 600 000
C23	Electric Grid	1 691 000
C231	Offshore Converter	604 000
C232	Onshore Converter	483 000
C233	Electric Cables	966 000

Installation Costs – C3

Installation costs include the assembly costs of all equipment at *C2*, such as the cost of the turbine installation, the foundation and of the electric grid components, given by the following formula:

$$C3 = C31 + C32 + C33 + C34$$

where:

Table 4 – Offshore Wind Energy Park's Costs of 5MW

Parameter	Cost	Amount (€)
C3	Installation	4 707 700
C31	Turbine Installation	1 690 000
C32	Foundation Installation	1 207 000
C33	Converters Installation	120 700
C34	Cable Installation	1 690 000

Exploitation, Operation, and Maintenance Costs – C4

O&M costs consider all vessels and man work that are included in the maintenance operations activities. An annual cost of 677k€ were considered for each turbine in the project.

Dismantling Costs – C5

Dismantling occurs in the final stage of the project and it has a cost of 1,8M€ on last year. This is the stage for the cleaning operations and disposal removal and taking off all equipment.

Energy Production/ Revenues

Wind energy production is influenced by the speed and consistency of the wind itself and also by the wind turbine power curve. Each wind turbine has its own shape.

It was considered that the wind turbine of 5MW has an annual energy production of 2193,26kW, which has a 44% load factor. It also means a 3,1M€ per year revenue.

Discount rates

Discount rates for offshore wind technology have an 8%-15% range. A higher rate means the project has a higher risk. A 10% discount rate was set for project in study (Entec UK Ltd , 2006).

Offshore wind project summary

The Table 4 shows all important parameters for the offshore wind project.

Table 5 – Offshore wind project main data

Project Data	Values
Turbine	5MW
Life Cycle	20 years
Distance to shore	6 km
Distance to port	12 km
Water depth	40 a 50 m
Wind speed (*Weibull*)	8,55 m/s
Energy Price	0.168€/kWh
Capacity Factor	44%
Grid losses	2%
Turbine availability	98%
Initial Investment	18 654 950 €
Annual O&M cost	677 000 €
Dismantling costs	1 800 000 €
Debt (70% Inv.)	13 058 465 €
Interest rates	5,4%
Loan maturity	15 years
Taxes	30%
Discount rate	10%

4. Petri Nets modelling

In this chapter a Petri bet model is developed to estimate maintenance costs and availability of the wind turbine. This is done by constructing a Petri Nets to simulate corrective maintenance of an offshore wind turbine of 5 MW. This model is developed only for the turbine maintenance of four major components: rotor, generator, gearbox and pitch system. The model includes all replacement cost, labor work and vessel mobilization dependent on each element.

Further, uncertainty on the components' time to failure and repair times are included in the model to calculate the turbine availability.

4.1 Reliability, Availability and Maintenance Reliability

Reliability refers to the probability of an element or system to perform its function in a certain period of time. It is given by (Lewis, 1994):

$$R(t) = \int_{t}^{\infty} f(t)dt$$

Maintainability

Maintainability is the concept that allows to measure the system's repair process and it is given by the following formula (Lewis, 1994):

$$M(t) = \int_{0}^{t} m(t')dt'$$

Availability

Availability measures if a reparable system is likely to be available for use at any given time. It may be also considered as the percentage of time that the system is operating. This concept allows to measure the performance on maintaining and repairing a system (Lewis, 1994).

The availability can be expressed in the formula:

$$A^{*}(T) = \frac{1}{T}\int_{0}^{T} A(t)\, dt$$

4.2 Maintenance of offshore wind project

In the maintenance process it is assumed that the turbine is the only equipment to fail, so it is based on corrective maintenance, *i.e.* repair only occurs on the equipment at the time of a failure.

The four turbine components need to be repaired in the turbine life cycle and different ships are needed to replace each part: jack-up, crane, and supply.

For each maintenance operation it is always necessary to have at least one supply vessel in each operation. The supply vessel has all maintenance crew responsible for the operation. If it is necessary to maintain a jack-up vessel or crane, the operation is performed with the support of supply ship. The crew and the parts required for replacement of the four components of the turbine are allocated in the supply vessel. (Santos *et al.*, 2013)

The maintenance team works every day and it is requested on 12-hour shifts, depending on availability of spare parts, boats and weather conditions. The supply vessel has to return to port each time the maintenance operation outlast the round of 12 hours. The remaining boats are kept in the turbine to finish the repair/replace operation of the equipment.

Supply Vessel

Supply vessel can carry the pitch system when a replace is necessary. In spite of this factor, the role of this vessel is mainly of support for the other vessels.

Jack up Vessel

Vessel used to carry large loads of equipment and it is capable of supporting a rotor of a 5 MW turbine. It weighs between 90 to 150 tons. This ship is slower comparing to other vessels, so it's used for carry heavy equipment like a rotor.

Crane Vessel

This vessel is widely used for offshore wind maintenance operations since it allows transportation of much of the parts, with the exception of the rotor. It can carry generators and gearboxes that can weigh between 20 and 65 tons, dispensing the use of the jack-up ship that is slower and has higher mobilization cost.

Table 6 shows all vessel logistic and traveling times.

Table 6 – Vessel Traveling and Logistic time

Vessel	Traveling time	Logistic time
Supply	0,6 hours / 0,025 days	48 hours/ 2 days
Crane	0,8 hours / 0,033 days	160 hours / 6,67 days
Jack Up	1,2 hours / 0,05 days	504 hours / 21 days

Weather conditions

The incidence of bad weather and the waiting time for the vessels to perform repairs are seasonal factors, *i.e.* it depends on the year seasons. Table 7 presents a data survey to the probability of having good sea conditions to sail and also has the average waiting times for each season. It is noted that in summer weather conditions are more favourable.

Table 1 – Weather conditions and waiting times of seasons (Santos *et al.*, 2013)

Year Seasons	Probability of having good sea conditions	Waiting time (days)
Winter	0,3	10
Autumn	0,5	7
Spring	0,6	5
Summer	0,8	2

MTTF and MTTR

The turbine is defined as a system in series, which means that if a single component of the turbine fails, the whole system stops functioning.

Mean time to failure (MTTF) were considered for each component based on Weibull parameters, as seen in Table 8.

Table 8 – MTTF of each turbine component

Component	MTTF (days)
Rotor	2679
Gearbox	2143
Genarator	2925
Pitch	1659

Mean time to repair (MTTR) was estimated based on Exponential parameter. MTTR is directly associated to the vessels performance on replacing a component.

Table 9 – MTTR of each vessel

Vessels	MTTR (Exponential)
Supply	0,42 days / 10,1 hours
Crane	2,08 days / 49,9 hours
Jack Up	1,67 days / 40,1 hours

O&M costs

Three different types of costs can be considered: replacement costs, mobilizing costs and operating costs.

The replacement costs for the equipment are given in Table 10, given in unit cost(€).

Table 10 – Replacement cost of each equipment

Equipment	Unit Cost (€)
Rotor	1 849 000
Gearbox	863 000
Genarator	247 000
Pitch	123 300

Mobilizing and demobilizing are associated to the vessel rent. These costs are only for crane and jack-up vessel, seen in Table 11.

Table 11 – Mobilizing and demobilizing costs

Vessel	Mobilizing and demobilizing costs (€)
Crane	45000
Jack-up	57000

Operational costs are converted from hour's maintenance costs into costs by operation, by considering the vessels mean time to repair. The values are shown in Table 12.

Table 12 – Operational costs

Vessel	Cost by operation (€)
Supply	6050
Crane	312000
Jack-up	250500

4.3 Modelling Petri Nets

The first step to model Petri nets is to characterize all seasons, represented in Figure 2. Each state represents a season and the seasonal changes are represented with a deterministic transition in daily values (Dirac function). Both autumn and winter last 91 days, while spring and summer last 92 days.

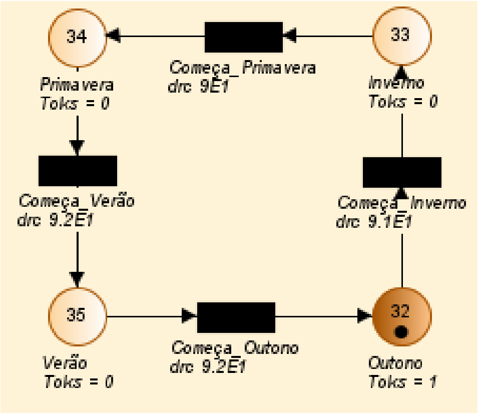

Figure 2 – Petri net for year seasons

For maintenance data, each state features four components of the turbine. The turbine components can be represented by three states: working, failure and repairing.

Figure 3 shows the various states of the rotor and its constraints, the rotor only transits from state 1 to 2, after the average failure time of 2679 days.

The beginning of the equipment repair, despite a deterministic duration to zero (Dirac function), only triggers when the Boolean variables: JackUp_Turb and Equipa_oper are True. Which means that maintenance operation cannot be done without the presence of jack-up vessel on the turbine and without the maintenance team in operation.

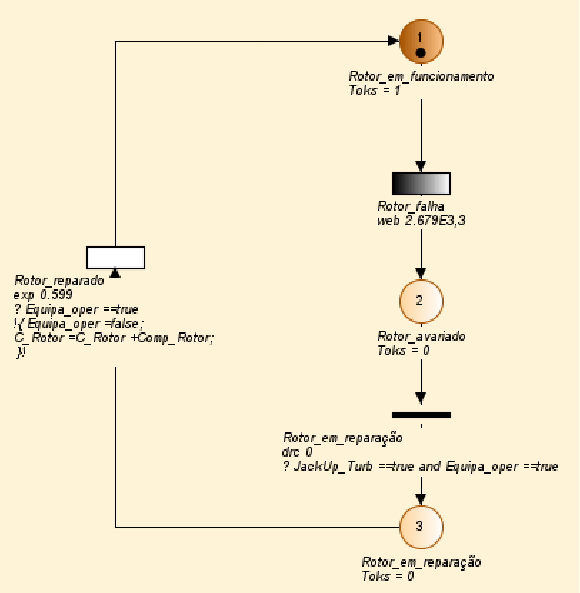

Figure 3 – Petri net for the states of rotor

Every time the maintenance staff leaves the operation, the maintenance stays on standby until the next shift of the team. They work in 7.5 hours shifts and their presence is essential to finish the replacement.

In the transition, the rotor presents a repair rate of 0.599 days^{-1} for an exponential distribution. When the process ends, the state changes to "working", thereby the variable Equip_oper changes to "false" and updates the value of the variable cost C_Rotor by adding a replacement cost.

The other components have a similar Petri net modelling, differing in the Boolean variables that guards each vessel operation.

To calculate the total availability of the wind turbine, it was built a petri net with two states for turbine: working and failure, shown in Figure 4.

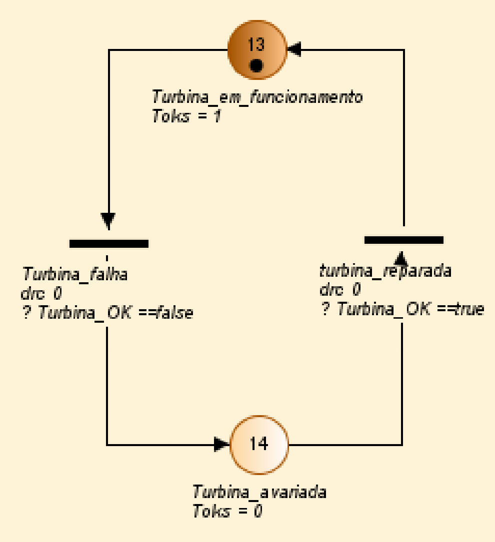

Figure 4 – Petri net for the turbine states

Turbina_OK is the variable that allows to measure the new availability of the turbine, because the simulated Boolean variables assume the value zero for false and one for true. The average value obtained in the end of the life times is represented as percentage. Having this variable on guard with a zero Dirac, means that the system will automatically turn to failure every time that any of the 4 tokens leave the working states (1,4,7,10) for rotor, gearbox, generator and pitch.

The activity of the jack-up can be seen in Figure 5. There is a Boolean variable Rotor_OK that needs to be true to mobilize the vessel. This variable is programmed with the command "ite (# 1 == 1, true, false)". "Ite" is a statement for if then else, so in this case the token is allocated in the state 1 (Turbina_em_funcionamento), the variable takes the value true, otherwise is set to false.

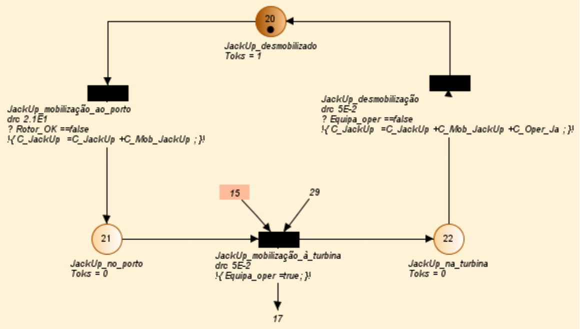

Figure 5 – Petri nets for the states of the jack-up

When the token is in the state # 21 (JackUp_no _porto), the variable C_JackUp is updated by adding the cost of mobilization. This variable are also added up the operational and demobilization cost in the assignment of JackUp_desmobilização transition. The JackUp_mobilização_à_turbina transition can only be executed when there are token in the elements 15, 21, 29. Elements 15 e 29 can be seen in the Petri networks for maintenance team and favorable sea events.

Figure 6 shows the states for the sea with two possible targets: one with the operational sea Tempo_operacional and another with non-operational sea Tempo_não_operacional. The transaction to the targets are made randomly follow by the probabilities in Table7. If the token appears on sate 28 it will have a waiting time before transacts to the operational sea state 29.

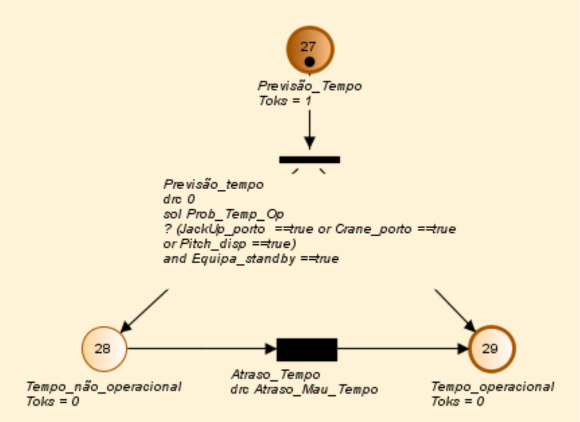

Figure 6 – Petri net for the states of sea

In the maintenance team, an initial state of the team is in stand-by state 15, once the team is located on port where it is ordered to go to the turbine. Figure 7 presents the Petri network maintenance team. The structure of the team varies greatly during the maintenance process, hence it is necessary to insert several states. The reference state is 17 Equipa_Man_em_trab that two possible paths. The piece was repaired which means the destruction of the token 17 and creation of new tokens in states 19 and 27 and the last part was not repaired. The token 17 is also destroyed and it creates a new token in place 18.

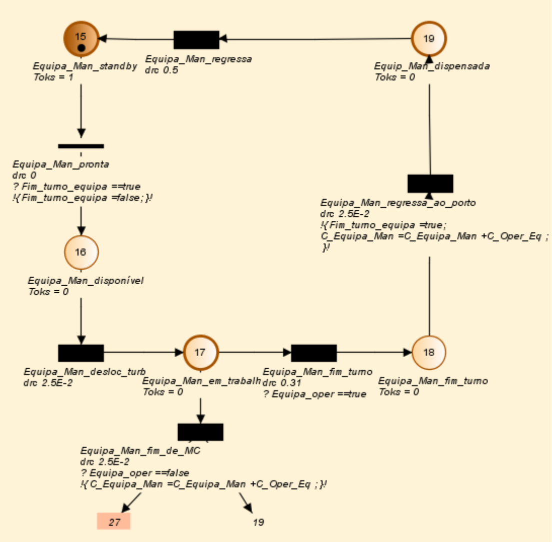

Figure 7 – Petri net for maintenance team

Simulation results

Through Monte Carlo simulation of the Petri model for a 20 years period it was possible to obtain new maintenance costs and system availability.

The results of the Monte Carlo simulation were obtained through 5,000 histories for a period of 7300 days (365x20). Table 13 presents the average value of cumulative costs registered in year twenty.

Table 13 – Simulation results

Variable	Value (t=20years)
Turbina_OK	97.40%
C_Crane	2033610
C_Equipa_Man	473095
C_Gearbox	2536870
C_Gerador	522454
C_JackUp	827723
C_Pitch	510905
C_Rotor	4195380

These variables allow to obtain two new important indicators for the project: Turbine availability and annual maintenance costs, seen in Table 14.

Table 14 – Indicator of Petri nets model

Indicators	Value
Turbine availability	97.40%
Total maintenance cost	555 000 €/year

Parametric study

This section presents a parametric study of Petri nets model for maintenance operations. The goal is to understand the behaviour of the annual maintenance costs and system availability by changing the MTTF and MTTR of each turbine component.

The increasing of MTTF has a positive influence on the indicators, since the turbine components fail less. So it means a decreasing of annual maintenance costs and an increasing of turbine availability, as seen in Figure 8 for MTTF rotor.

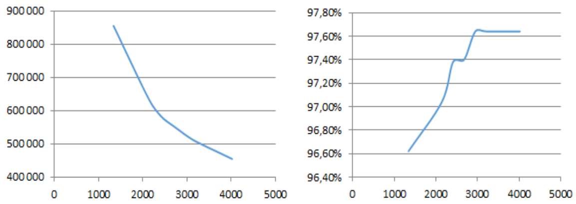

Figure 8 – MTTF rotor vs annual cost and availability

By contrast, the increasing of MTTR has a negative influence on the indicators, since the turbine components take longer to repair. So it means an increasing of annual maintenance costs and a decreasing of turbine availability, as seen in Figure 9 for MTTR rotor.

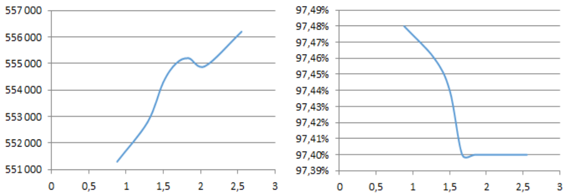

Figure 9 - MTTR rotor vs annual cost and availability

5. Results

5.1 Financial project assessment for baseline scenario

The project assessment was made based on three indicators: NPV, IRR and Payback. The Table 15 shows the indicators for the LCC model.

Table 15 – Indicators of LCC model

Indicators	Value	Units
IRR	13,01	%
NPV	1 205 885	€
Payback	8	Years

It was not expected a high financial performance for a small project. Larger wind farms help to mitigate the effect of large investments by reducing the cost per energy project (Sun, Huang, & Wu, 2012).

5.2 Financial project assessment for new maintenance scenario

The feasibility of the project, was recalculated by replacing in the cash flow the operating and maintenance costs of the baseline scenario. These costs were calculated by the Monte Carlo simulation of the developed by Petri model. Also, the value of annual revenues has changed given the loss of turbine availability.

The new annual values for revenues and O&M costs are 3,080,978€ and 555,000€, respectively. The project assessment of this new scenario was performed with the same values of the baseline scenario, with the exception of these two mentioned.

Table 16 shows an expected improvement of the indicators.

Table 16 – Indicators of new maintenance model

Indicator	Value	Units
IRR	14,38	%
NPV	1 764 025	€
Payback	6	years

This project turns out to be more attractive for the investor, since the Payback and NPV values have improved. In spite of increasing the IRR, there is still a risk of taking a project with an IRR in the range the discount rates 8-15%, used in offshore wind projects, given the uncertainties in this type of projects.

6. Conclusions

The objective of this work was to carry out a financial analysis of investing in a wind energy offshore project, using cost models supported by a literature review and maintenance simulation by Petri net models. The Petri net models allowed to calculate new maintenance costs and measures of turbine availability by Monte Carlo simulation.

The LCC based cost model allowed to obtain a Net Present Value for the 1,2M€ for the project's baseline scenario. The project is feasible but risky nevertheless, because of its 8 year Payback and 13,01% value for IRR. The risk associated with the wind energy offshore projects can reach values between 8 and 15%.

The primary adversities of the offshore wind energy are the high investment costs for the turbine and support foundation, and the uncertainties on maintenance and operational costs. Maintenance and operational costs uncertainty can be analysed and reduced through the development of simulation models of the maintenance activities required after failure of the wind turbine elements.

For the turbine's corrective maintenance model, the annual cost was 555000€ and 97,4% of availability. By parametric studies on the effect of MTTF and MTTR values of each component, it was possible to identify the tendency for the availability indicators and maintenance annual cost. Availability tends to grow and the annual O&M cost tends to decrease, as the MTTF grows. The opposite happens for the MTTR, which tends to increase the annual maintenance cost and reduce the availability value, as it grows.

In the end, the project's uncertainty was lightly mitigated when the maintenance costs were recalculated for the new maintenance scenario. This allowed the NPV to be over 1,7M€, due to the maintenance cost reduction. In this project, Payback and IRR were 6 years and 14,38%, respectively. It should be noted that, although the improvements, the IRR is still in the reference limit, as uncertainty plays an important role in this type of projects.

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