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# Availability Analysis of an Offshore Wind Turbine Subjected to Age-Based Preventive Maintenance by Petri Nets

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**Abstract:** This paper analyses the production availability and the associated maintenance costs of an offshore wind turbine with a horizontal axis configuration using Petri Nets modelling with Monte Carlo Simulation. For this purpose, different features are implemented: the reliability and maintainability characteristics of the components; the logistics of the production and maintenance operations, including different types of vessels, the mobilization time, costs and weather window. The maintenance strategies consist of corrective maintenance and age-based imperfect preventive maintenance that depends on the components' age and age reduction ratio. Thereby, to increase the operating income and to reduce the costs associated with the operation and maintenance activities, the optimal parameters of the age-based preventive maintenance are estimated. As a case study, a generic offshore wind turbine that operates at the Viana do Castelo wind farm in Portugal is adopted. The wind farm is located 18 km off the shore. The turbine's total exploration life is 25 years.

**Keywords:** age-based preventive maintenance; Monte Carlo Simulation; offshore wind turbine; Petri Nets; production availability assessment



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## 1. Introduction

An offshore wind turbine (OWT) is a complex production system that includes various engineering disciplines. Today, the total offshore wind farm capacity is approximately 18.9 GW and the installation rate has grown in recent years [1]. To improve the turbine's performance, an availability assessment is required, since it is able to evaluate the impact of the equipment reliability and maintainability qualities on the system productivity.

The main challenges in the production optimization and in maintenance planning are the realistic representation of the system's behaviour main characteristics and the implementation of the interactions and dependencies among various components of the same production system [2,3]. The classical reliability tools, starting from the identification of failures with Failure Mode and Effect Analysis [4,5] and including the Reliability Block Diagram, the Fault Tree and the Event Tree, [6,7] are not appropriate for analysing industrial production systems, since they do not take into consideration the interdependencies between the failures, which require other tools [8]. The dynamic interactions between operation and maintenance (O & M) decisions are relevant to be modelled, too [9]. The classical reliability tools use the concept of Boolean algebra, in other words, they are convenient to assess rare events with serious consequences, while the dependability analyses are able to assess more likely events but with low effects on the operation [10].

Markov modelling is an effective tool for the mathematical representation of component failure interactions and systems with independent failures [11–13]. Castanier et al. [14] proposed a Markov decision process to determine the optimal maintenance and operation policy of an offshore wind farm considering the stochastic wind and weather conditions. Li et al. [15] assessed the reliability of OWT's Gearbox and formulated the optimal maintenance policy by using Markov process. The main limitations of Markov modelling are:

the state-explosion, because the increasing of the system automatically takes to the high expansion of the number of states, and the assumption of fixed repair and failure rates, because this limits its application to simple systems with exponentially distributed events [13]. Thus, to represent the complexity of a production system considering all the interactions and dependencies among the sub-systems, various authors use simulation techniques, e.g., Bris [16] and Santos et al. [17].

Zio et al. [18] proposed a Monte Carlo Simulation (MCS) model for availability assessment of a multi-state and multi-output offshore installation. It was shown that Monte Carlo simulation can describe the uncertainty of various production system features, such as: the degradation of the system components, the corrective and preventive maintenance policies with pre-defined repair priorities, and the limited number of repair teams. MCS approach has proven to be an adequate tool to model continuously deteriorating systems and to determine the “on-condition” maintenance plan that minimises the expected total system cost over a specified mission period [19]. Condition-based maintenance is becoming increasingly more relevant for this type of equipment [20,21].

Petri Nets (PN) is a tool that combines graphical and mathematical modelling capabilities to simulate and analyse discrete event systems [22]. It was developed in 1962 by Carl Adam Petri in his Ph.D. dissertation [23]. The main objective of his study is to find an efficient way to model several competing or co-operating processes using graphical representation. Recently, different techniques based on the Stochastic Petri Nets (SPN) have been developed to improve the modelling of real and complex production systems [24,25].

Due to the complexity of the stochastic evolution of real systems that is not easily captured by analytical models [26], their application to quantitative analyses of SPN is rather limited [27]. To overcome this difficulty, techniques based on SPN combined with Monte Carlo simulation have been proposed for modelling and analysing the complex behaviour of industrial multi-unit systems regarding their reliability, availability and production efficiency [9,22,24,28].

Santos et al. [29] modelled an offshore wind turbine located at the North Sea close to the German shore combining SPN and MCS in order to assess the operation behaviour and maintenance policies. The reliability characteristics of OWT’s components were based on typical onshore reliability data provided by Ding and Tian [30]. Using SPN coupled with MCS, Santos et al. [31] presented a parametric study on the availability, operation, and maintenance costs of OWT.

The effect of age-based preventive maintenance on the availability and maintenance costs of offshore wind turbines [32] and oil and gas production systems [33] has also been assessed through SPN and Monte Carlo simulation. To build the failure models of the offshore components, the onshore data were used considering an empirical approach based on stress factors for mechanical systems.

An individual wind turbine is basically a multi-state system composed by several major components in a series configuration (i.e., Gearbox, Generator, Pitch System, and Rotor). Many industrial/real systems are characterised by series-parallel structures that have been widely investigated [34]. A production system can be classified as either the series-parallel (s-p) or the parallel-series (p-s) system [35]. In reliability and maintenance assessments, various industrial and production systems belong to s-p class (e.g., water supply systems and production lines in manufacturing factories) [36,37]. Besides, s-p class is used to represent in simplified mode the main sub-components of the total engineering system. Kawauchi and Rausand [38] and Bris et al. [39] provided this approach to estimate a performance measure (i.e., “production regularity”) of the system, and to minimise the preventive maintenance cost, respectively.

Usually, the availability assessment of an OWT production system adopts the simplified maintenance policy. In the implementation of reliability characteristics, it is common to model only critical failures, considering every equipment as a binary system (i.e., either as good as new or failed). Besides, in the assessment of age-based preventive maintenance, the age-reduction ratio and the repair threshold parameters are typically fixed and not opti-

mised. In order to increase the OWT availability, Sobral et al. [40] proposed a methodology to weight the influencing factors, considering operational and maintenance data, distance to shore, water depth, site accessibility, meteorological and oceanographic factors. Kang and Guedes Soares [41] introduced the conditional-based maintenance strategy based on the support vector machine algorithm to optimise the maintenance arrangement of OWTs.

According to Nielsen and Sørensen [42], the operation and maintenance (O & M) costs of offshore wind turbines are major contributors to the price of energy and can reach 30% of it. Castro-Santos et al. [43] indicated that in terms of the life-cycle of OWT, the higher cost corresponds to the exploitation period (i.e., insurance, administration, operation, and maintenance), followed by the manufacturing and installation periods. The maintenance and equipment replacements are dependent on the weather windows [44]; thus, the correct planning of O & M activities in advance is important to minimise the expected outlay over the turbine's lifetime. Besides, the distance to shore must be also considered, since it influences the investment, operation, and maintenance costs [1]. Castro-Santos et al. [45] assessed the economic feasibility of offshore wind farms based on the meteorological data, bathymetry, and distances between wind farm-shore, -shipyard, and -port.

To minimise the maintenance costs of offshore wind farms, Kang and Guedes Soares [41] introduced an opportunistic strategy considering imperfect maintenance and the weather window effects, using the rolling horizon approach. Castro-Santos et al. [46] compared in economic terms the offshore wind farms with other alternatives to harness wind and wave energies, such as floating offshore wave energy devices, floating offshore co-located systems, and floating offshore hybrid systems.

The main objective of this paper is to develop a framework capable to assess the effect of an age-based preventive maintenance on the availability of an OWT with horizontal axis configuration by Petri Nets and Monte Carlo Simulation. For this purpose, two variables are highlighted: the equipment age reduction ratio and the time threshold between maintenance interventions based on the component's age. The variation of both allows to visualise the effects of maintenance policy on the production system availability and associated costs. Besides, it provides the tool capable to identify adequate values that provide a balance between production availability and costs. As a case study, a singular OWT that operates at the Viana do Castelo wind farm in Portugal, located 18 km off the shore, is used. The total exploration life of the turbine is 25 years. The present case study adopts a parallel-series system (i.e., wind farm, thus, p-s) composed of p subsystems in parallel (i.e., one wind turbine, thus, p = 1), each of them with s components in series (i.e., four degraded components, thus, s = 4). The modelled degraded components (i.e., Rotor, Gearbox, Generator, and Pitch System) have the higher influence on the total system availability [47].

Based on empirical offshore reliability data provided by Santos et al. [32], the equipment definition is based on the reliability and maintainability stochastic characteristics that follow non-exponential distributions. In addition to as good as new and failed conditions, the degraded states of the components are also considered. Thereby, three types of failure are modelled: incipient (i.e., the transition from as good as new state to degraded one), degraded (i.e., the transition from degraded state to failed one), and critical failure (i.e., the transition from as good as new state to failed one). The maintenance policy is divided into three categories based on [48]. These categories differ on the weight of the repaired equipment and, therefore, the involved logistics.

The Corrective Maintenance (CM) intervention encompasses the manufacture time of a new component in a factory, the transportation time from the supplier to the port, and the replacement of the damaged equipment by a new one on the OWT [48]. The Preventive Maintenance (PM) strategy is age-based and imperfect. Each PM activity reduces the equipment age by a ratio  $q$ , and it is performed when the component's age reaches at least  $p \times \text{MTTF}$  hours, where  $p$  is a threshold parameter and MTTF is a Mean Time to Failure of the equipment [30,32]. Both,  $q$  and  $p$  are the main input variables that influence the O & M costs. Thereby, the main PM parameters are optimised to obtain the lower costs and higher income

(i.e., the higher accounting rate of return). Both corrective and preventive maintenance activities can be subjected to the time delay due to adverse weather conditions [29]. All vessels required for maintenance activities are anchored in Portuguese harbours.

This paper mainly consists of two parts. The first one is Materials and Methods. This section starts with a brief introduction of the main elements of Petri Nets. Next, the case study description is presented, explaining in detail the production configuration and component failure data of OWT’s equipment. A special attention is given to the maintenance policy delineation with a clear description of CM and PM activities. The implemented models of costs and weather window are formulated. The PN models of equipment, total system switch, PM, seasons, and vessels are described step by step. At the end of the section, the main cost models for economical assessment are presented. The second part of the paper is Results. In this section the age-based PM parameters are derived based on economical assessment, availability assessment, and sensitivity analysis. The obtained results are discussed.

## 2. Materials and Methods

### 2.1. Petri Nets

Petri Nets (PN) is a generic name for modelling tools that can represent a complex production system graphically. PN are divided into three categories [49]: the Elementary Net Systems for small size system representation; the Place/Transition Systems for a more compact representation of the Elementary Net Systems models; Predicate/Transition Nets or Coloured Nets for even more compact representations of real applications using algebraic and logical elements.

In Figure 1, the basic graphic elements of the Place/Transition System (i.e., place, transition, token, and arc) are presented [50].

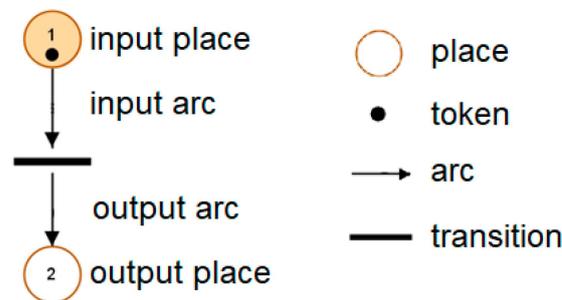


Figure 1. Basic elements of Petri Nets.

The place is represented by circles, it models the system’s states or resources. The transition is represented by rectangles and it is used to model the events (e.g., system failure) that influence the available resources. The token is a small black dot that represents the resources. The token is always held inside the places. The arc is represented by directed arrows that specifies the interconnection between the places and transitions, and indicates which states are changed by a certain event.

The positioning of the token in the place, called by marking, defines a specific state of the system. In the case of system state change, the transition moves the tokens to new places or removes them in accordance with the arcs’ directions. This property enables the simulation of dynamic systems [34]. The Place/Transition net is a bipartite graph, thus, it is only possible to connect Place-Transition or Transition-Place, meaning that neither Place-Place nor Transition-Transition are acceptable connections [51].

Another frequently used tool is the Generalized Stochastic Petri Nets (GSPN) with predicates. This tool has more computing power than conventional Petri Nets and allows to perform a modular model [28]. In the GSPN, the transition is equipped with guards and assignments. The guards are pre-condition logical functions identified by prefix “??” and used to enable or inhibit the firing of transitions. The assignments, represented by “!!!”, are

the post-condition messages that update the variables used in the model. To learn more about Petri Nets, studies [50,51] are recommended; a comprehensive overview of GSPN is provided in [52].

## 2.2. Case Study Description

For case study analysis, a generic OWT with Horizontal Axis Wind Turbine (HAWT) configuration is considered. The OWT is a multi-unit and multi-state system with complex dependencies between components. In this paper, only the equipment that most influence the system availability is considered, namely: Rotor (RT), Gearbox (GB), Generator (GT), and Pitch System (PS).

The case study is defined based on various sources of information. The reliability parameters of the OWT's components are based on empirical offshore reliability data provided in [32]. The corrective and preventive maintenance policies are based on [30,32,48]. The weather window is adopted from [29].

The case study OWT is located at the Portuguese wind farm close to Viana do Castelo. The wind farm area is located 18 km off the shore, that is, close to the global average of distance to the shoreline, i.e., 18.8 km [1]. The wind resource at the location is given in [53], while the wave conditions are indicated in [54]. The total exploration life of OWT is 25 years with a capacity factor of 50.8% per year [55]. The electric power is 5 MW. The tariff for wind energy produced by OWT in Portugal is considered to be 0.1544 EUR/kWh [56].

### 2.2.1. Production Configuration

The OWT system can be divided into eight main subsystems, namely: support structures, pitch and hydraulic system, gearbox, generator, speed train, electronic components, blades system, and yaw system [6]. All of them are installed in a series configuration. Thus, any subsystem failure of OWT can undermine the total production. Hence, the critical or degraded failure of RT, GB, GT, or PS leads to the total production stop. Besides, the Place/Transition Petri Nets has a limitation: different events cannot occur simultaneously (i.e., the firing of the differently enabled transitions is sequential). Thereby, the defining of equipment sequence switch is needed. To shut down the OWT production, the equipment sequence switch is: RT → GB → GT → PS. To start up the wind turbine production, the equipment sequence switch consists of: PS → RT → GB → GT. The Pitch System controls the blade pitch to follow a predetermined speed ramp during startup and shutdown of the turbine. Thus, the PS is the last one in the first sequence and the first one in the second one. In the case of failure of one of the pieces of equipment presented in the sequences, the order in which the subsystems are switched off is preserved, giving priority to the damaged equipment.

### 2.2.2. Component Failure Data

In this case study, only the failures of the RT, GB, GT, and PS are considered. The component failure data is given in Table 1.

The non-perfect systems can be in three different states: "As good as new", "Degraded" and "Failed". "As good as new" state is a component in normal operation. "Failed" state corresponds to a non-functioning component. "Degraded" state means that the function of a component is maintained, but the system has a higher probability of failure. The equipment can be repaired in "Failed" or in "Degraded" states.

The incipient and critical failures are described by the Weibull Truncated distribution, which accounts the equipment's age. The shape parameters,  $\beta$ , chosen for the transitions are 2 and 3, respectively [30,32]. Both are larger than 1, representing the equipment in the wear-out period of life. In this period, the larger the shape parameter, the higher degradation effect.

The degraded failure is described by the exponential distribution, with the failure rate,  $\lambda$ , due to the failure being independent from the equipment's age.

**Table 1.** Component failure data.

Component	Failure	Distribution	$\beta$ <sup>1</sup>	MTTF <sup>2</sup> (h)	$\lambda$ <sup>3</sup> (h <sup>-1</sup> )
Rotor (RT)	Incipient	Weibull Truncated	3	19,948	-
	Critical	Weibull Truncated	3	22,164	-
	Degraded	Exponential	-	-	$4.51 \times 10^{-4}$
Gearbox (GB)	Incipient	Weibull Truncated	3	15,952	-
	Critical	Weibull Truncated	3	17,724	-
	Degraded	Exponential	-	-	$5.64 \times 10^{-4}$
Generator (GT)	Incipient	Weibull Truncated	2	17,215	-
	Critical	Weibull Truncated	2	19,128	-
	Degraded	Exponential	-	-	$5.23 \times 10^{-4}$
Pitch System (PS)	Incipient	Weibull Truncated	3	12,355	-
	Critical	Weibull Truncated	3	13,728	-
	Degraded	Exponential	-	-	$7.28 \times 10^{-4}$

<sup>1</sup> Shape parameter. <sup>2</sup> Mean Time to Failure. <sup>3</sup> Failure rate.

### 2.3. Maintenance Policy

The case study OWT with four degraded components is subjected to corrective maintenance (CM) when necessary and to age-based preventive maintenance (PM) only in the summer. To keep the functioning of the OWT system, three different maintenance categories are used [48]. Each of them depends on the weight of the component being replaced (CM) or repaired (PM), thus according to the vessel involved:

- Jack-Up vessel (JU)—is used in CM activities to replace the Rotor (its weight is between 90 t and 150 t).
- Crane Barge (CB)—is used in CM activities to replace the Generator (up to 20 t) or the Gearbox (up to 65 t).
- Supply Vessel (SV)—is used in CM activities to replace the Pitch System and to support the CM operations of the larger vessels. Moreover, SV is used in all PM activities.

The technical specifications of each vessel and the summary of maintenance categories are presented in Tables 2 and 3, respectively. The SV is the only one docked at the nearest available port to the OWT, in Viana do Castelo; whereas the JU and CB are docked in Porto and Aveiro, respectively, see Table 4.

**Table 2.** Technical specifications of the vessels.

Categories (Vessels)	Draught (m)	Service Speed (Knots)
Jack-Up (JU)	5.8	12
Crane Barge (CB)	3.8	7
Supply Vessel (SV)	3.8	7

**Table 3.** Maintenance categories.

Categories (Vessels)	Turbine's Components			
	RT	GB	GT	PS
JU	CM			
CB		CM	CM	
SV	CM & PM	CM & PM	CM & PM	CM & PM

**Table 4.** Principal constraints of Portuguese harbours.

Harbour	Terminal	Draught (m)	Distance to OWT (km)
Viana do Castelo	Commercial port	8	19.48
Porto (Leixões)	General cargo I	10	63.51
	General cargo II	11	63.51
Aveiro	Multipurpose	12	124.77

The Supply Vessel is used to transport a unique maintenance crew of 4 technicians and spares for the Pitch System. The maintenance crew is considered as always available. Moreover, it can start at any time of the day as long as all the logistics are concluded and there is a weather window available. It is worth noting that the Supply Vessel is set to arrive at the turbine at the same time with the Jack-Up (or the crane vessel), so the maintenance team can start working immediately upon arrival.

2.3.1. Corrective Maintenance

CM activity consists of replacing the damaged equipment by a new one including all the operation steps from the production of equipment in a factory to its commissioning on the turbine. The component manufacture in a factory and the equipment transportation from the supplier to the port constitute the vessels’ logistic time, see Table 5 [48]. It is worth noting that the SV is available 24 h per day to depart to an OWT immediately, and only in the case of PS’s corrective repair, the Supply Vessel possesses a logistic time, since the arrival of the new Pitch System takes 2 days (i.e., 48 h). The logistic time follows a Log-normal distribution with a coefficient of variation of 30%.

**Table 5.** Vessels’ logistic times.

Categories (Vessels)	Logistic Time (h)	SD <sup>1</sup> (h)
JU	504	151.2
CB	160	48
SV	48	14.4

<sup>1</sup> Standard Deviation.

The time spent on transportation of the new component from the port to the OWT is estimated from the vessels’ service speed and the travelled distance. Additionally, the sailing time follows a Log-normal distribution with a coefficient of variation of 20%. Please note, the manoeuvres and the transit time in port are neglected.

Table 6 contains the information regarding the mean duration of component replacement and the respective standard deviation (SD). This time depends on both the equipment type and the production state (i.e., degraded or failed). The time of CM activities follows a Log-normal distribution with coefficient of variation of 20%.

**Table 6.** Corrective maintenance data (replacement phase) by equipment.

Transition		RT	GB	GT	PS
Failed → As good as new	Mean (h)	40	50	50	10
	SD <sup>1</sup> (h)	8	10	10	2
Degraded → As good as new	Mean (h)	52	65	65	13
	SD <sup>1</sup> (h)	10.4	13	13	2.6

<sup>1</sup> Standard Deviation.

### 2.3.2. Preventive Maintenance

The RT, GB, GT, and PS are subjected to imperfect age-based PM. This maintenance action can start whether the equipment is in the perfect state or the component is stopped, but not damaged. Please note, once a PM begins, it must be concluded, even if a critical or degraded failure occurs in another component. PM is performed by the same maintenance team as the CM, which is located on the Supply Vessel.

PM tasks are performed based on age reduction ratio,  $q$  ( $0 < q < 1$ ). Thus, after repair activity, the component is  $q$  younger (i.e., the age is reduced by  $q$  percent). After PM activity, the age is defined by [30]:

$$Age_i = Age_i^{acc} \times (1 - q) \Leftrightarrow Age_i = (t_i - t_{i-1} + Age_{i-1}) \times (1 - q) \tag{1}$$

where,  $Age_i$  and  $Age_{i-1}$  are the component’s consecutive ages after  $i^{th}$  and  $(i - 1)^{th}$  maintenance tasks, respectively;  $Age_i^{acc}$  is the age at the beginning of the  $i^{th}$  maintenance action, accumulated from the  $(i - 1)^{th}$  maintenance task;  $t_i$  and  $t_{i-1}$  are the calendar times at the beginning of the  $i^{th}$  and at the end of the  $(i - 1)^{th}$  maintenance actions, respectively. It is worth noting that after corrective maintenance activity, the component is new, so its age is  $Age_i = 0$ .

PM is carried out only in the summer season, and when the age of a component is at least equal to  $p \times MTTF$  hours [17]:

$$(t_i - t_{i-1} + Age_{i-1}) \geq p \times MTTF, \text{ where } 0 \leq p \leq 1 \tag{2}$$

where,  $p$ , is a preventive repair threshold parameter which is the same for all components.

In this case study, four different PM activities are considered and presented in Table 7. The frequency of the maintenance depends on the equipment’s age and it is assumed to be Delta Dirac distributed. The duration of PM depends on the age reduction ratio,  $q$ , and on the Mean Time to Repair (MTTR) of critical failure. The Log-normal distribution with coefficient of variation of 30% is used to describe the duration of PM.

**Table 7.** Preventive maintenance models of individual component.

Component	Period (h)	Duration (h)	Recovered Age (%)
RT	$p \times MTTF_{RT}$	$q \times MTTR_{RT}$	$q \times 100$
GB	$p \times MTTF_{GB}$	$q \times MTTR_{GB}$	
GT	$p \times MTTF_{GT}$	$q \times MTTR_{GT}$	
PS	$p \times MTTF_{PS}$	$q \times MTTR_{PS}$	

### 2.4. Costs

In Table 8, the approximate costs for the new turbine’s components are presented. These values are based on an offshore wind farm guide from [57]. Please note, the transportation outlay of a new equipment from the manufacturer to the port is included in the overall price of the component.

**Table 8.** Overall cost of the turbine’s components.

Component	Cost/Unit (EUR)
RT	1,849,000
GB	863,000
GT	247,000
PS	123,300

The costs related to the vessels and technicians, Table 9, are approximate values based on [48], where the hourly rate of a technician is EUR 70 by person.

**Table 9.** Hourly rates and mobilization costs.

Service	Hourly Rate (EUR)	Mobilization (EUR)
JU	6250	57,000
CB	6250	45,000
SV	600	0
Technician	70	0

The cost of the imperfect PM,  $C_p$ , depends on the age reduction ratio,  $q$ . According to [30], it is given by:

$$C_p = \begin{cases} q^2 \times C_{pv} + C_{pf}, & 0 < q \leq 1 \\ 0, & q = 0 \end{cases} \quad (3)$$

where,  $C_{pv}$  is the preventive component replacement cost;  $C_{pf}$  is a fixed maintenance cost. Since the PM is stochastically driven,  $C_p$  is not considered in this paper, thereby,  $C_{pv}$  comprises the total replacement cost of a new component. After the simulation, the number of occurred PM activities per component is obtained. Then, this number is multiplied by the component’s cost/unit (see Table 8). Hence,  $C_{pv}$  per turbine’s component is calculated. The cost of PM considers neither hourly rates of SV nor technician crew. The hourly rates and the mobilization costs are calculated separately considering the expenses of CM and PM activities together.

### 2.5. Weather Window

The corrective and preventive maintenances are only performed when the weather window (WW) is available (i.e., the wind speed and the significant wave height are within the operational limits of the marine operation for a period long enough due to safety reasons). The probability of favourable WW,  $P_w$ , and the time delay due to bad weather conditions,  $T_w$ , are presented in Table 10 [17]. Please note that these values are merely illustrative. The probabilities of the available WWs are conservative based on the typical behaviour of each season. So, the increase of probability of available WW corresponds to the decrease of waiting time for a WW. More realistic correlations can be obtained from available weather data at the offshore wind farm.

**Table 10.** Availability of weather window and waiting time.

Season	Availability of WW ( $P_w$ )	Availability Random Number	Waiting Time for a WW ( $T_w$ ) (h)
Winter	0.3	[0, 0.3]	240
Autumn	0.5	[0, 0.5]	168
Spring	0.6	[0, 0.6]	120
Summer	0.8	[0, 0.8]	48

The WW must be available when a maintenance activity (i.e., CM or PM) is to be performed. As a result, as soon as the ships and the maintenance team are in port, the model randomly generates a number between 0 and 1. If this value is less than or equal to the seasonal  $P_w$ , a WW is available and the maintenance activity can start, otherwise a waiting time,  $T_w$ , for a weather window is set. When the waiting period expires, a WW becomes available.

Due to the relatively small distances between the ports, the available WW is required only for the first departure ship by maintenance activity.

### 2.6. System Modelling by Petri Nets

The case study OWT is modelled by GSPN with predicates and the production availability and maintenance costs are obtained from Monte Carlo simulation. At the initial instant, the PN model of turbine has all components of offshore production plant in op-

eration with initial age equal to zero (i.e., all equipment components are as good as new), the maintenance team and the Supply Vessel are localised in Viana do Castelo, the Jack-Up vessel is anchored in Porto, while the Crane Barge is anchored in Aveiro.

### 2.6.1. Equipment

Each component of OWT is schematised using the same type of PN model, consisting of a sequence of events, which includes the simulation of failure and of the repair process. To avoid a too extensive description, only the simplified model of Rotor (RT) is presented (see Figure 2).

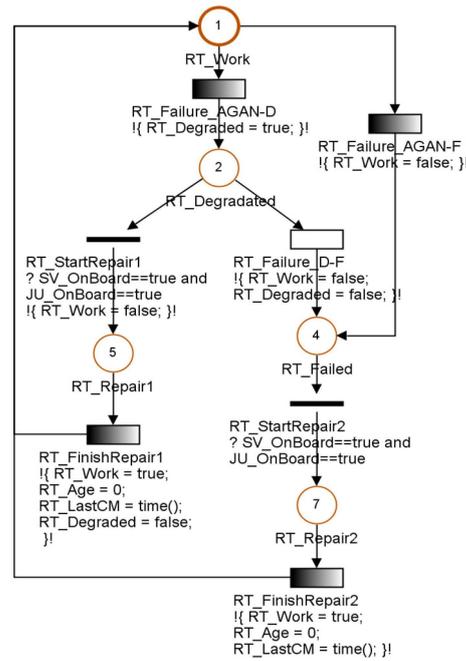


Figure 2. PN model of equipment (Rotor).

To ensure a logical sequence, the PN model of the equipment is accompanied by various variables. Thus, the variable *RT\_Work* is used to determine whether the equipment fulfils its technical mission (i.e., *RT\_Work == true*), or not (i.e., *RT\_Work == false*). The variable *RT\_Degradation* is used to determine whether the equipment is degraded and available or not degraded. Moreover, due to the PM activity, the model is complemented by: *RT\_Age* and *RT\_LastCM*. The first registers the equipment’s age in hours; the second records the time of the completion of the last corrective repair. These variables are used in calendarization of the preventive maintenances. After every CM, *RT\_Age* is set to zero.

When the place *RT\_Work* is marked, Rotor is in operation and the variable *RT\_Work* is *true*. While *RT\_Work* is marked, RT can fail (i.e., critical failure) or degrade (i.e., incipient failure). RT fails when the transition *RT\_Failure\_AGAN-F* is enabled. Please note, AGAN means As-Good-As-New and F means Failure. Through the firing rule, *RT\_Work* is unmarked, the token moves to the place *RT\_Failed* and the variable *RT\_Work* changes to *false*. The token stays at *RT\_Failed* place until *RT\_StartRepair2* becomes enabled, in other words, until a repair team and both Supply Vessel (SV) and Jack-Up vessel (JU) arrive to the offshore installation (i.e., *SV\_OnBoard == true* and *JU\_OnBoard == true*). During the repair activity, *RT\_Repair2* place is marked. The duration of CM activity is introduced in the delay of *RT\_FinishRepair2*. When this transition is enabled, it means the conclusion of CM repair, thus the token moves to *RT\_Work*, the variable *RT\_Work* changes to *true*, the variable *RT\_Age* turns to zero, and the variable *RT\_LastCM* records the time of completion of corrective repair.

The incipient failure occurs when the transition *RT\_Failure\_AGAN-D* is enabled. Through the firing rule, *RT\_Work* is unmarked, and the token moves to the place *RT\_Degraded*, the variable *RT\_Degraded* changes to *true*, and the variable *RT\_Work* remains *true*. When the Rotor is degraded, both transitions *RT\_StartRepair1* and *RT\_Failure\_D-F* can fire, depending on the failure history of the component, because the first failure is repaired if it is degraded or critical and the next failure only if it is critical. Thus, if the Rotor is degraded and the previous failure was critical, *RT\_StartRepair1* is enabled, the token moves to the place *RT\_Repair1* and the corrective maintenance team is reserved. Moreover, if the Rotor is degraded and the previous failure was degraded, the transition *RT\_Failure\_D-F* is enabled, the token moves to the place *RT\_Failed*, and the variable *RT\_Degraded* turns *false*.

### 2.6.2. Total System Switch

Stochastic Petri Nets cannot simulate different operations at the same time. All actions must be sequential. Therefore, all components of the OWT are impossible to switch off simultaneously. Hence, the total system switch includes four different fail scenarios. Each scenario has the same order of equipment turning-off, starting with the unavailable component. The PN model of total system switch is presented in Figure 3.

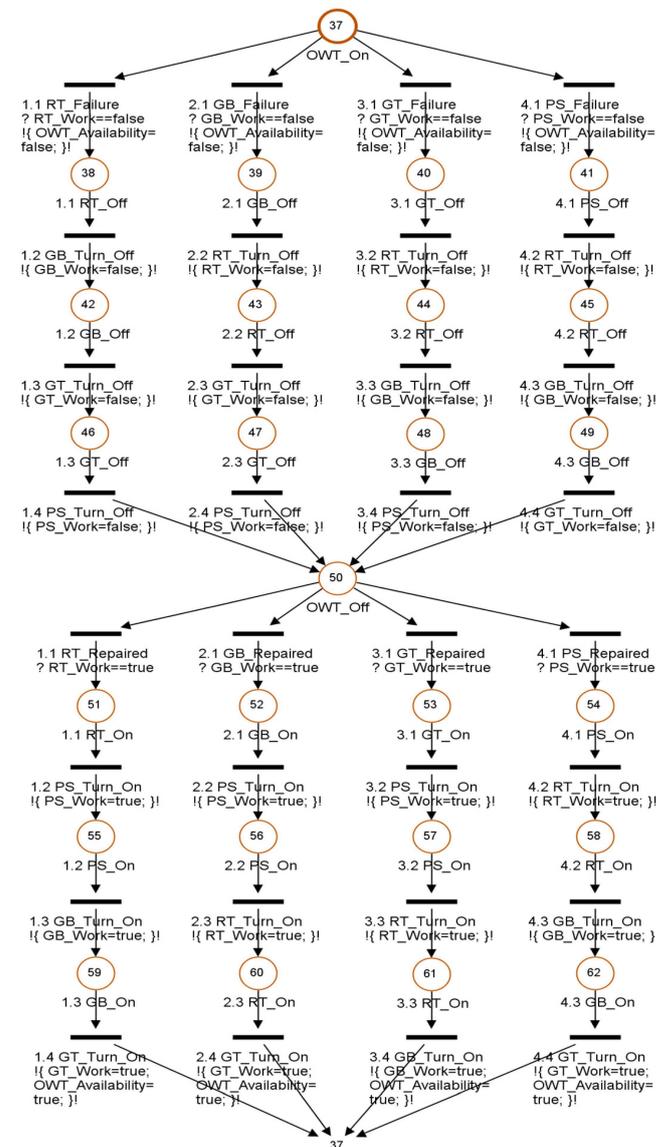


Figure 3. Total system switch.

Total system switch has two objectives: to calculate the availability of the total system, through the Boolean variable *OWT\_Availability*, and to turn off offshore processing plant equipment when at least one important production component (i.e., RT, GB, GT, and PS) is not available, through the Boolean variable *Equipment Abbreviation\_Off*. If the system is available, *OWT\_Availability* is true, in the unavailable state, it is false. *Equipment Abbreviation\_Off* is true only when the system component is shut down due to failure of another component.

### 2.6.3. Preventive Maintenance

The preventive maintenance is a scheduled activity. Regardless of the type, the generic PN model of PM repair is the same for every equipment. As an example, the simplified PN model of preventive maintenance activity of the RT is shown in Figure 4.

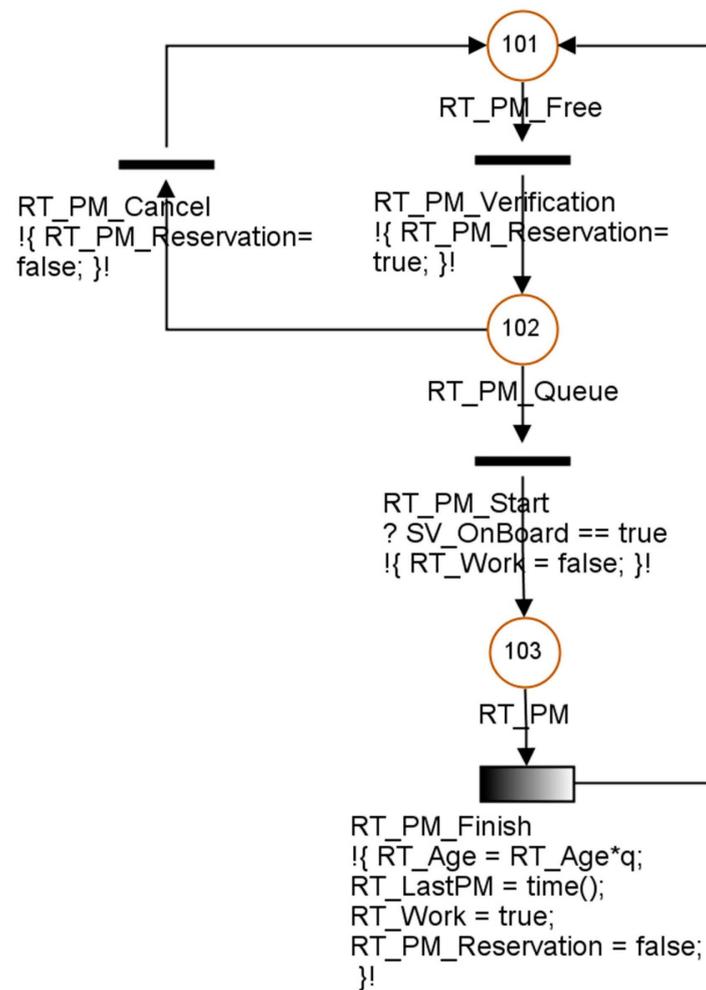


Figure 4. PN model of PM activity (Rotor).

The PN sub-model for PM activity is accompanied by variables: *RT\_PM\_Reservation* and *RT\_LastPM*. *RT\_PM\_Reservation* is a Boolean variable that identifies with the “true” condition (i.e., *RT\_PM\_Reservation* == true) that the Rotor reserves the PM team for itself. *RT\_LastPM* records the time of the completion of the last preventive repair.

When the place *RT\_PM\_Free* is marked, the equipment is waiting for preventive maintenance, thus, the variable *RT\_PM\_Reservation* is false. The main objective of the transition *RT\_PM\_Verification* is the validating of PM conditions. Namely, it must be a summer, the component’s age must be more than  $p \times MTTF_{rotor}$ , and the equipment must be functional.

When the *RT\_PM\_Verification* is satisfied, the transition fires and the token moves to the place *RT\_PM\_Queue*. The variable *RT\_PM\_Reservation* turns true. At this instant, to proceed with the PM activity, the simulation verifies another two conditions. The first condition is represented by the transition *RT\_PM\_Start*, which is enabled only when the PM team arrives to the wind. The second condition (i.e., the transition *RT\_PM\_Cancel*) verifies whether the Rotor is still functional, while the turbine is waiting for the Supply Vessel coming. In the case of unexpected Rotor's fail, the variable *RT\_Work* becomes false (i.e., *RT\_Work == false*), therefore, the transition *RT\_PM\_Cancel* enables, and the PM is cancelled (i.e., *RT\_PM\_Reservation == false*).

When the first mentioned condition is met, the transition *RT\_PM\_Start* is enabled, the token moves from the place *RT\_PM\_Queue* to *RT\_PM*. When the PM is concluded, the transition *RT\_PM\_Finish* is enabled, and the token moves to *RT\_PM\_Free*. After the transition enabling, the component's age is updated (i.e.,  $RT\_Age = RT\_Age \times q$ ), the variable *RT\_LastPM* changes the registered time, and the Boolean variables return their values to the initial ones.

#### 2.6.4. Seasons

Figure 5 shows the simplified PN model that identifies the seasons. The transitions between the seasons follow the Delta Dirac distribution. The delay of each transition corresponds to the time of three months, considering 30 days in each one. The simulation starts on the 1 December.

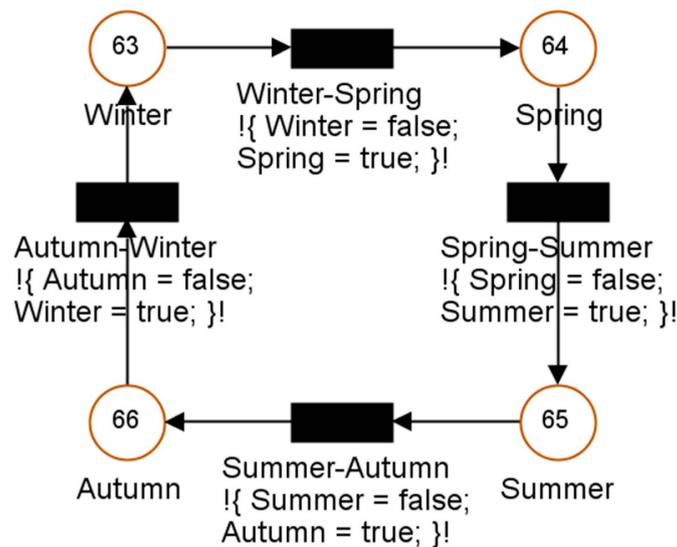


Figure 5. PN model for seasons.

#### 2.6.5. Vessels

The maintenance policy of the OWT system consists of three different maintenance categories according to the vessel involved: Jack-Up vessel, Crane Barge, and Supply Vessel. In order to avoid an extensive description, only the simplified model of JU vessel is presented (see Figure 6).

To ensure a logical sequence, the PN model of JU vessel is accompanied by variables: *JU\_Availability* and *JU\_OnBoard*. *JU\_Availability* is a binary variable. When *JU\_Availability == true*, it identifies the time under which the Jack-Up vessel is localised at the port with no reservation order. Thus, while JU vessel is waiting for an available weather window, *JU\_Availability* is equal to *false*, since the vessel is already reserved for a specific corrective maintenance task. *JU\_OnBoard* is a binary variable, too. *JU\_OnBoard* is used to identify the time interval when the JU vessel is localised at the OWT (i.e., *JU\_OnBoard == true*).

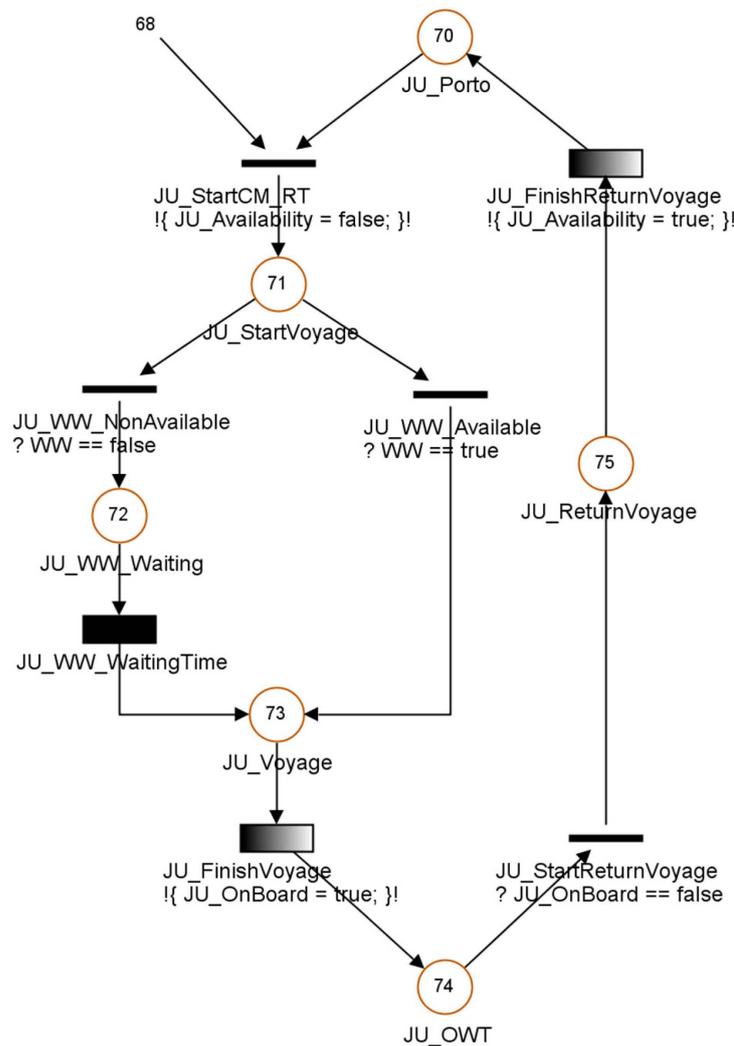


Figure 6. PN model of Jack-up vessel.

When the place *JU\_Porto* is marked, the Jack-Up vessel is available at the port of Porto. Moreover, from the transition firing rule, the transition *JU\_StartCM\_RT* is enabled when both the place #68 (i.e., a new Rotor arrived at the port) and the place *JU\_Porto* are marked. The main objective of this transition is to give a start for the CM activity. When the transition *JU\_StartCM\_RT* fires, the place *JU\_Porto* is unmarked. Thus, from the firing rule, the place *JU\_StartVoyage* is marked. Further, the variable *JU\_Availability* turns *false*.

When the vessel is available to start the voyage (i.e., the place *JU\_StartVoyage* is marked), the weather window must be validated. For this purpose, two transitions are used, namely: *JU\_WW\_NonAvailable* and *JU\_WW\_Available*. If the WW is available, the transition *JU\_WW\_Available* fires and the token moves from the place *JU\_StartVoyage* to the place *JU\_Voyage*. In the case of a non-available weather window, the token moves from the place *JU\_StartVoyage* to the place *JU\_WW\_Waiting*. The token preserves at the new place until the enabling of the transition *JU\_WW\_WaitingTime*. After the enabling of *JU\_WW\_WaitingTime*, the token moves from the place *JU\_WW\_Waiting* to the place *JU\_Voyage*.

The voyage time of the JU vessel is defined by the time delay of the transition *JU\_FinishVoyage*. When the transition *JU\_FinishVoyage* fires, the token moves from the place *JU\_Voyage* to the place *JU\_OWT*, changing the variable *JU\_OnBoard* to *true*. When the CM activity is concluded, the variable *JU\_OnBoard* is *false*, hence, the transition *JU\_StartReturnVoyage* fires and the token moves from the place *JU\_OWT* to the place *JU\_ReturnVoyage*. The token at the place *JU\_ReturnVoyage* means that the JU is in return-

ing voyage. The duration of the voyage is defined by the time delay of the transition *JU\_FinishReturnVoyage*. After the enabling of *JU\_FinishReturnVoyage*, the token moves from the place *JU\_ReturnVoyage* to the place *JU\_Porto*. Moreover, the variable *JU\_Availability* changes to *true*.

### 2.7. Economical Assessment

The efficiency of an age-based imperfect PM depends on two parameters: an age reduction ratio,  $q$ , and a repair threshold parameter,  $p$ . To assess optimal values of  $q$  and  $p$ , it is necessary to determine the lower related costs for the higher possible profit.

The O & M costs ( $C_{O\&M}$ ) correspond to the sum of different features, such as: a new turbine’s component cost, hourly rates, mobilization costs, and the cost of PM. To determine the operation and maintenance expenses (OME), the sojourn times and the number of triggers obtained from the implemented PN model are used. The sojourn time corresponds to the time during which the token is located at the *place ##* throughout the simulation time. Through the sojourn time, the identifying of the number of hours of each vessel (i.e., JU, CB, and SV) dispatched to the O & M activities and the PM duration record of each OWT’s component (i.e., RT, GB, GT, and PS) are possible. The number of triggers corresponds to the total number of transition fires. Through the number of triggers, it is possible to identify the number of failures of each component, the number of mobilizations of each vessel, and the number of realised PM activities.

The variation of  $q$  and  $p$  influences the  $C_{O\&M}$  and the total system availability ( $A_{system}$ ), which in turn influences the revenue or Gross Income ( $GI$ ):

$$GI = A_{system} \times P \times \eta \times T_{simulation} \times C_{PT} \tag{4}$$

where,  $P$  is an electric power in MW,  $\eta$  is a capacity factor of OWT,  $T_{simulation}$  is a total simulation time in hours, and  $C_{PT}$  is a cost for wind energy produced by OWT in Portugal in EUR/MWh.

Knowing the value of  $C_{O\&M}$  and  $GI$ , the profit or Operating Income ( $OI$ ) is possible to determine:

$$OI = GI - C_{O\&M} \tag{5}$$

To assess an optimal value for  $q$  and  $p$ , it is necessary to minimise  $C_{O\&M}$  and to maximise  $OI$ . Hereupon, the optimum  $q$  and  $p$  correspond to the highest value of Accounting Rate of Return ( $ARR$ ):

$$ARR = \frac{OI}{C_{O\&M}} \tag{6}$$

## 3. Results

To perform the availability analysis of an OWT, the GRIF (Graphical Interface for reliability Forecasting) analysis software is used [58]. To simulate the PN model, GRIF uses MOCA-RP computation engine based on Monte Carlo simulation.

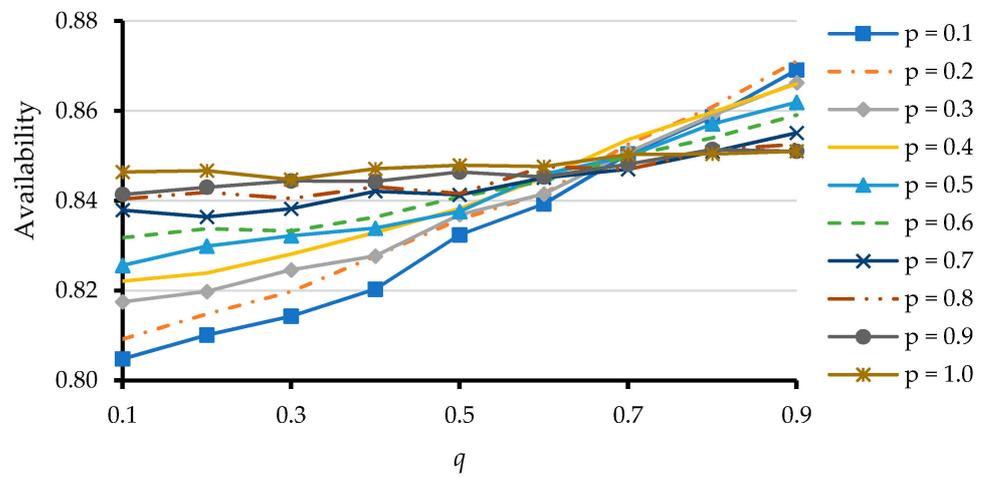
The simulated time of the base model is defined by iterations from instant 0 to instant 219,000 h (i.e., 25 years) with a step of 100 h for 1000 different scenarios (i.e., histories). The average error related to the 90% CI (Confidence Interval) of the model outcomes corresponding to the number of simulated histories is less than 0.04%.

### 3.1. Age-Based PM Parameters’ Decision Based on Economical Assessment

To obtain the optimal values of  $q$  and  $p$ , variations  $0 < q < 1$  and  $0 < p \leq 1$  in steps of 0.1 are considered. Table 11 and Figure 7 present the availability of the total system for different  $q$  and  $p$  values. As can be observed, the higher the values of  $q$  and  $p$ , the greater the availability. Furthermore, the increase of  $q$  is more notable for low values of  $p$ . Thus, as expected, in terms of availability, the  $q_{optimal}$  is 0.9 and the  $p_{optimal}$  is 0.1.

**Table 11.** Availability of the total system for different  $q$  and  $p$  (in MEUR). Matrix representation.

		$p$									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
$q$	0.1	0.80	0.81	0.82	0.82	0.83	0.83	0.84	0.84	0.84	0.85
	0.2	0.81	0.81	0.82	0.82	0.83	0.83	0.84	0.84	0.84	0.85
	0.3	0.81	0.82	0.82	0.83	0.83	0.83	0.84	0.84	0.84	0.84
	0.4	0.82	0.83	0.83	0.83	0.83	0.84	0.84	0.84	0.84	0.85
	0.5	0.83	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.85	0.85
	0.6	0.84	0.84	0.84	0.85	0.85	0.84	0.85	0.85	0.85	0.85
	0.7	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	0.8	0.86	0.86	0.86	0.86	0.86	0.85	0.85	0.85	0.85	0.85
	0.9	0.87	0.87	0.87	0.87	0.86	0.86	0.86	0.85	0.85	0.85



**Figure 7.** Availability of the total system for different  $q$  and  $p$ . Graphic representation.

Table 12 and Figure 8 show the O & M costs for different  $q$  and  $p$  values, considering the cost structure described in Section 2.4 and the results of sojourn times and of number of triggers obtained from PN model. Comparing the results from Table 11 with Table 12, it is concluded that the greater the availability, the greater the operation and maintenance costs.

**Table 12.** O & M costs for different  $q$  and  $p$  (in MEUR). Matrix representation.

		$p$									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
$q$	0.1	57.3	57.4	57.6	58.1	58.6	57.9	59.5	59.4	59.7	59.8
	0.2	56.5	56.8	57.1	57.6	58.1	58.1	59.2	59.3	59.5	59.8
	0.3	57.1	57	56.9	57.4	58	58.4	58.9	59.4	59.5	59.9
	0.4	58.9	58.2	57.9	57.8	58.2	58.7	59.2	59.6	59.6	59.7
	0.5	61.7	60.3	59.8	59.2	59	59.2	59.4	59.8	59.8	59.8
	0.6	66.0	63.9	62.4	61.5	60.8	60.3	60.1	59.9	60.0	60.3
	0.7	72.7	69.9	67.2	65.7	63.6	61.9	60.8	60.4	60.3	60.2
	0.8	81.7	78.1	74.3	71.3	66.8	63.2	61.7	61.1	60.5	60.2
	0.9	94.3	89.9	83.5	77.9	68.7	64.5	62.8	61.7	61.0	60.4

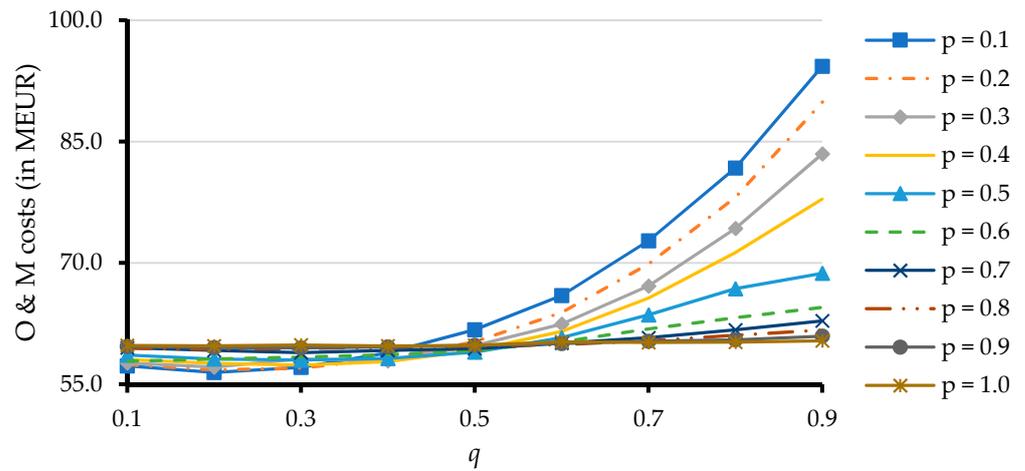


Figure 8. O & M costs for different  $q$  and  $p$  (in MEUR). Graphic representation.

Table 13 and Figure 9 show an Operating Income (OI) for different  $q$  and  $p$  values calculated by Equation (5). For  $q > 0.7$ , the operating income represents the financial loss. This means that the O & M costs are higher than the profit for high values of age reduction values. Despite the lower values of availability, the values of  $q \leq 0.7$  lead to more profitable scenarios.

Table 13. Operating income for different  $q$  and  $p$  (in MEUR). Matrix representation.

		$p$									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
$q$	0.1	11.9	12.1	12.6	12.5	12.3	13.6	12.4	12.7	12.6	12.9
	0.2	13.1	13.2	13.3	13.2	13.2	13.5	12.7	13.0	12.9	13.0
	0.3	12.8	13.4	13.9	13.8	13.5	13.2	13.1	12.8	13.0	12.7
	0.4	11.6	12.9	13.2	13.7	13.4	13.2	13.1	12.8	12.9	13.0
	0.5	9.7	11.5	12.1	12.8	13.0	13.0	12.8	12.5	12.9	13.0
	0.6	6.1	8.4	9.8	11.1	11.9	12.3	12.5	12.9	12.6	12.5
	0.7	0.3	3.3	5.9	7.7	9.4	11.1	12.0	12.4	12.5	12.9
	0.8	-8.0	-4.2	-0.5	2.6	6.8	10.1	11.4	12.0	12.6	12.8
	0.9	-19.7	-15.1	-9.1	-3.5	5.3	9.3	10.6	11.5	12.1	12.7

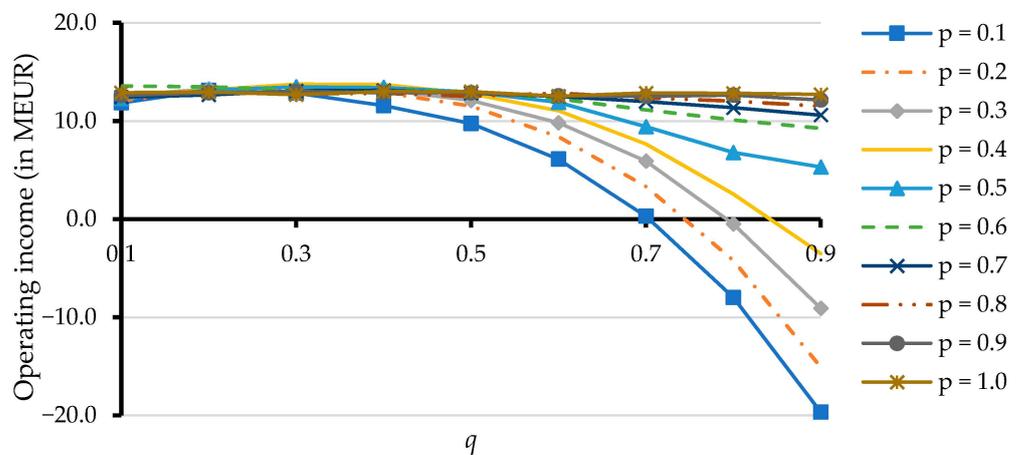


Figure 9. Operating income for different  $q$  and  $p$  (in MEUR). Graphic representation.

Finally, Table 14 and Figure 10 show the Accounting Rate of Return (ARR) calculated for different  $q$  and  $p$  values by dividing the operation income by the O & M costs. The higher ARR is within  $0.2 \leq q \leq 0.4$  and  $0.2 \leq p \leq 0.6$ , where the maximum  $ARR = 0.244$  corresponds to the optimal values of  $q$  and  $p$ . Hence, the lower related costs for the higher possible profit corresponds to  $q_{optimal} = 0.3$  and  $p_{optimal} = 0.3$ .

Table 14. Accounting rate of return for different  $q$  and  $p$ . Matrix representation.

		$p$									
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
$q$	0.1	0.207	0.21	0.218	0.216	0.21	0.235	0.209	0.214	0.211	0.216
	0.2	0.232	0.232	0.232	0.229	0.226	0.232	0.214	0.219	0.216	0.217
	0.3	0.225	0.235	0.244	0.240	0.232	0.226	0.222	0.215	0.219	0.212
	0.4	0.196	0.222	0.228	0.237	0.231	0.224	0.222	0.216	0.216	0.218
	0.5	0.158	0.191	0.202	0.216	0.22	0.22	0.216	0.209	0.215	0.217
	0.6	0.093	0.131	0.157	0.180	0.196	0.204	0.208	0.215	0.209	0.208
	0.7	0.004	0.048	0.088	0.117	0.148	0.180	0.197	0.205	0.208	0.214
	0.8	-0.098	-0.054	-0.007	0.036	0.102	0.160	0.184	0.197	0.209	0.213
	0.9	-0.209	-0.168	-0.109	-0.045	0.077	0.143	0.169	0.187	0.199	0.210

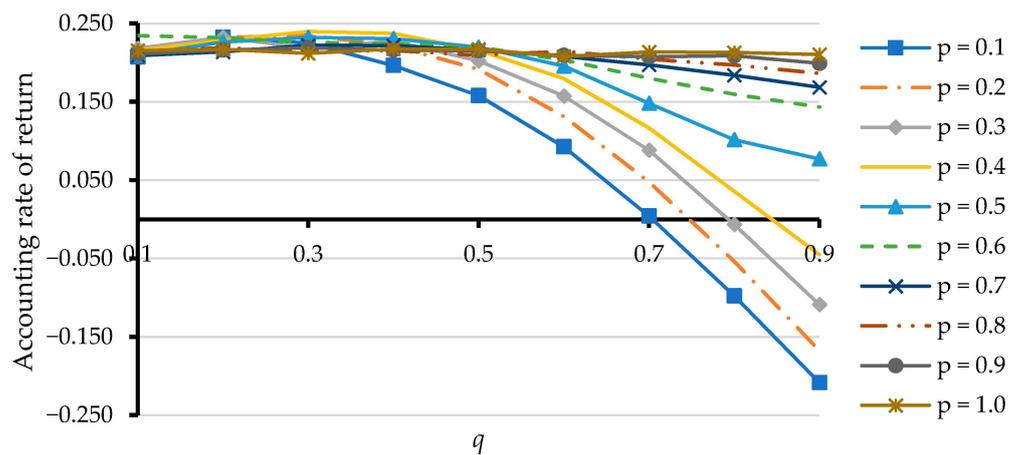


Figure 10. Accounting rate of return for different  $q$  and  $p$ . Graphic representation.

In Table 15, to validate the optimal values of  $q$  and  $p$ , the main system results for two maintenance strategies are presented, namely: CM only and age-based PM. As can be observed, the introduction of PM reduces the total system availability from 84.9% to 82.5%. However, from the economical point of view, the OWT production with PM is more profitable, as  $ARR_{CM\ only} < ARR_{optimum\ age-based\ PM}$ .

Table 15. Main system results for CM and optimum age-based PM.

Results	CM Only	Age-Based PM with $q = 0.3$ and $p = 0.3$
$A_{system}$	84.9%	82.5%
OME (MEUR)	59.9	56.9
OI (MEUR)	12.9	13.9
ARR	0.216	0.244

### 3.2. Sensitivity Analysis: OWT Availability

A sensitivity analysis is conducted to identify the parameters (i.e., input values) that significantly impact the production availability of the OWT. For this purpose, an elasticity factor is used, as:

$$E_{x_i} = \frac{|\Delta y_j|}{|\Delta x_i|} \tag{7}$$

where,  $x_i$  is the input value, and  $y_j$  is the output result.

The elasticity factor is a nondimensional measure defined by the ratio of the variation of OWT availability by 10% increase of input variable. The elasticity analysis is applied to the optimal scenario (i.e.,  $q_{optimal} = 0.3$  and  $p_{optimal} = 0.3$ ). Each input value is analyzed separately. The analyzed input parameters are the component failure data described in Table 1 (i.e., shape parameters, MTTF, and failure rate); the voyage time of SB, JU, and SV vessels obtained from Tables 2 and 4; the logistic time carried out as a part of corrective maintenance summarized in Table 5 and the duration of replacement phase in Table 6; the duration of PM activity, Table 7; the availability of WW and the waiting time for a WW given in Table 10. The output is the OWT availability resulted from the input value change.

Figure 11 shows, in decreasing order of importance, the input parameters with the highest elasticity factor. In Table 16, the description of each parameter is presented. The obtained results show that the ranking of the input parameters on OWT availability are the failure rates of RT, GT, PS; probability of available weather window, the voyage time of SV and JU; shape parameter of RT.

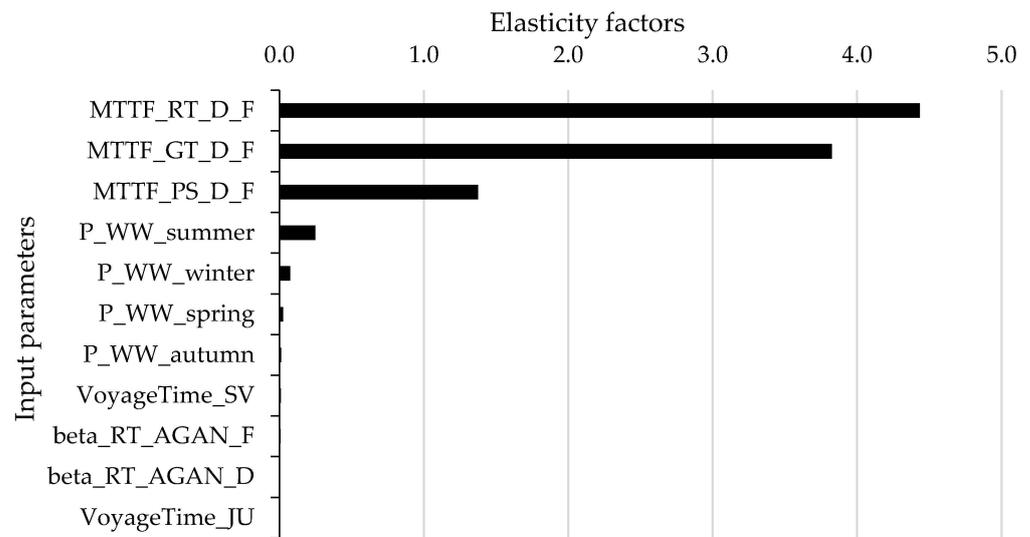


Figure 11. Elasticity factors of input parameters in terms of availability.

Table 16. Description of the input parameters.

Input Parameter	Description
MTTF_RT_D_F	Failure rate of Rotor from the degraded state to the failure
MTTF_GT_D_F	Failure rate of Generator from the degraded state to the failure
MTTF_PS_D_F	Failure rate of Pitch System from the degraded state to the failure
P_WW_summer	Probability of the weather window to be favorable in summer
P_WW_winter	Probability of the weather window to be favorable in winter
P_WW_spring	Probability of the weather window to be favorable in spring
P_WW_autumn	Probability of the weather window to be favorable in autumn
VoyageTime_SV	Total voyage time of Supply Vessel
beta_RT_AGAN_F	Shape parameter of Rotor from the as good as new state to the failure
beta_RT_AGAN_D	Shape parameter of Rotor from the as good as new state to the degraded
VoyageTime_JU	Total voyage time of Jack-Up vessel

### 3.3. Sensitivity Analysis: Accounting Rate of Return

A sensitivity analysis is also conducted to understand how the operational costs may affect the financial aspect of production. For this case, the elasticity factor is defined by the ratio of the variation of accounting rate of return by 10% increase of input costs. The elasticity analysis is applied to the optimal scenario (i.e.,  $q_{optimal} = 0.3$  and  $p_{optimal} = 0.3$ ). Each input cost is analysed separately. The analysed input parameters are the cost of a new turbine’s components (Table 8), the hourly rate of technician and vessel rental (Table 9), and the mobilization costs (Table 9).

Figure 12 shows in decreasing order of importance, the operation and maintenance expenses input parameters. The obtained results show that the most influential costs on ARR are the hourly rates of technician and vessel rental.

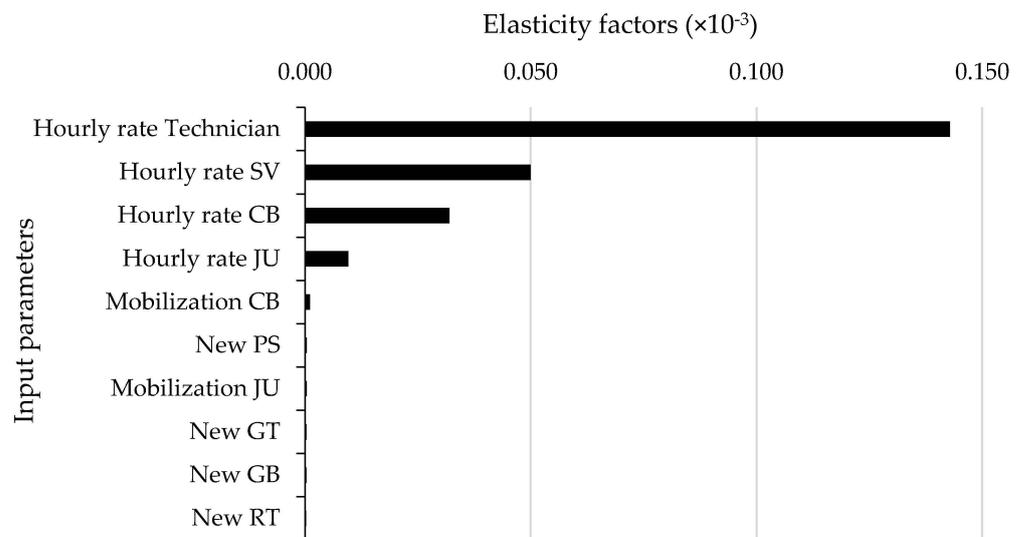


Figure 12. Elasticity factors of input parameters in terms of accounting rate of return.

### 3.4. Discussion on the Availability Assessment

Considering the logistics, the operation and maintenance activities presented in Section 2, an age reduction ratio,  $q = 0.3$ , and a repair threshold parameter,  $p = 0.3$ , the availability of the OWT system is 82.5%, which compares favourably with those obtained by other studies. Pfaffel et al. [59] showed that the availability of the onshore wind farm is around 95%, while of the offshore wind farm, it is around 88%. Scheu et al. [60] determined that the mean availability of a wind farm constituted by 80 OWT is 91%. In the SPARTA project, the availability is 93%, in the OWEZ wind farm, it is 80%, in the Stratch-off wind farm, it is 84% [61]. As one can see, some studies show that the production availability can be higher than 90%, however, it is important to note that these values refer to the availability of the wind farm with several wind turbines. This means that in the case of the critical failure at one wind turbine, the availability of that turbine will decrease, while the total availability of the system will not be significantly affected as the rest of the turbines are working. Moreover, the logistic of the maintenance activity for a single wind turbine is different from the entire offshore wind farm. In the case of wind farm, it is possible to combine different maintenance activities, thus, reducing the logistic and voyage time of a repair team. Hence, it is expected that the availability of the single wind turbine be slightly lower than of the wind farm.

The obtained 82.5% availability also reflects some conservative modelling assumptions that can be relaxed. The main reasons for low availabilities of OWT are: the low reliability values, the overestimation of restrictions for maintenance activities, and the non-availability of technical support vessels [62]. From the effectuated sensitivity assessment, it is possible to see that the MTTF of PS, GT, and RT represent the highest sensitivity factors. This means that the availability of OWT can increase for more recent and reliable components. In this

study, the reliability parameters are based on empirical offshore reliability data from 2014. The second factor that decreases the availability is the underestimation of the probability of an available weather window. Due to the lack of WW data for Viana do Castelo wind farm, the conservative values were used. From the sensitivity analysis, the availability of WW in summer is the most influential factor if comparing with other seasons. However, the increase of WW availability in winter and spring can positively influence the OWT availability, too. The voyage time of technical support vessels (i.e., JU and SV) is also important to production availability increase.

Among the support vessels, the higher availability is provided by Jack-Up vessel (i.e., 97.5%), as JU is used only to transport the new Rotor from port to the OWT. From the base model results, the JU vessel is used 9.8 times in 25 years. The Crane Barge vessel has slightly lower availability (i.e., 92.6%). CB vessel is used to support the replacement of the Generator and Gearbox. From the base model results, the CB vessel is used 27.1 times in 25 years. The lowest availability belongs to the Supply Vessel (i.e., 82.9%). SV is a unique vessel that is used in all maintenance activities. Over 25 years, this vessel is used 105.8 times.

It is worthwhile to note that the repair maintenance team is unique and is used in both CM and PM actions. Moreover, the repair team always uses the Supply Vessel, thus, the availability of the repair team is equal to the availability of the Supply Vessel.

#### 4. Conclusions

The main objective of this paper is to analyse the availability of an offshore wind turbine system subjected to an age-based preventive maintenance, considering the optimal age reduction ratio,  $q$ , and repair threshold parameter,  $p$ . For this purpose, the Generalized Stochastic Petri Nets with predicates coupled with the Monte Carlo Simulation method are used.

An economical assessment of the production availability and maintenance costs of the offshore wind turbine is performed to estimate the optimal values for  $q$  and  $p$ . The influence of  $q$  and  $p$  on the availability, O & M costs, operating income, and accounting rate of return are assessed. The higher availability occurs at the high values of  $q$  and at the low values of  $p$ . However, at this range of  $q$  and  $p$ , the O & M costs are very high, leading to negative incomes. Using the results obtained from the accounting rate of return, the optimal values for  $q$  and  $p$  are obtained. Hence,  $q = 0.3$  and  $p = 0.3$  correspond to the lower O & M costs and provide the higher possible profit.

A sensitivity analysis is conducted to identify the parameters (i.e., input values) that significantly impact the production availability of the OWT. The obtained results show that the ranking of the input parameters on OWT availability are the failure rates of RT, GT, PS; probability of available weather window, the voyage time of SV, and JU, and shape parameter of RT. Another sensitivity analysis is also conducted to understand how the operational costs may affect the financial aspect of production. The obtained results show that the most influential costs on accounting rate of return are the hourly rates of technician and vessel rental.

The simulation results show that the availability of the OWT is 0.825, which reflects some conservative model parameters, but is in line with the values obtained by other studies for offshore wind farms. The Jack-Up shows the higher availability between vessels: 0.975. The availability of Crane Barge vessel is 0.926, while the availability of Supply Vessel is 0.829. The availability analysis of the OWT adopted a Simple Place/Transition PN. This tool becomes difficult to read graphically as the complexity of the production system increases. Hence, it is recommended to use Coloured PN in further works, which facilitates the graphical representation.

To obtain more accurate estimates from the O & M model, real weather data for weather window implementation is recommended. Knowing the wind speed and the wave height at the OWT location, and specific operational limits of the different vessels, it is possible to calculate their availability more precisely. Moreover, real wind data together

with the power performance curve of the OWT allows the assessment of the real power output of the system.

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### Abbreviations/Nomenclature

ARR	Accounting Rate of Return
CB	Crane Barge
CI	Confidence Interval
CM	Corrective Maintenance
GB	Gearbox
GI	Gross Income
GRIF	Graphical Interface for reliability Forecasting
GSPN	Generalized Stochastic Petri Nets
GT	Generator
HAWT	Horizontal Axis Wind Turbine
JU	Jack-Up vessel
MCS	Monte Carlo Simulation
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
O & M	Operation and Maintenance
OI	Operating Income
OME	Operation and Maintenance Expenses
OWT	Offshore Wind Turbine
PM	Preventive Maintenance
PN	Petri Nets
PS	Pitch System
RT	Rotor
SD	Standard Deviation
SPN	Stochastic Petri Nets
SV	Supply Vessel
WW	Weather window

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