Availability analysis of an offshore oil and gas production system by Petri Nets

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ABSTRACT: The main objective of this thesis is to model an offshore oil production system by Petri Nets and to evaluate its availability by Monte Carlo Simulation. The oil processing and the separation equipment with their reliability and maintenance characteristics, the corrective and preventive maintenance policies and the operational dependencies that lead to the reconfiguration of the system after the failure are implemented. Moreover, the variation of the oil and gas flows from the well over the years is accounted by the model. As case study, a generic offshore production installation that operates in a Brazilian oilfield is adopted. The oilfield is located 300 km off the shore and has an exploration life of about 27 years. The obtained availability results are validated, and a sensitivity analysis on the model parameters is conducted. In particular, the influence of the maintenance policy on the system availability and on the oil production is assessed.

Keywords: production availability; 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 (Dutuit et al. 1997). These models are based on Boolean algebra (i.e., the values of the variables either *true* or *false*) (Briš and Kochaníčková 2006; Teixeira and Guedes Soares 2009) 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) (Signoret 2010).

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 (Lewis 1994). 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 (Santos et al. 2015a). 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. (2015a).

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 (Zio et al. 2004). Zio et al. (2007) and Brissaud et al. (2015) presented a MCS model for the evaluation of the availability of a multi-state and multi-output offshore installation.

Petri Nets (PN) is a tool that combines graphical to mathematical modelling capabilities in order to simulate and analyse discrete event systems (Santos et al. 2013). It was first introduced by Carl Adam Petri in 1962 in his Ph.D. dissertation (Petri 1962), where he discussed the problem of representing co-operating, concurrent, or competing processes by a graphical modelling.

A quantitative analysis of the Stochastic Petri Nets (SPN) can be performed by an analytical method, but it is simpler to use MCS (Rausand 2011). The reason is in the determination of system stochastic evolution, which is not easily captured by analytical models (Marseguerra and Zio 2002).

SPN coupled with MCS has many applications in complex system simulations. Santos et al. (2012) present SPN coupled MCS as a flexible method for assessing the regularity of the system's production, quantified by its throughput capacity distribution. Grunt and Briš (2015) use SPN and MCS for modelling of risk to personnel safety in process industries. Santos et al. (2015b) simulate the operation and maintenance activities of offshore wind turbines, considering logistic resources, time vs costs, and weather constraints.

Briš and Kochaníčková (2006), Teixeira and Guedes Soares (2009) and Briš (2013) combine SPN 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 (Guedes Soares 2010). The case study included different processes like the corrective and preventive maintenance policy, component degradation, production re-configuration and production level. However, the implemented simulation model has various limitations. In the proposed test case, only the failures of the Turbo-Compressors, Turbo-Generators, Electro-Compressor and Tri-Ethylene Glycol unit are considered. The maximum capacities of oil, gas and water production are constant throughout simulated time. All transitions related to component fail/degradation and all maintenance actions are exponentially distributed. The number of corrective maintenance teams is fixed to one.

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 a generic 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 and of the offshore production plant, including each component's failure states, the maintenance policy, and the production levels. The equipment is defined in terms of their reliability and maintainability random characteristics, which also followed non-exponential distributions.

2 PETRI NETS

Petri Nets is a generic name for tools that can be divided into three levels (Reisig and Rozenberg 1998): 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.

2.1 Basic elements

In addition to modelling and analysing systems, Petri Nets provide a graphical representation of the system. The basic graphic elements, Figure 1, of the Place/Transition System are (Murata 1989):

- **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.

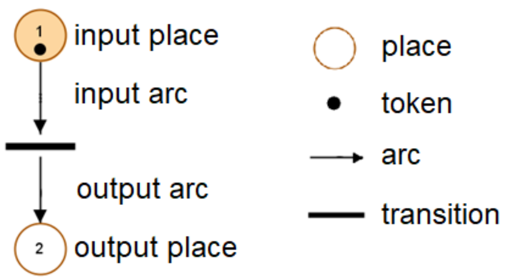

Figure 1 – Basic graphic elements of Petri Nets (GRIF)

The system state is defined by the positions of the tokens in the places, i.e. by its marking (Murata 1989). 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 (Peterson 1981). This property allows to simulate the dynamic behaviour of a system (Teixeira and Guedes Soares 2009). 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 (Bause and Kritzinger 2002).

2.2 Advanced elements

The advanced elements increase the calculation capacity and simplify the visualization and graphical interpretation. The most common advanced elements used in the PN model are messages and arc multiplicity.

Any transition is conditioned by guards and assignments. The guards are pre-conditions that can enable or inhibit the firing of transitions, while the assignments are post-condition messages that update variables used in the model (e.g., in transitions). Both are identified with the prefixes *??* and *!!* respectively (Santos et al. 2015a). In other words, the guard is the received message by a transition and the assignment is the emitted message.

The arc multiplicity is the number of tokens which can be moved through the arc. In the graphical representation, the multiplicity is written beside the arc. If the arc is without a number, it is mean that the multiplicity is one. To implement the order of priority, the inhibitor arcs are normally used, which graphically are represented by dotted lines. While the multiplicity of normal arc has a positive weight meaning, in the inhibitor arcs it has a negative weight meaning.

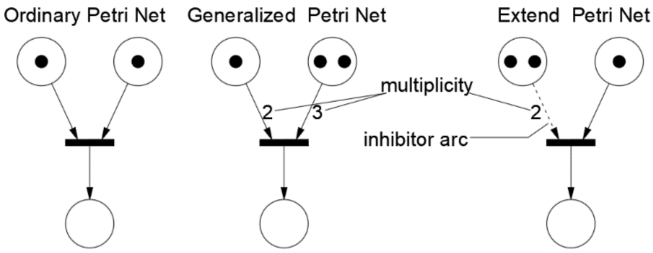

Figure 2 – Simple examples of different Petri Net types

A net in which all arcs have a multiplicity of one is called the Ordinary Petri Net (Peterson 1981), (Murata 1989). When the net has an arc with multiplicity larger than one, it is called the Generalized Petri Net (Peterson 1981). If the net contains an inhibitor arc, it is called the Extended Petri Net (Murata 1989). Figure 2 illustrates the different types of PN.

2.3 Enabling and firing rules

The enabling and firing rules are associated with transitions. An enabling rule defines the conditions under which transitions are allowed to fire, while the firing rule describes the marking modification included by the firing of the transition (Marsan et al. 1995). Both rules are specified through the arcs.

Enabling rule (see Figure 3): a transition is called enabled if and only if each input place contains a number of tokens greater or equal than a given multiplicity of arc and if each inhibitor place contains a number of tokens strictly smaller than a given multiplicity of inhibitor arc.

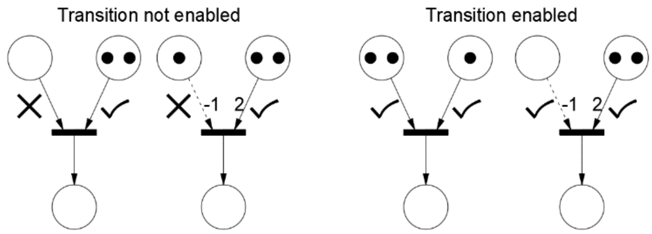

Figure 3 – Examples of enabling rule application

Firing rule (see Figure 4): when transition fires, it removes from each place in its input set as many tokens as the multiplicity of the arc connecting to that place indicates and adds to each place in its output set as many tokens as the multiplicity of the output arc indicates.

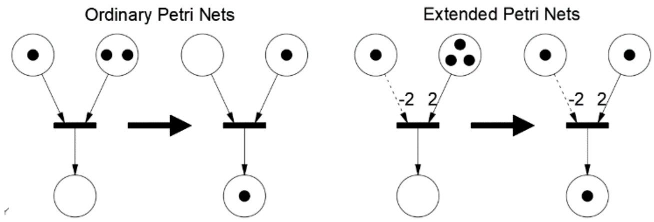

Figure 4 – Two examples of transition firing rule in PN

3 CASE STUDY DESCRIPTION

The case study is defined based on general information related to the production of the reservoir's (Souza et al. 2017) and of the offshore production plant, including each component's failure states, the maintenance policy, and the production levels (Signoret 2004). The Floating Production System (FPS) is connected to 18 wells and operates in a Brazilian oilfield located 300 km off the shore.

3.1 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 0.15×10^6 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 $0.3\text{x}10^5$ 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 Qp means the flow at Peak period, and t is the instant in hours.

$$Q_{oil} = \begin{cases} \dfrac{Qp_{oil}}{14400} \cdot t \ (m^3/h), \_Ramp-up \\ Qp_{oil} \ (m^3/h), \_Peak \\ Qp_{oil} \cdot e^{-1.8\times10^{-5}\cdot(t-36000)} \ (m^3/h), \_Decline \end{cases} \quad (1)$$

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

$$Q_{gas} = \begin{cases} \dfrac{Qp_{gas}}{14400} \cdot t \ (Sm^3/h), \_Ramp-up \\ Qp_{gas} \ (Sm^3/h), \_Peak \\ Qp_{gas} \cdot e^{-1\times10^{-5}\cdot(t-36000)} \ (Sm^3/h), \_Decline \end{cases} \quad (3)$$

3.2 FPS plant

Figure 5 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 through 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.

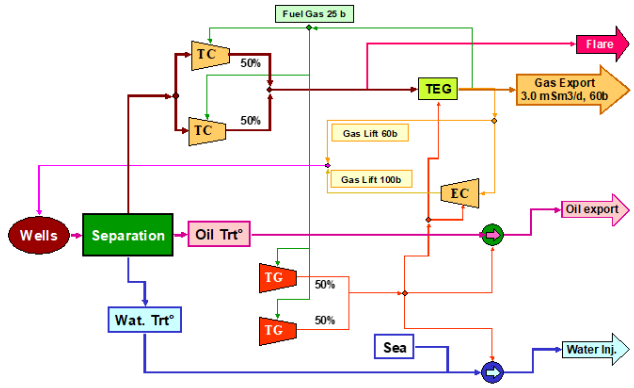

Figure 5 – Floating production system plant (Signoret 2004)

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 $0.1\text{x}10^6$ 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 $1.0\text{x}10^6$ 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.

3.3 Component failure state

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. In Table 1, the component failure data is given.

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 the failure, in this case, is independent of the equipment's age.

Table 1 – Component failure data

Comp	Transition	Distribution	β	MTTF (h)	λ (h^{-1})
TCs	**0 → 1**	Weibull Truncated	2.5	1493	-
	0 → 2		2.5	1351	-
	1 → 2	Exponential	-	-	2.12×10^{-3}
TGs	**0 → 1**	Weibull Truncated	2.5	1266	-
	0 → 2		2.5	1299	-
	1 → 2	Exponential	-	-	1.86×10^{-3}
EC	**0 → 2**	Weibull Truncated	2.5	5882	-
TEG	**0 → 2**		1.5	17544	-
Wells	**0 → 2**		1.5	87719	-
OPU	**0 → 2**		1.5	43668	-
WTU	**0 → 2**		1.5	2924	-

3.4 *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.

3.5 *Maintenance policy*

3.5.1 *Corrective maintenance (CM)*

CM activity consists of both transportation of the equipment from the port to the FPS and replacement of the damaged equipment by a new one. The new equipment to replace is considered always available in the port.

CM can be performed by up to three maintenance teams, where only one team is required to replace one equipment. Each team is located at the shore, and is only unavailable, if it is in service with another fault on the platform.

One supply vessel per CM team is considered, which is anchored at the port and is used to transport the team and the new equipment (regardless of its weight). The weather window is deemed available. The one-way voyage is about 50 hours, which include: 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. The voyage time follows a Log-normal distribution with coefficient of variance of 20%.

Table 2 – Duration of CM (in hours) by equipment and its operational state

Transition		TC	TG	EC	TEG	Wells	OPU	WTU
1 → 0	Mean	30	31	-	-	-	-	-
	20%	6	6.2	-	-	-	-	-
2 → 0	Mean	21	26	31	33	168	3	4
	20%	4.2	5.2	6.2	6.6	33.6	0.6	0.8

Table 2 presents the mean duration of equipment replacement. 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 variance 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.

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

3.5.2 Preventive maintenance (PM)

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 onboard the FPS and is ready to intervene immediately. PM tasks are performed considering an age reduction ratio, q $(0 < q < 1)$. 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 (Santos et al. 2015b):

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

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 $Age_i = 0$.

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

Table 4 – Preventive maintenance strategy

Type of PM	Component	Period (h)	Duration (h)	Recovered age (%)
1	TCs, TGs	2160	80	20
2	EC	2666	113	50
3	Wells	17520	120	50

4 NUMERICAL RESULTS

To perform the availability analysis of an offshore oil and gas production system, GRIF analysis software is used (http://grif-workshop.com/). To effectuate the simulation of PN model, GRIF uses MOCA-RP computation engine based on MCS.

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), all the CM teams are localized at the port and the PM team is onboard the FPS. It is worth noting, depending on the number of CM teams, the base model is simulated in three different conditions, as shown in Table 5.

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 0.04%.

Table 5 – Simulated conditions in the base model

Condition	Base model particularity
1	1 CM team
2	2 CM teams
3	3 CM teams

4.1 Equipment availability

This section evaluates the availability of equipment, when varying the condition number of CM teams.

The availability of total system is presented in Figure 6. In this figure, three asymptotic availabilities, one per simulation condition, are presented (i.e., Ai, i={1,2,3}). It can be observed that the availability of the system with only one CM team available is 0.9546. If the number of teams increases, the availability of the total system is 0.9685, in Condition 2, and 0.9698, in Condition 3.

That is, assuming the Condition 1 as the base condition, if the number of CM teams is 2, the total system availability will increase 1.4%; and, if three CM teams are available for the repair, the total system availability increases 1.5%. Therefore, the use of more than two teams does not bring any substantial improvement and may not be economically viable.

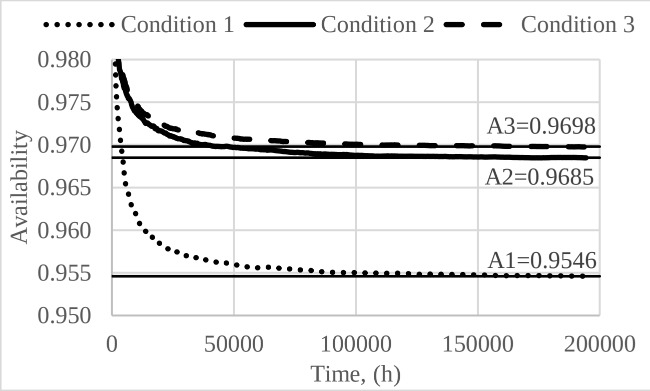

Figure 6 – Availability of total system

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 6 presents the availability of redundant components.

Table 6 – Availability of redundant equipment

Condition	EC	TC1	TG1
1	0.7891	0.8974	0.8902
2	0.8326	0.9230	0.9187
3	0.8360	0.9253	0.9211

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 same processing capacity. The EC shows the lowest availability of all components of the offshore processing plant (0.7891 in Condition 1, while the total system is 0.9546).

4.2 PM effect on equipment availability

The PM effect on equipment availability is analysed in Condition 1 (i.e., 1 CM team available for repair), considering all components as perfect, except the analysed one. For this purpose, three different conditions are assessed: equipment with no PM intervention, equipment with predicted PM by case study description, and equipment with perfect PM repair, after which the component is as good as new (i.e., the recovered age of equipment is 100%).

Table 7 shows the influence of PM of Type 1 on TC's and TG's availabilities. The obtained results show that the PM of Type 1 reduces both the equipment's availability and the number of failures. Besides, the increase of efficiency of PM by increasing the recovered age does not improve the availability and does not reduce significantly the number of failures.

Table 7 – The influence of PM of Type 1 on TG's and TC's availabilities

	TG1		TC1	
	Availab.	Nº of failures	Availab.	Nº of failures
Without PM	0.9471	169.6	0.9518	160.1
PM Type 1	0.9452	169.3	0.9495	159.9
Rate of change	-0.20%	-0.18%	-0.24%	-0.12%
Perfect PM Type 1	0.9453	168.9	0.9500	158.6
Rate of change	-0.19%	-0.41%	-0.19%	-0.94%

Table 8 shows the influence of PM of Type 2 on EC's availability. As it is possible to see, this reduces the availability by 2%, but it is efficient intervention, since the number of failures decreases significantly: from 32.1, without PM, to 6.9 in the perfect PM of Type 2, that is -79%.

Table 8 – The influence of PM of Type 2 on EC's availability

	EC	
	Availability	Nº of failures
Without PM	0.9866	32.1
PM Type 2	0.9581	19.6
Rate of change	-2.89%	-38.94%
Perfect PM Type 2	0.9596	6.9
Rate of change	-2.74%	-78.50%

Table 9 shows the influence of PM of Type 3 on availability of Wells. As it is possible to see, this PM reduces the availability of Wells by 0.5%, but it is efficient intervention, since the number of failures decreases 32% in the predicted PM and 58% in the perfect PM.

Table 9 – The influence of PM of Type 3 on Wells availability

	Wells	
	Availability	Nº of failures
Without PM	0.9978	1.9
PM Type 3	0.9924	1.3
Rate of change	-0.54%	-31.58%
Perfect PM Type 3	0.9927	0.8
Rate of change	-0.51%	-57.89%

4.3 Availability of repair maintenance teams

The availability of CM team in Condition 1 is 0.5234. If the system has two CM teams available, the availability of corrective maintenance team is much higher, it is 0.9155 (+39.2%). In the Condition 3, the total availability of CM teams is 0.9906, which is nearly 100%. The increasing number of CM teams does not influence on the availability of PM team. Thus, the availability of PM team in any simulated condition is 0.9659.

4.4 Oil production

The changes in oil production over time with one CM team available is presented in Figure 7. 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., 36000 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 796 m3/h, which corresponds to 92.1% 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.

The average flow of oil production at peak period for 3 conditions is presented in Table 10. The results show that the increase of the CM teams increases the oil production by 2%.

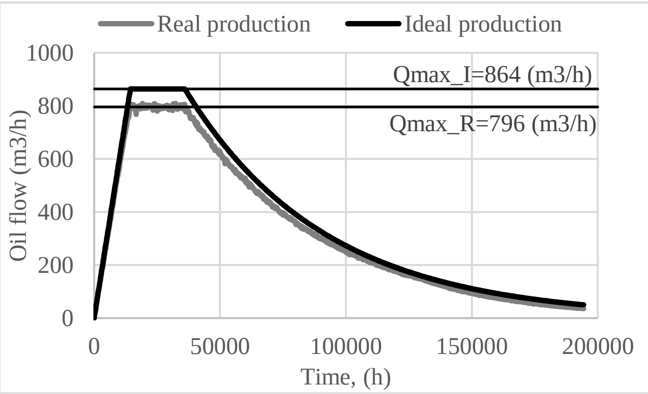

Figure 7 – Behaviour of oil production over time in Condition1

Table 10 – Average oil production at peak period

Condition	Average oil production (m^3/h)	% of Qmax_I	% of improve in relation to Condition 1
1	796	92.1	0.0
2	813	94.1	2.0
3	815	94.4	2.2

4.5 Gas production

The behaviour of gas export and production is presented in Figure 8. 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.

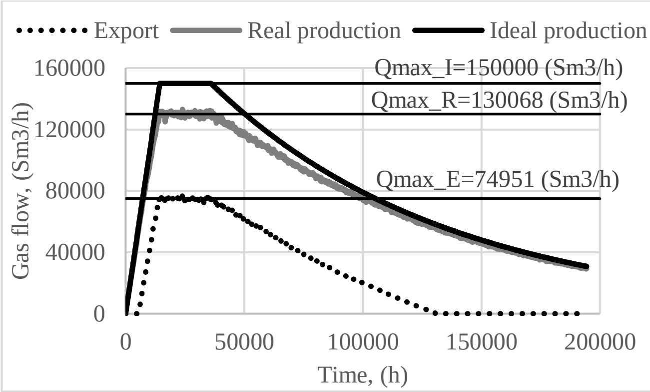

Figure 8 – Behaviour of gas export and production over time in Condition 1

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 130068 Sm^3/h, which is 87% 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 5000 – 130400 hours interval. In the remaining time, the system does not produce the sufficient quantity of gas to be exported.

Table 11 – Average gas production at peak period

Condition	Average gas production (Sm^3/h)	% of Qmax_I	% of improve in relation to Condition 1
1	130 068	86.7	0.0
2	134 652	89.8	3.1
3	135 163	90.1	3.4

The influence of increasing the number of CM teams on the gas production capacity is presented in Table 11. These results show the average flow of produced gas at peak period for the 3 conditions and conclude that the increase of the number of CM teams increases the gas production by 3%.

4.6 Sensitivity analysis

A sensitivity analysis is conducted at the peak period of production. The simulated time of the base model is defined by iterations from instant 14400 h to 36000h with a step of 200 hours for 4000 different scenarios (i.e., histories). Each input parameter is analysed individually.

Figure 9 shows the partial derivative sensitivity measure of each input parameter in decreasing order. As can be seen, the most influential input parameters on the oil production capacity are the corrective maintenances of the OPU and of the WTU, the duration of the PM of type 1 (i.e., PM of the TCs and TGs, which is conducted every 2160 h with 80 h of duration and which recovers 20% of the equipment age), the duration of the PM of type 3 (i.e., PM of the wells, which is carried out every 17520 h with 120 h of duration and which recovers 50% of the equipment age), and the CM team voyage time.

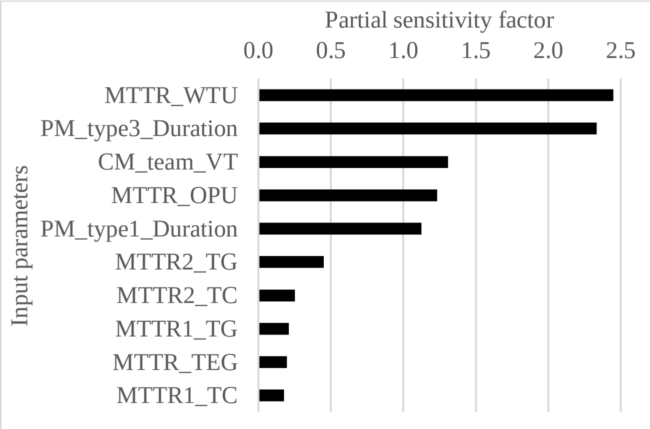

Figure 9 – Sensitivity analysis of the input parameters

5 CONCLUSIONS AND FURTHER WORKS

The main objective of this paper is to analyse the availability of an offshore oil and gas production system. 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 is used.

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

The availability results show that the use of more than two CM teams is not reflected into substantial improvements. The availability of the system with one CM team is 0.9546, with two CM teams it is 0.9685 (+1.4%), and with three CM teams it is 0.9698 (+1.5%).

At the peak period, in Condition 1, the model oil flow production is 796 m3/h, which corresponds to the 92.1% of the maximum predicted capacity (i.e., 864 m3/h). The maximum gas production of the model is about 130068 Sm3/h, which is 87% of maximum expected (150000 Sm3/h). The increase of the number of CM teams (from two CM teams to three) increases the oil production by 2% and gas production by 3%.

A sensitivity analysis showed that the most influential model parameters on the oil production capacity are the CM of the OPU and of the WTU, the duration of the PM of Type 1, the duration of the PM of Type 3, and the voyage time of CM team.

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 the 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 module the time of manufacture of the equipment in a factory, the transportation time of that 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 waterflooding and gas re-injection on the production availability.

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