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Availability Assessment of an Offshore Gas Treatment System Using Stochastic Petri Nets

Andre Gustavo Ramos and Gilberto Francisco M de Souza
Universidade de São Paulo – Escola Politécnica
Departamento de Engenharia Mecatrônica e de Sistemas Mecânicos
São Paulo, SP, Brasil

ABSTRACT

Reliability and availability of the gas treatment system is a major concern in the challenge of minimizing oil and gas losses in an offshore oil production facility. In this work, a model is built using stochastic petri Nets to analyze the availability and reliability of a simplified gas treatment. Subsystem availability increases up to a limit as the number of dedicated maintenance crews increases. The availability and reliability for gas injection is the lowest. A sensitivity analysis shows that the greater the mean time to repair the greater the influence of the mean time to failure on the availability results.

KEY WORDS: Availability; reliability; stochastic petri nets; offshore; gas treatment.

INTRODUCTION

An offshore FPSO (floating, production, storage and offloading) separates and treat oil, gas and water to meet requirements for utilization, exportation, injection and disposal. The treated oil is transferred through tankers while the treated gas can be used as fuel gas, exported through the gas distribution network, injected into the reservoir to promote oil recovery or used for artificial oil lifting. In Brazil, the National Petroleum Agency regulates and limits flaring gas volumes and controls the gas utilization based on the operator's estimations. Failures on the gas treatment system will eventually cause the oil production to stop in order to respect the flaring gas volumes. Reliability and availability analysis of the gas treatment system may contribute to evaluate and to stablish maintenance and logistics strategies that will minimize oil and gas losses.

Even though reliability block diagrams and fault tree analysis are still the most widely used tools for reliability and availability analysis, the need of dynamic features such as dependent events and spare parts modeling allowed the development of alternatives to those methods such as the use of "state machines" represented by stochastic Petri nets. A Petri net graph is a description of a system using a symbolic language. The modeling permits the analysis of complex systems or network of systems. As a graphical modeling tool, the Petri net is composed of places, transitions and directional arcs. Places represent conditions; transitions represent events and arcs direction connection, access rights or logical connections between places and transitions.

Stochastic Petri nets (SPN) includes a firing time with each transition that may represent failures occurrence. The firing of a transition causes a change of state of a given system.

Stochastic Petri nets were shown to be efficient to model interactions and dependencies between components, maintenance effects and logistics constraints (Santos et al., 2014); to model redundant systems dealing with parallelism, synchronization and resource sharing (Liu et al., 2015); to take into account dependencies between failures modes (Whiteley et al., 2015); to identify the components that cause most failures (Zeiler and Bertsche, 2015) and to test the interactions between several systems and maintenance schemes (Meyer et al., 2015).

The production availability in an FPSO has been evaluated recently through stochastic Petri nets (Bris, 2014; Meng et al., 2015), nevertheless, gas treatment and gas flaring limits implications were not addressed and other maintenance aspects such as number of repair teams available can still be discussed. This paper proposes the development of a simplified stochastic Petri net model to analyze the availability of a gas treatment system.

The paper is organized as follows: after an introduction where the gas treatment system is presented, the Petri net model of that system is presented in Section 2. In Section 3, reliability and availability analysis of the system are performed. At the end, the main conclusions of the analysis are presented.

Gas treatment system

The gas undergoes a series of processes to remove or to reduce the contaminants content and to meet the dew point specifications, maximum sulfur, carbon dioxide and water content. The compression subsystems allow reaching the pressure level required for each application. Fig. 1 presents a schematic diagram of a typical gas treatment system. The main compression subsystem receives gas from the separators and from the vapor recovery unit. The dehydration subsystem and dew point control subsystem remove water from gas enabling its use as fuel gas beyond this point. Additionally, this is a fundamental step for the CO2 removal subsystem which is intolerant to wet gas. The CO2 removal subsystem can be bypassed depending on the carbon dioxide content or availability of this subsystem. To acquire enough energy to overcome the head loss across the pipelines, the gas passes through a second compression in the exportation compression subsystem. At this pressure level, the gas can also be used for artificial oil lifting. Finally, the injection compression subsystem raises the gas pressure enough to allow its injection into the reservoir. The flaring system burns the gas streams from relief and safety valves to maintain the system pressure stable during normal operation and in the case of emergency events, such as compression subsystems failure or execution of corrective maintenance action, or during the plant commissioning.

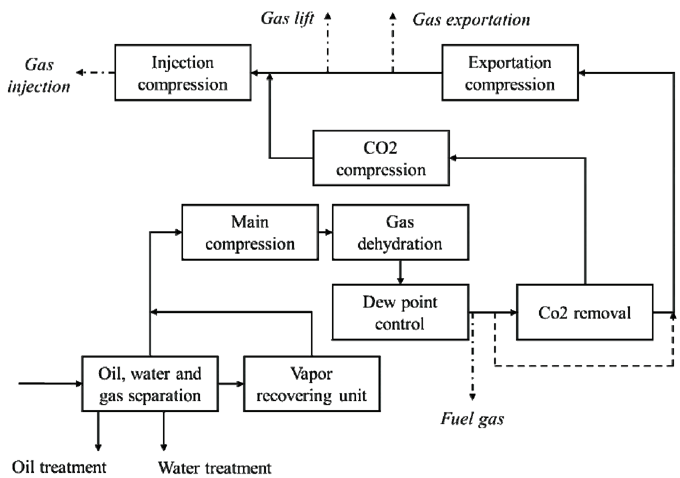

Fig. 1 Gas treatment system schematic diagram

MATERIAL AND METHODS

Petri nets describe relationships between states through the use of four main graphic symbols called places, transitions, arcs and tokens. When applied to reliability analysis, the places represented by open circles correspond to the system states, the transitions represented by rectangles can represent failures and repairs, arcs represented by arrows connect places to transitions, inhibition arcs prevent firing of transitions and tokens represented by dots identify the system state at a given time. In this paper, the eDSPNs (extended deterministic and stochastic petri nets) module of the TIMENET 4.3 (Zimmermann, 2012) is used to evaluate the availability of a simplified gas treatment system.

The simplified system contains the most representing dynamic pieces of equipment of the gas treatment system, which are: the motocompressors of the main compression subsystem, the motocompressors of the exportation compression subsystem and turbocompressors of the injection compression subsystem. The CO2 removal and compression was suppressed in this simplification since it can by bypassed, the gas dehydration and dew point control subsystems were suppressed since they are composed mainly with static equipment. Fig. 2 presents a reliability block diagram for the simplified gas compression system.

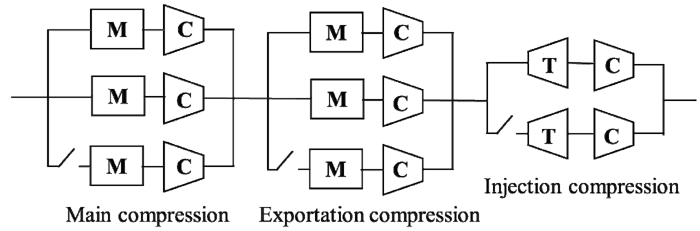

Fig. 2 Reliability block diagram for the simplified system

The reliability and maintenance data used for system simulation were extracted from the OREDA-2015 database (SINTEF and NTNU, 2015). Table 1 presents the mean time to failure and mean time to repair considered in the analysis.

Table 1. Mean time to failure and mean time to repair

Equipment	Mean time to failure (h)	Mean time to repair (h)	Source
Gas turbine	Min.551 Mean 1893 Max.269542	Mean 25 Max.504	OREDA-2015 - Gas Turbine Aeroderivate (20-40MW) - pg.98
Electrical motors	Min.16093 Mean 39936 Max.268097	Mean 24 Max.344	OREDA-2015 - Electric Motors Compressor - pg. 239
Centrifugal compressors	Min 1643 Mean 4967 Max. 142450	Mean 16 Max.232	OREDA-2015 - Compressors Centrifugal Electric Driven (30-10MW) - pg. 70

The three subsystems have standby redundancy, named k-out-of-N, which is an N-component system that works (or is "good") if and only if at least k of the N components work (or are good). The main compression and the exportation compression have a configuration 2 out of 3 and the injection compression has a configuration 1 out of 2.

Fig. 3 shows the model for the injection compression, a subsystem with configuration 1 out of 2. Both units are modeled as repairable equipment with standby redundancy and repair restrict to one at a time. Places ic_up and ic_down represent the system states Operational and Out of operation respectively. The system state depends on the state of equipment tbcp_ic_A and tbcp_ic_B. Equipment may be on states Stand-by (tbcp_ic_A/B_stb), Operational (tbcp_ic_A/B_up), Out of operation (tbcp_ic_A/B_down) and In repair (tbcp_ic_A/B_rep). Place repair_team represent the availability of the repair team that will perform corrective maintenance on the equipment. In the initial configuration, the net marking indicates that tbcp_ic_B is operational, tbcp_ic_A is in stand-by, the system is operational and the repair team is available. Exponential transitions T131 and T1111 represent the failure of equipment and the value of the MTTF (mean time to failure) is assigned to their transition. Immediate transitions T531 and T5111 when fired take equipment from state Out of operation to In repair. To enable these transitions the repair team must be available. Exponential transitions T031 and T0111 represent equipment repair and the value of MTTR (mean time to repair) is assigned to those transitions. These transitions take equipment from state In repair to Stand-by and return a token to the place repair_team making the repair team available once more. The inhibition arcs connecting place tbcp_ic_A_up and transition T231and tbcp_ic_B_up and T2111 prevents the firing of transitions T231 and T2111 so that equipment in Stand-by will only pass to its Operational state when the other equipment is not on its Operational state. The immediate transition T451 take the subsystem from place ic_up to place ic_down when both pieces of equipment are unavailable hence when there is not any token on places tbcp_ic_A_up and tbcp_ic_B_up. Immediate transitions T4411 and T7 take the system from ic_down to ic_up when tbcp_ic_A or tbcp_ic_B are available.

The models for the main compression, exportation compression and injection compression were built and then assembled to construct the model for the complete system, shown in Fig. 4. Two places were created to quantify the availability of the exportation gas (exp_up; exp_down) and injection gas (inj_up; inj_down).

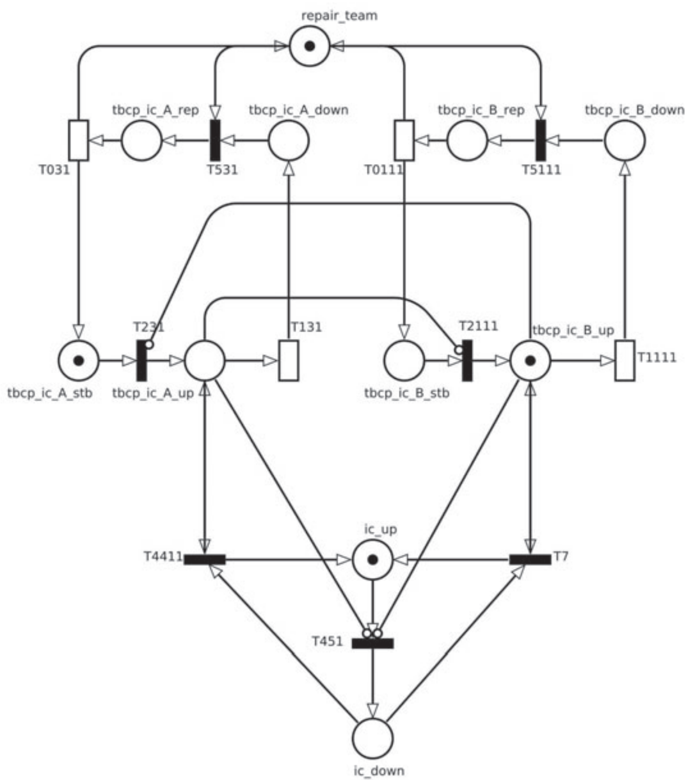

Fig. 3 Petri net for subsystem 1 out of 2

Table 2 shows the description of the places and dependencies to achieve the states. A single place is shared by all subsystem. The number of tokens in place repair_team represents the number of repair teams available. In Fig. 4 a single repair team is available. In order to evaluate reliability the number of tokens in place repair_team can be set to zero thus no repair will be performed.

Table 2. Gas demand places

Places	Description	Dependencies
exp_up	Gas exportation available	Main compression available (mc_up) AND Exportation compression available (ec_up)
exp_down	Gas exportation unavailable	Main compression unavailable (mc_down) OR Exportation compression unavailable (ec_down)
inj_up	Gas injection available	Exportation compression available (exp_up) AND Injection compression available (ic_up)
inj_down	Gas injection unavailable	Exportation compression unavailable (exp_down) OR Injection compression unavailable (ic_down)

Availability is obtained through the stationary analysis that computes the steady-state solution of the Petri net. Reliability is obtained through the transient analysis that computes the transient solution of the Petri net. The availability or reliability of a certain equipment or subsystem is measured as the expected value for the number of tokens in the place corresponding to the operational states. The availability or reliability for the gas exportation and gas injection are measured as the expected value for the number of tokens in the exp_up and inj_up places. The results presented in the next section consider a base case with the mean values for mean time to failure and mean time to repair. At the end, a sensitivity analysis is presented.

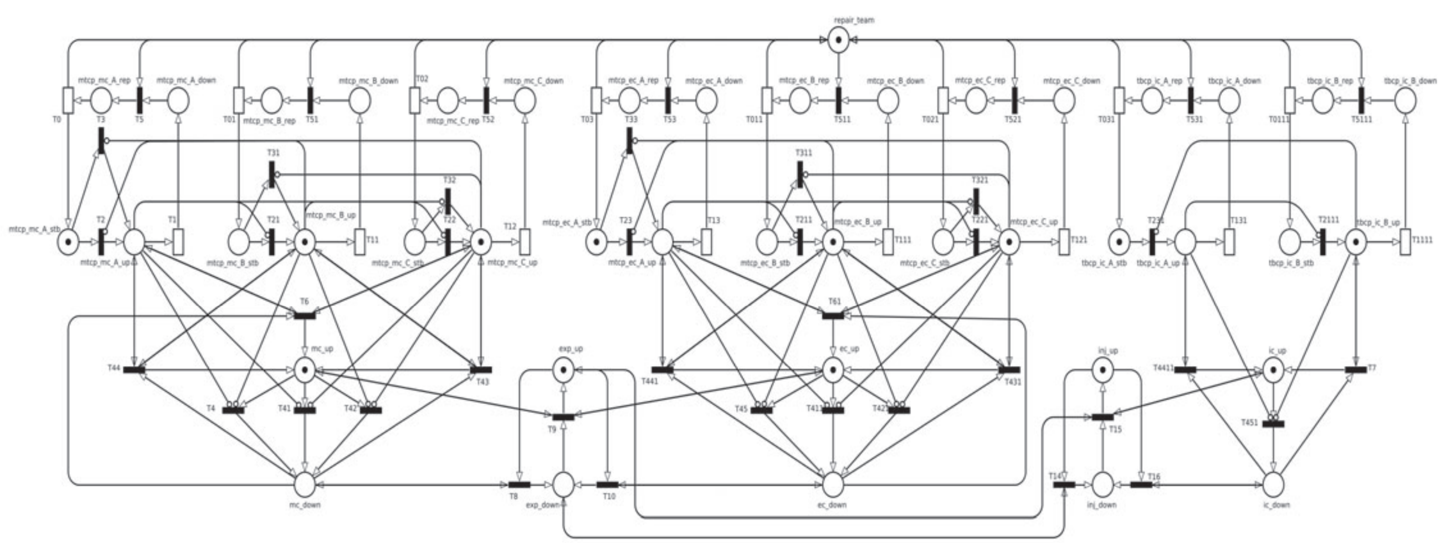

Fig. 4 Petri net for the gas treatment system

RESULTS AND DISCUSSION

The steady state solution reaches convergence in 136 iterations with accuracy of 1E-07. Table 3 presents the results for average availability for the three subsystems while Table 4 shows the average tokens distribution for the steady-state solution for the equipment of each subsystem. These values can be interpreted as a percentage time distribution. The turbocompressor A and the turbocompressor B in the injection system for example expends 49.99% of time in operation. Motocompressors of Main compression and Exportation compression subsystems are both of types 2 out of 3 thus have the same results for availability.

Table 3. Subsystems availability

Subsystem	Availability (place s_up)	Unavailability (place s_down)
Main Compression	0.99989	0.00011
Exportation Compression	0.99989	0.00011
Injection Compression	0.99982	0.00018

Table 4. Average tokens distribution in places for equipments of each subsystem for the steady-state solution

Subsystem	Standby	In operation	Out of operation	In repair
Main compression	0.32979	0.66663	0.00011	0.00347
Exportation compression	0.32979	0.66663	0.00011	0,00347
Injection Compression	0.49326	0.49991	0.00027	0.00656

Table 5 presents the results for the average gas demands availability. As expected, the availability for gas injection is lower than for gas exportation since the number of subsystems in series increases for gas injection operation according to the description presented in Section 1.

Table 5. Gas demand availability

Demand	Availability	Unavailability
Gas exportation	0.99978	0.00022
Gas injection	0.99960	0.00040

In order to evaluate the influence of repair teams in the availability, five steady-state analyses are performed varying the number of repair teams from 1 to 5. Fig. 5 shows availability versus number of repair team. As the curves show, for a number of repair teams greater than 2 there is no significant change in the availability results.

Fig. 6 shows Reliability versus time for the motocompressor A which initiates operation in standby state, motocompressor B and C which initiate in operational state and resultant reliability for the Main compression subsystem. Reliability for the motocompressor A is higher since it does not consume reliability until it starts operating after a failure in motocompressors B or C.

The reliability for the Main compression subsystem is smaller than the reliability for the motocompressor B/C for times longer than 8 months since for longer times the reliability for motocompressor B or C is so small that it cannot be compensated by the higher reliability of motocompressor A.

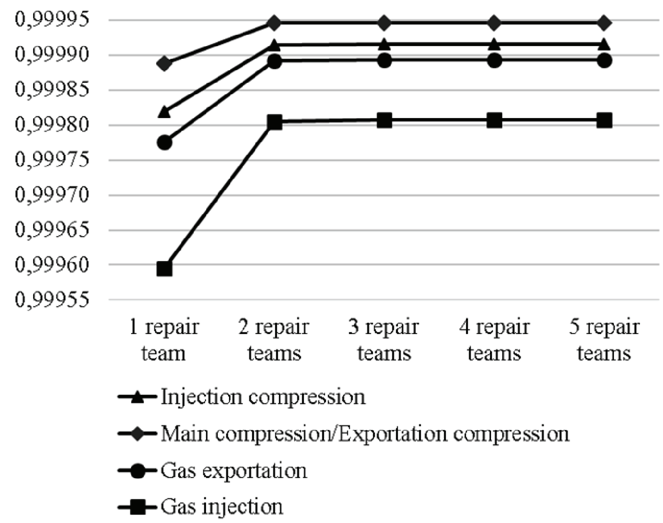

Fig. 5 Availability versus number of repair teams

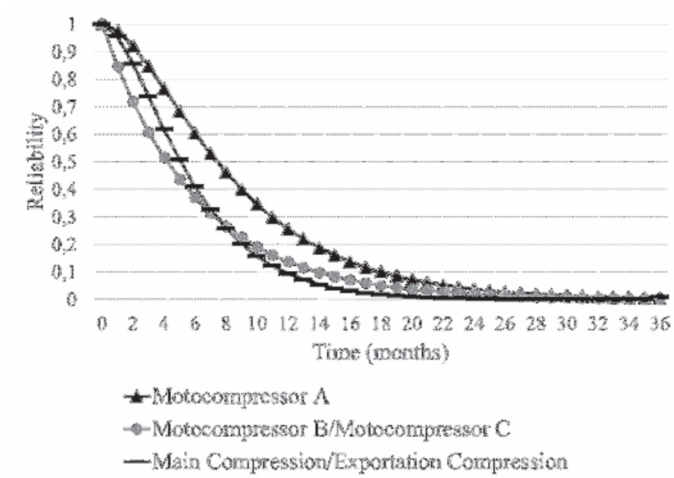

Fig. 6 Reliability versus time for Main Compression and equipment

Fig. 7 shows Reliability versus time for the turbocompressor A which initiates operation in standby state, turbocompressor B which initiates in operational state and resultant reliability for the Injection compression subsystem. Reliability according to Markov Chain modeling Lewis (1994) is also presented. The reliability of turbocompressor A is higher since it does not consume reliability until it starts operating after a failure in turbocompressor B. Reliability for the Injection compression subsystem is similar to reliability of turbocompressor A and B and is also in accordance to the model based on Markov chain proposed by E.E. Lewis (1994).

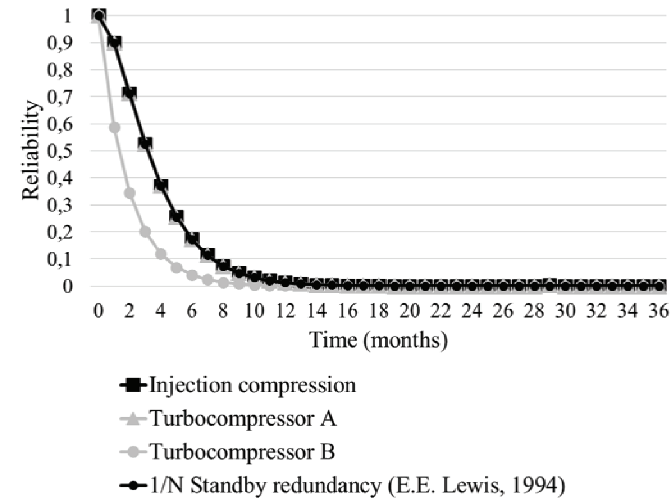

Fig. 7 Reliability versus time for Injection compression and equipment

Fig. 8 shows Reliability versus time for the Main Compression, Exportation Compression, Injection Compression, Gas Exportation and Gas Injection. After 6 months of operation, even though the reliability of the Main Compression and Exportation Compression subsystems are 40%, the reliability for Gas Exportation and Gas Injection is 17% and 2% respectively. The reliability for Gas Injection is the lowest since it depends on all other subsystems.

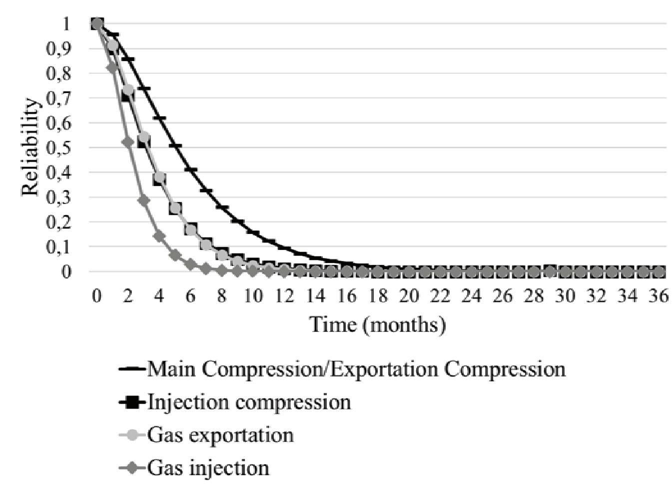

Fig. 8 Reliability versus time

Fig. 9 and Fig. 10 show a sensitivity analysis considering lower, mean and maximum mean time to failure (MTTF) for the motocompressor and turbocompressor simultaneously and mean and maximum mean time to repair (MTTR) for the motocompressor and turbocompressor simultaneously, shown in Table 1. It can be noticed that the greater the mean time to repair the greater the influence of the mean time to failure on the availability results. In addition, apart from the extreme cases (minimum MTTF and maximum MTTR), the availability results are greater than 0.92 for Gas Exportation and greater than 0.86 for Gas Exportation, these values are closer to the base case where these values are 0.9978 and 0.99960 respectively.

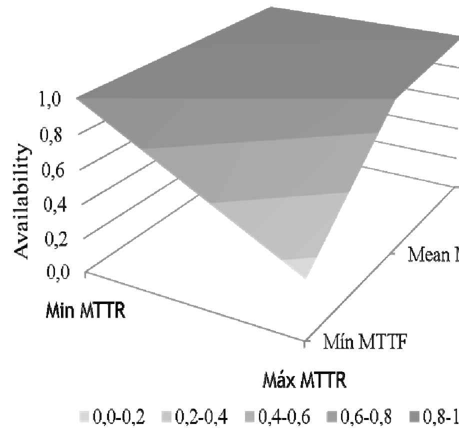

Fig. 10 Sensibility analysis for the availability of Gas Exportation

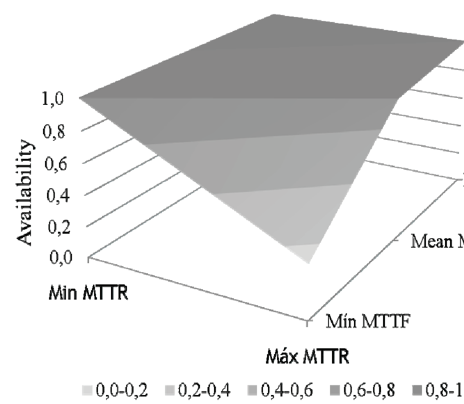

Fig. 9 Sensibility analysis for the availability of Gas Injection

CONCLUSIONS

In this work, a stochastic Petri net model for availability analysis of a simplified gas treatment system was built. The system consists of three subsystems with different redundancy configurations.

It was shown that subsystem availability increases as the number of dedicated maintenance crews increases but there is no significant change in the availability results for a number of repair teams greater than 2. The availability and reliability for gas injection is the lowest since it depends on the operation of all subsystems. Finally, the sensitivity analysis showed that the greater the mean time to repair the greater the influence of the mean time to failure on the availability results.

The use of Petri net for systems reliability and availability analysis proved to be suitable for modeling systems with different subsystems configurations. It could represent situations such as equipment repair constraints associated with the availability of maintenance crews and reconfigurations of equipment operating with standby redundancy. The models developed for the subsystems with different k-out-of-N configurations can be used to build many others systems since this kind of configuration is very common in the offshore industry.

Future work should consider analyzing other distributions for failure and repair time and consider failures on demand. The model may also include the dehydration, dew point control and CO_2 removal subsystems and estimate the expected number of failure events during a time interval. The model may also be used to study the system reconfigurations arising from flaring limits reaching.

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