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Availability analysis of an offshore oil and gas production system subjected to age-based preventive maintenance by Petri Nets

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Highlights

- Availability assessment of an offshore oil and gas production system.
- Age-based perfect and imperfect preventive maintenance strategies are considered.
- Petri nets and Monte Carlo simulation are adopted for availability assessment.

Abstract

The main objective of this paper is to model an offshore oil production system subjected to age-based preventive maintenance strategies by Petri Nets and to evaluate its availability by Monte Carlo Simulation. The oil processing and the separation equipment with their reliability and maintainability characteristics, the corrective and preventive maintenance policies and the operational dependencies that lead to the reconfiguration of the system after the failure are implemented. A special attention is given to the effect of age-based perfect and imperfect preventive maintenance strategies on the system availability. The maintenance actions consider the components' age thresholds and an age reduction ratio. Moreover, the variation of the oil and gas flows from the well over the years is accounted by the model. As case study, an offshore production installation that operates in a Brazilian oilfield is adopted. An elasticity analysis on the model parameters is conducted to assess influence of the maintenance policy on the system availability and on the oil production.

Keywords

production availability, age-based imperfect preventive maintenance, offshore installation, oil and gas production, Petri Nets, Monte Carlo Simulation.

1. Introduction

The offshore oil and gas production is a very complex industrial system that includes different areas of engineering. Its performance can be improved by means of an availability analysis that assesses the effect of the reliability and maintainability characteristics of the equipment on the system production.

The classical reliability tools (e.g., Reliability Block Diagram, Fault Tree, Event Tree) are unsuitable to analyse industrial production systems, since they do not account for the dependencies or the dynamic interactions [8]. These models are based on Boolean algebra (i.e., the values of the variables either *true* or *false*) [4, 34] and are designed to deal with rare events, but with severe sequences. This is the opposite of dependability analysis that deals with frequent events with low consequences (e.g., minor production or financial losses) [30].

Markov modelling is a standard technique for the mathematical representation of dynamic systems, since component failure interactions, as well as systems with independent failures, may be effectively modelled as Markov processes [14]. However, Markov model has two main limitations: the number of states increases with system size so fast that it can lead to state-explosion, limiting the approach to very complex systems. Moreover, the Markov model only works with exponentially distributed events, i.e. constant failure and repair rates [27]. Therefore, to capture the complexity of real systems and to model the dependencies and interactions between the system components, simulation techniques have been adopted by several authors, e.g., Santos et al. [27].

Monte Carlo Simulation (MCS) provides all necessary information to describe the behaviour of different realistic aspects of a production system, such as component degradation, corrective and preventive maintenances, limited number of repair teams and associated component repair priorities [38]. Zio et al. [39] presented a MCS model for availability evaluation of a multi-state and multi-output offshore installation. Besides, Naseri et al. [20] used MCS for availability assessment of oil and gas processing plants considering the time-dependent effects of Arctic weather conditions on the components' failure and repair rates. Simulation based approaches have been adopted for dealing with condition monitoring of multi-component deteriorating systems [2] and condition-based maintenance optimisation problems [37] and can also be applied to assess condition-based maintenance strategies of other production systems such as offshore wind turbines [12].

Petri Nets (PN) is a tool that combines graphical to mathematical modelling capabilities in order to simulate and analyse discrete event systems [29]. It was first introduced by Carl Adam Petri in 1962 in his Ph.D. dissertation [23], where he discussed the problem of represent-

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ing co-operating, concurrent, or competing processes by a graphical modelling.

Over the years several techniques have been developed from the original Petri nets concept. Stochastic Petri Nets (SPN) proposed in the 80's adopt exponentially distributed state transition delays and, more recently, Generalized Stochastic Petri Nets (GSPNs) with predicates include non-exponentially distributed timed and immediate transitions, which are devoted to the representation of logical actions that do not consume time. Also, new attributes or predicates are associated to the transitions such as guards (pre-condition messages) to enable or inhibit the firing of transitions, and assignments (post-condition messages) that can be used to update model variables.

Besides SPN, and GSPN, other Petri nets-based techniques with extended capabilities are also well-known, such as the coloured Petri nets (CPN) and the timed hybrid Petri nets (THPN), among others. In particular, CPNs in which tokens carry data values and can hence be distinguished from each other, have been adopted for example for maintenance modelling and availability of railway systems, taking full advantage of the CPN capabilities to represent the main parameters of the maintenance strategies [32].

GSPN with predicates coupled with MCS are a powerful approach for modelling reliability, maintenance, production and the general performance of multi-unit and multi-state systems (e.g. [28], [6], [36]). A quantitative analysis of the Stochastic Petri Nets (SPN) can be performed by analytical methods. However, the use of MCS is more flexible in representing the system stochastic evolution [24], which is not easily captured by analytical models [16]. This allows the analysis of complex industrial/real systems and the modelling of the realistic features of the system performance, as well as the dependencies and dynamics of the interactions between the system components.

Briš and Kochaníčková [4], Teixeira and Guedes Soares [34] and Briš [5] combined GSPNs and MCS to model and analyse the production availability of an offshore installation case study in different scenarios. The above-mentioned studies were developed within the scope of the European thematic network SAFERELNET – Safety and Reliability of Industrial Products, Systems and Structures [10]. The case study included different processes like the corrective and preventive maintenance policy, component degradation, production reconfiguration and production level. This production system has also been analysed by Zio et al. [40] using a MCS algorithm based on the minimum and maximum cut sets of the system, and later by George-Williams et al. [9] using a MCS algorithm based on a load-flow approach without reference to the system cut-sets or pre-defined system performance levels prior to simulation.

Meng et al. [17] performed the production availability assessment of a case study Floating Production Storage and Offloading system (FPSO), using SPN as the modelling tool. Besides the availability assessment, this work analysed the expected and predicted annual oil flow behaviour under different calendarized preventive maintenance policies. The same case study was applied to identify the production availability and to conduct a sensitivity analysis through the modelling language AltaRica 3.0 [1] and through the simplified version of Guarded Transition Systems [18].

The availability analyses of offshore oil and gas production systems have adopted simplified maintenance strategies. Besides, in the implementation of stochastic events, it is common to use the exponential distributions, which are not appropriate to describe the equipment´s availability behaviour at wear-out period of life. Moreover, to assess the production performance of the two-phase hydrocarbon reservoir, the analysis of oil and gas flows over an exploration lifetime is necessary. These factors influence the production availability, leading to less credible results.

The applications of GSPNs to offshore oil and gas production systems mentioned above have considered corrective and simple preventive maintenance strategies over components with constant failure and repair rates. Both strategies comprised the replacement of the components by new ones upon failure or at specific time periods. This simplified periodic preventive maintenance model is unable to represent the real effect that is expected of the PM actions and always leads to a decrease on the system production availability when the ageing processes of the components are ignored. Although the assumption of constant failure rates can be easily relaxed when using simulation based approaches, more realistic models of preventive maintenance that reflect the current industrial practices are necessary to properly assess the benefit of the different maintenance strategies in multi-unit and multi-state productions systems, as discussed in [13].

The present study adopts an age-based imperfect preventive maintenance model for assessing the availability of the offshore oil and gas production system, which allows a proper comparison of different maintenance strategies such as corrective replacements and age based perfect and imperfect preventive repairs. The age-based preventive maintenance is an imperfect repair action that after each intervention reduces the equipment age by ratio q [7]. The ratio q varies within 0 and 1 (i.e., $0 \le q \le 1$), thus, if $q = 1$, the component's age is updated to as-good-as-new, which is equivalent to the perfect preventive maintenance; besides, if $0 \le q < 1$, the preventive maintenance is imperfect. Santos et al. [26] assessed the effect of age-based preventive maintenance on the availability and maintenance costs of offshore wind turbine through Stochastic Petri Nets. This preventive maintenance strategy applied to an oil and gas production system is also adopted in the present paper.

The main objective of this paper is to conduct an availability analysis of an offshore oil and gas production system by Petri Nets and Monte Carlo Simulation. This investigation is supported by a case study of an offshore production installation that operates in a Brazilian oilfield located 300 km off the shore. The case study is defined based on general information related to the production of the reservoir's [33] and of the offshore production plant, including each component's failure states, the maintenance policy, and the production levels [31]. The equipment is defined in terms of their reliability and maintainability random characteristics, which also followed non-exponential distributions. The corrective maintenance (CM) activity includes the delay of equipment transportation from the port to the production installation [11], in addition to the damaged equipment replacement phase. The applied preventive maintenance is age-based and imperfect [7, 26]. The variation of oil and gas production flows over the exploration period are estimated.

2. Methodology

2.1. Petri Nets

Petri Nets is a generic name for tools that can be divided into three levels [25]: the Elementary Net Systems model, which is used to simulate the real-life system of trivial size; the Place/Transition Systems, or simply Petri Nets, which are the repetitive characteristics of Elementary Net Systems that give more compact representation; and the Coloured Nets, which use algebra and logic to create compact nets suitable for real applications. To simulate the behaviour of an offshore oil and gas production system, the Place/Transition System is chosen as a sufficient level for the intended objectives.

In addition to modelling and analysing systems, Petri Nets provide a graphical representation of the system. The basic graphic elements, Fig. 1, of the Place/Transition System are [19]:

- **Place** (represented by circles) – it models the system's states (e.g. system functioning).
- **Transition** (represented by rectangles) – it represents the events (e.g. system failure) which manipulate the available resources.
- **Token** (represented by small black dots) – it is a graphical representation of resources. They are always held inside the places.
- **Arc** (represented by directed arrows) – it specifies the interconnection between the places and transitions and indicates which states are changed by a certain event.

The system state is defined by the positions of the tokens in the places, i.e. by its marking [19]. A change in the marking or states is a function of the transitions and it is accomplished by removing and/or creating tokens in places according to the direction defined by the arcs [22]. This property allows to simulate the dynamic behaviour of a system [28]. It is worth noting that the Place/Transition System is a bipartite graph. Meaning that it is only possible to connect a place to a transition or vice versa, and not two places nor two transitions [3].

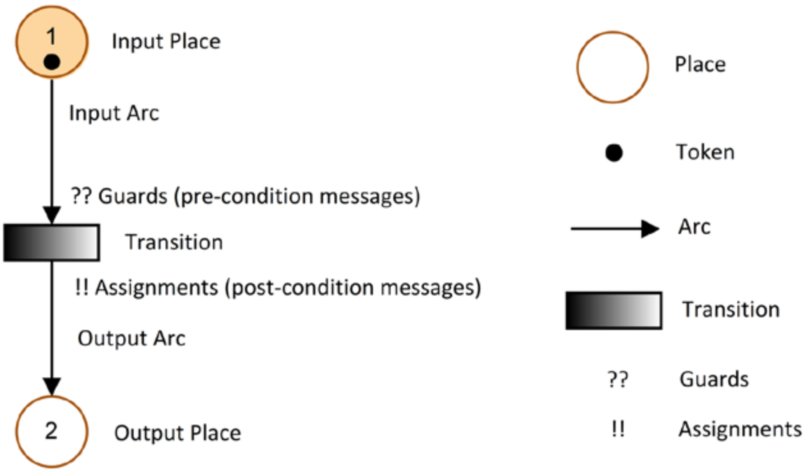

Fig. 1. Basic graphic elements of GSPN with predicates

GSPN with predicates have extended capabilities that facilitate the modelling of complex systems. For example, new attributes or predicates are associated to the transitions such as guards (pre-condition messages) to enable or inhibit the firing of transitions, and assignments (post-condition messages) that update the variables used in the model (e.g., in transitions). They are both identified with two prefixes, ? and !, respectively (Fig. *1*). Moreover, transitions can fire deterministically or stochaically. For a more in-depth insight on GSPN see e.g. [15].

2.2. Case study description

The case study is defined based on general information related to the production of the reservoirs [33] and of the offshore production plant, including the maintenance policy and the production levels [31]. The component's failure and repair times are adopted from the offshore reliability handbook OREDA [21]. The Floating Production System (FPS) is connected to 18 wells and operates in a Brazilian oilfield located 300 km off the shore.

2.2.1. Reservoir production

The oilfield reservoirs contain oil, gas and water. The maximum production capacity of liquid phase by well is 8000 bbl/day (i.e., 53 m^3/h) and of gas phase is 0.15x10^6 Sm^3/h. The pressure at the wells is considered constant through the water and/or gas injections effectuated across injection wells. Thus, the production flow is constant throughout operational life of the well.

The total oil and gas production has an evolution with three periods: Ramp-up, Peak, and Decline. The first period is two years long, the Peak period is three years long, and the total exploration life of oilfield is 27 years. It is worth noting that, one year of work is 300 days with 24 hours each. Hence, one year is equal to the 7200 hours.

During the Ramp-up period (0 – 14400 h), the 18 wells are successively connected to the FPS, i.e., 9 wells/year. Hence, the total flow of liquid phase at the Peak period (14400 h – 36000 h) is 960 m^3/h, where 10% is water and 90% is oil. The Decline period (36000 h – 194400 h) is characterized by the exponential decline. At this period, the percentage of water in liquid phase increases exponentially until 95% (thereby, the oil decreases exponentially until 5%), and the gas phase drops exponentially to 0.3x10^5 Sm^3/h.

Hence, the mathematical formulation of the oil flow is given by Equation (1), of the water flow by Equation (2), and of the gas flow by Equation (3), where Q_p means the flow at Peak period, and t is the instant in hours:

$$Q_{oil} = \begin{cases} \frac{Qp_{oil}}{14400} \cdot t \ (m^3/h), \ Ramp-up \\ Qp_{oil} \ (m^3/h), \ Peak \\ Qp_{oil} \cdot e^{-1.8\times10^{-5}\cdot(t-36000)} (m^3/h), \ Decline \end{cases} \quad (1)$$

$$Q_{water} = \begin{cases} \frac{Qp_{water}}{14400} \cdot t \ (m^3/h), \ Ramp-up \\ Qp_{water} \ (m^3/h), \ Peak \\ Q_{well} - Q_{oil\ at\ Decline} \ (m^3/h), \ Decline \end{cases} \quad (2)$$

$$Q_{gas} = \begin{cases} \frac{Qp_{gas}}{14400} \cdot t \ (Sm^3/h), \ Ramp-up \\ Qp_{gas} \ (Sm^3/h), \ Peak \\ Qp_{gas} \cdot e^{-1\times10^{-5}\cdot(t-36000)} (Sm^3/h), \ Decline \end{cases} \quad (3)$$

2.2.2. FPS plant

Fig. 2 shows the offshore production installation adopted as case study. The flow coming from the production wells (Wells) is separated through a separating unit into three different components: gas, oil and water. The gas is compressed by two 50% capacity Turbo Compressors (TCs or TC_1 and TC_2), dehydrated through a Tri-Ethylene Glycol unit (TEG) and then exported. The gas that is not compressed is burned by a flare system. The oil is exported through the Oil Pumping Unit (OPU). The water is first treated by the Water Treatment Unit (WTU), then, it is re-injected in addition with sea water in order to maintain the pressure in the oilfield.

Most components are powered by electricity. For this purpose, two 50% capacity Turbo Generators (TGs or TG_1 and TG_2) are installed to generate electricity for the production system. The electrical power production system constitutes the first operational loop. Because the processed gas by the TEG unit is used to power the TEG unit, through the connection with turbo-generators.

TCs and TGs are powered by gas. The fuel gas is taken from the output of the TEG unit and is then distributed to all TCs and TGs. Each of them consumes 0.1x10^6 Sm^3/day (i.e., 4200 Sm^3/h). The fuel gas generation system constitutes the second operational loop, where the gas compressed by the TCs is used to produce the fuel gas and the fuel gas is used to run the TCs.

To achieve the nominal level of production, the Gas Lift (GL) is used. An amount of 1.0x10^6 Sm^3/day (i.e., 42000 Sm^3/h) of the export gas is diverted and compressed by an Electro Compressor (EC), and then injected, at a pressure of 100 bar, in the well. The same amount of GL can be injected directly in the well at a lower pressure of 60 bar. In this case, the production level is reduced to 80% of its maximum. When the gas is not available for the gas lift, the production is reduced to 60% of its maximum. The gas lift system constitutes the third operational loop, since the incoming flow of the well depends on the output of the plant itself.

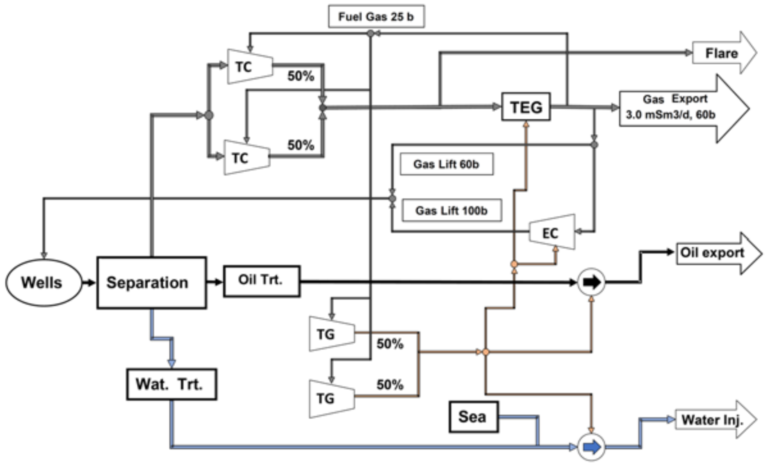

Fig. 2. Floating production system plant [31]

2.2.3. Component failure data

In this case study, only the failures of the TCs, TGs, EC, TEG, Wells, OPU and WTU are considered. All the other equipment are assumed to be perfect. Table 1 presents the component failure data.

Any equipment can be in three different conditions: the "**0** = As good as new" (i.e., the component is in an ideal state of operation), the "**2** = Failed" state (i.e., the equipment stops functioning), and the "**1** = Degraded" state (i.e., the component is maintained, but the system has a higher probability of passing to the "Failed" state). The equipment needs to be repaired when it is in the "Failed" or in the "Degraded" state.

The time, at which the equipment transitions from "As good as new" to "Degraded" or to "Failed", is represented by a Weibull Truncated distribution, with the shape parameter, β, due to this distribution accounting for the age of the equipment. The time, at which the transition from "Degraded" to "Failed" state occurs, is described by the Exponential Distribution, with the failure rate, λ, because, in this case, the failure is independent of the equipment age.

2.2.4. Production configuration

There are several production re-configurations that try to reduce the impact of a failure, first on the export of oil and then on the export of gas. The impact of the failure on the water injection is not analysed. The following paragraphs present the consequences of failures on the production configurations of each equipment:

- **TCs failures** – When one TC is lost, the quantity of non-compressed gas increases. This extra gas cannot be transported, so it is flared, thus reducing the quantity of exported gas, but the oil export, the fuel gas, and the gas lift do not change. When all TCs are lost, the production is interrupted, because the electricity power on installation depends on the fuel gas production.
- **EC failures** – the stopping of the EC reduces the pressure on the gas lift, which decreases the production capacity of the well, which in turn reduces the oil and gas exports.
- **TGs failures** - When one TG is lost, the EC and the water injection stop due to the low level of electricity production. Hence, the oil and gas exports reduce. When all TGs are lost, the total production is stopped, due to the interruption of electricity production.
- **TEG, Wells, OPU or WTU failures** – The total production is interrupted.

2.3. Maintenance strategies

The maintenance strategies considered include corrective maintenance (CM) and preventive maintenance (PM) actions. The CM tasks entail only unplanned replacements whereas PM activities are age-based and imperfect that after each intervention reduces the equipment age by a ratio q, i.e., the component is q% younger. The ratio q varies within 0 and 1 (i.e., $0 \le q \le 1$), thus, if $q = 1$, the component's age is updated to 0 and, therefore, the component is *as-good-as-new*, which is equivalent to a perfect preventive maintenance; besides, if $0 \le q < 1$, the preventive maintenance is imperfect.

2.3.1. Corrective Maintenance (CM)

CM activity consists of replacing the damaged equipment by a new one and includes a chain of processes from the production of equipment to its commissioning on the FPS. CM is performed by one maintenance team located at the shore. It is worth noting that, the CM team is only unavailable if it is in service with another fault on the platform.

A supply vessel, anchored at the port, is used to transport the CM team and the new equipment (regardless of its weight). The weather window is deemed available. The one-way voyage is about 200 hours (i.e., 150 hours of equipment transportation from the supplier to the port, 12 hours of loading, 24 hours of total transit time in port, 3 hours of manoeuvres in port, and 11 hours of sea trip at 14 knots speed), whereas the return trip is about 50 hours. The voyage time follows a Log-normal distribution with coefficient of variation of 20%.

Table 1. Component failure data

Comp	Transition	Distribution	β	MTTF (h)	λ (h^{-1})
TCs	**0 → 1**	Weibull Truncated	2.5	4225	-
	0 → 2		2.5	13607	-
	1 → 2	Exponential	-	-	1.50×10^{-4}
TGs	**0 → 1**	Weibull Truncated	2.5	8065	-
	0 → 2		2.5	20995	-
	1 → 2	Exponential	-	-	7.37×10^{-5}
EC	**0 → 2**	Weibull Truncated	2.5	724	-
TEG	**0 → 2**		1.5	11408	-
Wells	**0 → 2**		1.5	45033	-
OPU	**0 → 2**		1.5	5447	-
WTU	**0 → 2**		1.5	26316	-

Table 2. Corrective maintenance data (replacement phase) by equipment and its operational state

Transition		TC	TG	EC	TEG	Wells	OPU	WTU
1 → 0	Mean	17	14	-	-	-	-	-
	SD	3.4	2.8	-	-	-	-	-
2 → 0	Mean	6	40	7	13	33	53	66
	SD	1.2	8	1.4	2.6	6.6	10.6	13.2

Table 3. Repair priority levels of production components

LP	Description	System conditions
1	It applies to failure leading immediately to the total loss of the process	TEG, both TGs, both TCs failures
2	It is used when only a part of the export oil is lost	Single TC or EC failure
3	It pertains to failures when no export oil is lost	Single TG failure
4	It is used when the component is working, but with higher probability of moving to the Failed state	Single/both TCs degradation, Single/both TGs degradation

Table 2 presents the mean duration of equipment replacement and the respective standard deviation (SD). This time depends on the type of equipment and of its production state (i.e., degraded or failed). The duration of CM follows a Log-normal distribution with coefficient of variation of 20%.

CM policy is defined as follows:

- Equipment in series are repaired only when they are under a critical failure;
- For equipment in parallel (TGs or TCs), the first failure is repaired if degraded or critical and the next one only if it is critical;
- When several failures are waiting for repair at the same time, they are repaired according to their level of priority: 1 – 4;
- Once a repair begins it must be immediately finished, even if another failure with higher priority occurs;
- One corrective maintenance team can only repair one equipment per voyage.

Table 3 presents the level of priority (LP) of the critical failure repair that depends on the state of the system.

2.3.2. Age-based perfect and imperfect preventive maintenance

The TGs, TCs, EC and Wells are subject to periodic PM. This maintenance is started if the system is in the perfect state of operation or if the equipment is stopped, but not damaged. It is worth noting that, once a PM begins, it must be finished, even if a critical failure occurs in another equipment.

PM is performed by a single team, which is located on-board the FPS and is ready to intervene immediately. PM tasks are performed considering an age reduction ratio, q ($0 \le q \le 1$). Therefore, after repair intervention, the component is q younger, i.e., the age is reduced by q percent, and its age after PM activity is described by [7]:

$$\begin{gathered} Age_i = Age_i^{acc} \cdot (1-q) \Leftrightarrow \\ \Leftrightarrow Age_i = (t_i - t_{i-1} + Age_{i-1}) \cdot (1-q) \end{gathered} \tag{4}$$

where, Age_i and Age_{i-1} are the component's consecutive ages after i^{th} and $(i-1)^{th}$ maintenance tasks, respectively; $(i-1)^{th}$ 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 ac-

Table 4. Preventive maintenance strategy

PM Strategy	Component	Period (h)	Duration (h)	Recovered age (%)
1	TCs	6500	15	50
2	TGs	11000	30	50
3	EC	330	15	50
4	Wells	9000	60	50

tions, respectively. As referred before if $q = 1$ the component is as-good-as-new ($Age_i = 0$) after the intervention and the age-based PM is denoted as *perfect*. The age-based PM is *imperfect* if the intervention is not able to recover the component to its new condition, which corresponds to age reduction ratios q in the range $0 \le q < 1$.

Since the PM is stochastically driven, the fixed maintenance cost is not considered in this paper. Four different strategies of PM activities are considered and presented in Table 4.

3. Numerical Results

The availability analysis of the offshore oil and gas production system is conducted using the GRIF (Graphical Interface for reliability Forecasting) analysis software [35]. To simulate the PN model, GRIF uses MOCA-RP computation engine based on MCS. When the techniques based on Generalized Stochastic Petri Nets are combined with Monte Carlo Simulation, they can model and analyse the complex behaviour of an industrial multi-unit system [29], due to their transitions that can fire deterministically, stochastically and be conditioned by predicates (i.e., by guards and assignments).

At the initial instant of simulation, the PN model has all components of FPS in operation with null initial age (i.e., as good as new), the CM team is at the port and the PM team is on-board the FPS.

The simulated time of the base model is defined by iterations from instant 0 to instant 194400 hours with a step of 200 hours for 1000 different scenarios (i.e., histories). The average error related to the 90% CI (Confidence Interval) of the number of simulation histories is 0.03%.

First, a simple example illustrating the modelling of corrective and age-based preventive maintenance strategies on a single component is presented in section 3.1 and then the availability results of the offshore oil and gas production system subjected to age-based imperfect preventive maintenance are presented and discussed in section 3.2.

3.1. Corrective and age-based preventive maintenance modelling and analysis

The Petri Net models of the Electro Compressor (EC) subjected to corrective maintenance and age-base perfect and imperfect preventive maintenance are presented in Figure 3. The EC is an equipment that operates at its maximum capacity until the first critical failure. Hence, after each corrective maintenance, the damaged equipment is replaced by a new one. Using the case study data for the EC, the effect of different preventive maintenance strategies on the availability can be estimated. For this purpose, three cases are analysed:

- Case 1 – EC with only CM
- Case 2 – EC with CM and perfect PM - age reduction ratio $q = 1.0$
- Case 3 – EC with CM and age-based imperfect PM - age reduction ratio $q = 0.5$

It is worth noting that the analysis is independent from the behaviour of the rest of the system. Besides, the CM and PM teams are considered as always available.

Case 1 is represented by three places (i.e., *EC1_Work*, *EC1_Failed*, *EC1_Repair*) and three transitions (i.e., *EC1_Failure*, *EC1_StartRepair* and *EC1_FinishRepair*). The PN model of Case 2 is equal to Case 1 with perfect PM added (i.e., two transitions: *EC2_PM_Period* and *EC2_PM_Duration*; and one place: *EC2_PM*). Case 3 has the same PN model of Case 2, but with the age-based PM conditions added in guards and assignments of the transitions.

Additionally, the variable *EC_Available* is used to determine whether the equipment is working (i.e., *EC_Available == true*), or has failed (i.e., *EC_Available == false*). The PN model of EC subjected to preventive maintenance has three important variables: *EC_Age*, *EC_LastCM* and *EC_LastPM*. The first registers the EC's age in hours, the others record the time of the completion of the last corrective and preventive repair, respectively. Note that after each CM and perfect PM, *EC_Age* is set to zero.

When the token is located at place *EC_Work*, it means that EC is in operation and variable *EC_Available* is true. Electro Compressor fails when the transition *EC_Failure* is enabled, and the delay is elapsed according to the truncated Weibull distribution (see Table 1). Through the firing rule, *EC_Work* is unmarked, because the token is moved to the place *EC_Failed*; besides, *EC_Available* changes to false. Since the CM team is always available, after 200 hours, the transition *EC_StartRepair* is enabled and the token moves to the place *EC_Repair*. The duration of CM activity is given in Table 2. When this transition is enabled, the CM repair is concluded, thus, the token moves to *EC_Work*, the variable *EC_Available* changes to true, *EC_Age* changes to null, and *EC_LastCM* records the time of completion of corrective repair.

Preventive maintenance is a scheduled activity. When the place *EC_Work* is marked, the Log-Normal distribution delay (see Table 4) of transition *EC_PM_Period* is counting the time to set the time interval between PM activities. When the delay time of *EC_PM_Period* runs out, the token moves to the place *EC_PM*. When PM is conclud-

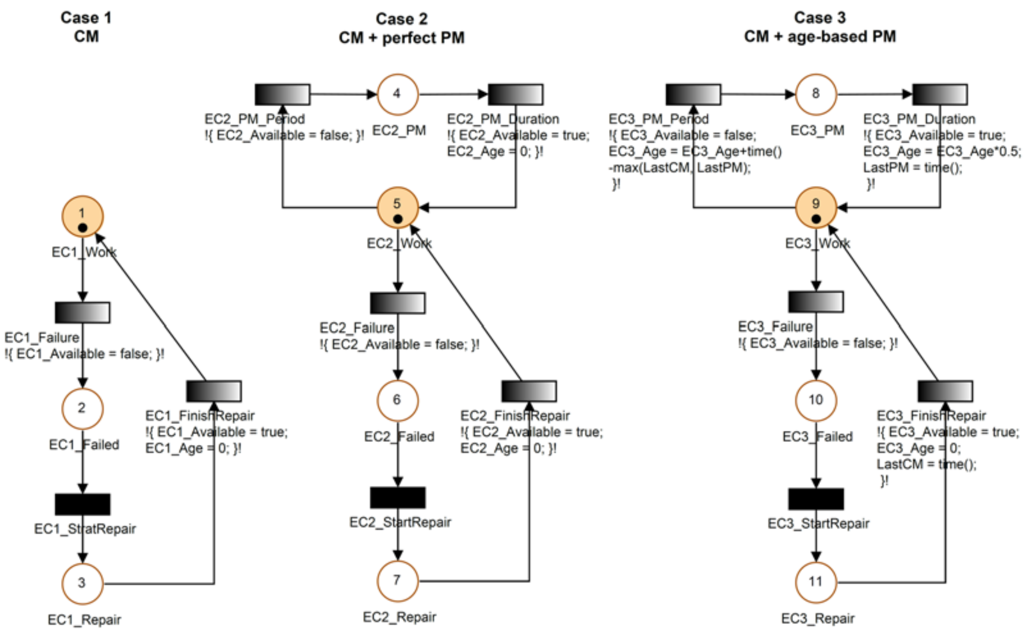

Fig. 3. PN models of Electro Compressor (EC)

ed, the transition *EC_PM_Duration* is enabled. Its delay is elapsed according to the Log-Normal distribution (see Table 4). After enabling the transition, the EC's age is updated according to the analysed case (i.e., in Case 2 the PM is perfect, hence, *EC2_Age = 0*; besides, in Case 3, the PM is age-based, hence, *EC3_Age = EC3_Age*0.5*).

To assess the EC's availability, it is considered that the simulation time is defined by iterations from instant 0 to 194,400 hours with a step of 200 hours for 1000 histories. The asymptotic availabilities of EC for different PM strategies (i.e., Ai, i={1,2,3}) are presented in Figure 4. As expected, the highest availability (i.e., A2 = 0.9012) corresponds to the Case 2 (i.e., EC with CM and perfect PM). Besides, the availability of EC with an age-based PM (i.e., A3 = 0.8202) is higher than with only a CM repair (i.e., A1 = 0.7778). Counting the number of transition *EC_Failure* firings, the number of EC's failures is possible to determine (see Table 5). From the obtained results, it is observed that PM reduces the number of failures.

Table 5. Number of EC's failures by Case

	Case 1	Case 2	Case 3
Nº of failures	208.7	57.0	139.5

The availability of system subjected to PM depends on the following factors: recovered age, period and duration of PM. The number of failures influences the equipment's availability, too. However, this factor is a consequence of PM policy. Thus, to improve the availability, it is possible to increase the recovered age, as the Case 2 shows, or to decrease the period or duration of PM. For example, considering the Case 3 and reducing by half the duration of PM, the availability increases from 0.8202 to 0.8335. Besides, considering the same Case 3 and changing the period of PM by ± 50% (see Table 6), the availability varies within ± 2%, but the rate of change of the number of failures is higher. Thus, the decrease of the time interval between PMs is efficient to reduce the number of failures.

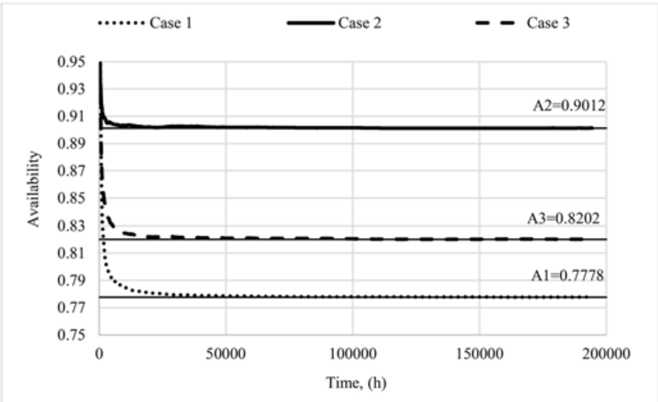

Fig. 4. Availability of EC for different PM strategies

Table 6. Influence of time interval between PMs on the availability of EC (Case 3)

Period (h)	165 (−50%)	330	495 (+50%)
Availability	0.8457	0.8202	0.8033
Nº of failures	75.6	139.5	168.7

3.2. Availability of the offshore oil and gas production system subject to different maintenance strategies

From the simulation results, the availability of the system is given in Table 7. Considering already conducted studies, it can be stated that the obtained availabilities are close to the expected interval (e.g., 90.3% [5], 96.4% [17], 97.3% [20]).

The availabilities of TEG, of TG and TC subsystems, of OPU, of WTU and of Wells are equal to the availability of total system. These constitute the non-redundant subsystems, that is, if at least one of them fails, the whole system will shut down, and this dependence results in all of them having the same availability. However, the availabilities of individual EC, TC, or TG are lower than the availability of the total system, due to the configuration of the production system. Table 8 presents the availability of redundant components with age-based PM (i.e., imperfect PM).

The availabilities of TC1 with TC2 and of TG1 with TG2 are very close to each other. This is because the components are working in parallel and with the same processing capacity. The EC shows the lowest availability of all components of the offshore processing plant.

Table 7. Availability of total system for different PM strategies

	Availability
Without PM	0.9067
Imperfect PM	0.9075
Perfect PM	0.9127

3.2.1. Effect of PM on equipment availability

The effect of PM on equipment availability is analysed considering the entire system. For this purpose, three different types of PM are assessed: equipment with no PM intervention, equipment with imperfect PM as defined by the case study, and equipment with perfect PM, after which the component is as good as new (i.e., the recovered age of equipment is 100%).

Table 9 shows the influence of PM on TG's and TC's availabilities. The obtained results show that the PM does not change significantly

Table 8. Availability of redundant equipment

Equipment	EC	TC1	TC2	TG1	TG2
Availability	0.7062	0.8896	0.8894	0.8961	0.8962

Table 9. Influence of PM on TG's and TC's availabilities

	TG1		TC1	
	Availability	Nº of failures	Availability	Nº of failures
Without PM	0.8955	13.8	0.8885	25.6
Imperfect PM	0.8961	13.4	0.8896	25.3
Rate of change	+ 0.06%	−2.8%	+ 0.12%	−1.3%
Perfect PM	0.9027	12.5	0.8969	24.1
Rate of change	+ 0.72%	−9.2%	+ 0.95%	−5.9%

the availability, neither the number of failures. Besides, the increase of recovered age does not interfere fundamentally, too. The reason is CM policy for equipment in parallel, where the first failure is repaired if degraded or critical and the next one only if it is critical.

Table 10 shows the influence of PM on EC's availability. As it is possible to see, this can improve the availability by up to 13%, besides, the number of failures decreases significantly: from 200, without PM, to 57 with the perfect PM, that is -71%.

Table 11 shows the influence of PM on the availability of Wells. As it is possible to see, the number of failures of Wells decreases 36% with the imperfect PM and 61% with the perfect PM.

Table 10. Influence of PM on EC's availability

	EC	
	Availability	Nº of failures
Without PM	0.6622	200.8
Imperfect PM	0.7062	137.3
Rate of change	+ 4.40%	-31.7%
Perfect PM	0.7953	57.7
Rate of change	+ 13.31%	-71.3%

Table 11. Influence of PM on Wells availability

	Wells	
	Availability	Nº of failures
Without PM	0.9067	4.1
Imperfect PM	0.9075	2.608
Rate of change	+ 0.08%	-36.4%
Perfect PM	0.9127	1.578
Rate of change	+ 0.60%	-61.5%

3.2.2. Oil production

Considering the age-based PM policy, the changes in oil production over time are presented in Fig. *5*. As can be observed, the oil production is divided in three parts. The first two years correspond to increasing numbers of the wells connected to the FPS. Beyond that, three years of oil peak production are observed. At the end of the fifth year (i.e., 36,000 h), due to the increase in the amount of extracted water, oil flow declines exponentially.

At the peak period, the model oil flow production is 748 m3/h, which corresponds to 87% of the maximum predicted capacity (i.e., 864 m3/h). In the exponential decline phase, the oil flow production of base model converges to that of the theoretical prediction.

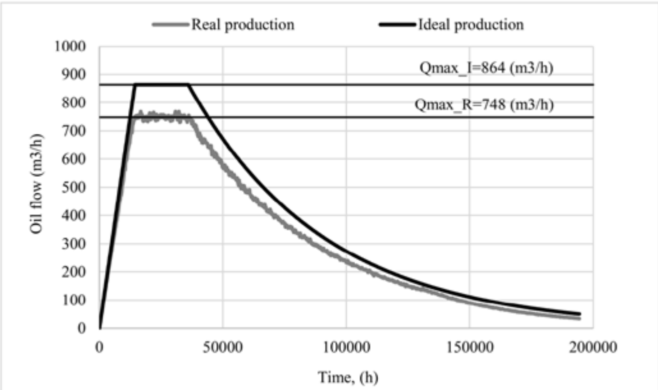

Fig. 5. Behaviour of oil production over time

3.2.3. Gas Production

Considering the age-based PM policy, the behaviour of gas export and production is presented in Fig. *6*. It is worth noting that, the generic behaviour of gas flow is equal to the oil production curve, with 3 production periods: the ramp-up, the peak and the decline.

The real production curve refers to the gas extracted from the wells. It has a similar behaviour that of ideal production prediction. At the peak period, the maximum gas flow of the model is about 127349 Sm^3/h, which is 85% of the maximum predicted capacity. In the exponential decline period, the model results converge to those of the theoretical prediction.

The export gas curve is defined within the 5400 – 130600 hours interval. In the remaining time, the system does not produce enough gas to be exported.

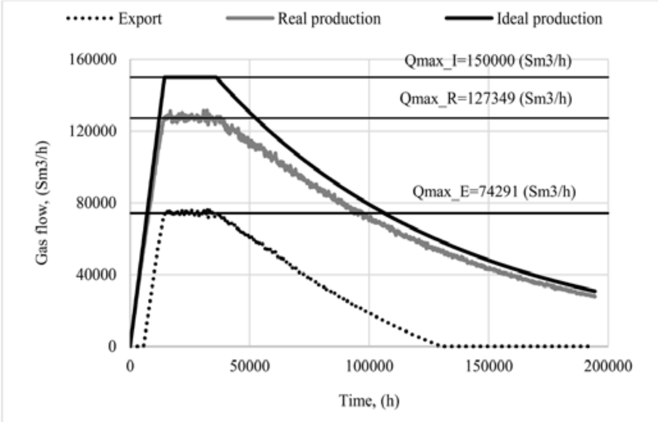

Fig. 6. Behaviour of gas export and production over time

3.2.4. Elasticity analysis

An elasticity analysis is conducted to identify the parameters that most influence the oil production capacity. The elasticity factor is a dimensionless measure defined as the percentage change in oil production flow, Q_{oil} , by 10% increase in input variable, x_i :

$$E_{x_i} = \frac{\%\Delta Q_{oil}}{\%\Delta x_i} \tag{5}$$

The elasticity analysis is conducted at the peak period of production of the system with age-based PM policy. Thus, the simulated time of the base model is defined by iterations from instant 14400 h to 36000 h with a step of 200 hours for 4000 different scenarios (i.e., histories). Each input parameter of the model is analysed individually. These include the voyage time of CM team, MTTF and MTTR of all offshore production system components, the duration and interval between PMs. Fig. *7* presents the magnitude of the elasticity factors of the top 10 most important input parameters, in decreasing order of importance, described in Table 12. As can be seen, the most influential input parameter on the oil production capacity is the CM team voyage time. The results indicate that a 10 % increase in the CM team voyage time results in a variation of around 1.3% on the oil production flow, according to Equation 5. The remaining important input parameters are the mean time to failure of OPU and EC, the period and duration of the preventive maintenance of the subsea production system (i.e., *PM_type3_Period* and *PM_type3_Duration*), the duration of TG's PM (*PM_type2_Duration*) and the mean time of corrective maintenances of TG, WTU and EC.

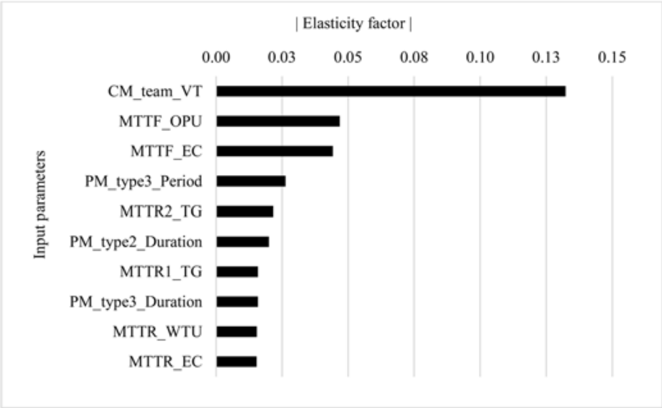

Fig. 7. Elasticity analysis of the input parameters

Table 12. Main input parameters of the PN model

Parameter	Description
CM_team_VT	Voyage time of corrective maintenance team from the port to the floating production system
MTTF_OPU	Mean time to failure of oil pumping unit from the as good as new condition to the failure
MTTF_EC	Mean time to failure of electro compressor from the as good as new condition to the failure
PM_type3_Period	Periodicity of preventive maintenance (PM) of type 3. This PM is applied to the subsea production system and it recovers 50% of the equipment age
MTTF2_TG	Mean time to failure of turbo generator from the degraded state to the failure
PM_type2_Duration	Duration of preventive maintenance (PM) of type 2. This PM is applied to the electro compressor and it recovers 50% of the equipment age
MTTR1_TG	Mean time to repair of turbo generator to substitute the degraded equipment by a new one
PM_type3_Duration	Duration of preventive maintenance (PM) of type 3. This PM is applied to the subsea production system and it recovers 50% of the equipment age
MTTR_WTU	Mean time to repair of water treatment unit to substitute the failed equipment by a new one
MTTR_EC	Mean time to repair of electro compressor to substitute the failed equipment by a new one

4. Conclusion

The main objective of this paper is to analyse the availability of an offshore oil and gas production system subjected to an age-based preventive maintenance. For this purpose, the classical reliability tools and the Markov approach are unsuitable. The first one is only applicable to binary systems and the Markov approach is used in small systems with events described by exponential distributions. Thus, in this paper the Generalized Stochastic Petri Nets coupled with the Monte Carlo Simulation method are used.

The analysed case study is defined based on general information related to the production of a reservoir and of an offshore production plant.

To assess the influence of age-based PM, a simple equipment availability assessment for EC is presented. From the obtained results, it is concluded that the availability of the equipment subjected to PM depends on the recovered age, period and duration of PM. More precisely: the greater the recovered age, the greater the availability. Besides, the greater the duration of PM, the lower the availability. The decrease of the time interval between PMs is efficient to reduce the number of failures.

The simulation results show that the availability of the system is 0.9075, which is in line with the values obtained by other studies.

At the peak period, the model oil flow production is 748 m3/h, which corresponds to the 87% of the maximum predicted capacity (i.e., 864 m3/h). The maximum gas production of the model is about 127349 Sm3/h, which is 85% of the maximum expected (150000 Sm3/h).

An elasticity analysis shows that the most influential model parameters on the oil production capacity are the CM team voyage time, the time to failure of OPU and EC, the period and duration of the PM of EC, the duration of the PM of TGs and the corrective maintenances of TG, WTU and EC.

The availability analysis of the FPS adopted a Simple Place/Transition PN. This tool becomes difficult to read graphically as the production system complexity increases. Hence, in further works it is recommended to use the Coloured PN, which facilitates the graphical representation.

To improve the detail of the availability analysis of the FPS, the separator, the flare system, the oil treatment unit and the water pumping unit can be added.

For a more detailed study, the maximum processing capacities of the production components and the electrical power consumption may be considered.

More accurate estimates of the time of CM can also include manufacturing time and the transportation time of the equipment from the port to the FPS and the weather window.

In order to improve the assessment of the oil, gas and water flows, additional studies should consider the natural factors that decrease the pressure at the wells, besides further studying the effects of water flooding and gas re-injection on the production availability.

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