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Production availability analysis of Floating Production Storage and Offloading (FPSO) systems

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ABSTRACT

Floating Production Storage and Offloading (FPSO) systems are currently the popular scheme in offshore oil and gas industry. The profitability of these systems is extremely dependent on their production availabilities. In this article, we report the lessons learned from the assessment of the production availability of a FPSO system. Regarding this study, we used stochastic simulation as the assessment tool because it is naturally suitable for performance evaluation of the production systems. To obtain relevant results, it requires a strong modeling discipline as well as rigorous experimental protocols. By adopting modeling patterns in the production availability analysis, we can model the target systems in a modular way. We propose here to build models by assembling modeling patterns dedicated to production availability studies. We discuss the performed experiments with a special focus on sensitivity analyses. The results by changing the failure rates are validated with those altering the repair rates.
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1. Introduction

Floating Production Storage and Offloading (FPSO) units are currently the popular scheme in offshore oil and gas industry [1,2]. They are employed to process and to store temporarily the crude oil/gas coming from the production platforms or directly from the subsea wells. The oil stored in FPSO is transferred periodically to shuttle tankers. FPSO have the capacity to work in both shallow and deep waters, as well as in rich and poor (marginal) oil reserves and gas fields. They can be shifted from one offshore field to another conveniently and economically. FPSO are however complex systems. Their operations may face lots of hazards and failures. Many incidents and accidents of FPSO have been reported and studied (see e.g. [3–10]). In recent years, an explosion on board of the FPSO *Cidade de São Mateus* left nine fatalities and several injured [11]. Besides such accidents (low probabilities and high consequences) that must be avoided at all costs, long outages can decrease seriously the performance of these systems and have strong economic effects [12]. This is the reason why the profitability of these systems is extremely dependent on their reliability, availability and maintainability (RAM) [13]. It is therefore of importance to assess these characteristics by means of the calculation of suitable performance indicators obtained from dedicated models.

Production availability is such an indicator, which measures how a system is capable to meet the demand for deliveries or performance [14]. It is defined as the ratio of the actual production to the planned production, or field capacity, over a specified period of time [15–17]. It combines thus both RAM indicators and production expectation. Production assurance, or production regularity have similar meaning [17–19].

FPSO have several specific characteristics that influence strongly the way production availability can be assessed [20]. Stochastic simulation is a candidate assessment tool because it is naturally suitable for performance evaluation in general [16,21]. Stochastic Petri nets (SPN, see e.g. [22,23]) are a candidate modeling formalism to support stochastic simulation. They can deal with arbitrary probabilistic distributions and describe both static and dynamic characteristics with a high algorithmic efficiency. They have been already applied for various types of offshore studies (see e.g. [24–27]). For our study, we use an extension of SPN, so-called Stochastic Petri nets with assertions and predicates (SPN-AP), as it is implemented in the GRIF modeling and simulation environment [28]. SPN and SPN-AP models are however far from easy to design and even more difficult to maintain and to share with stakeholders [28].

The pattern can be utilized for reusing capitalized knowledge, which was initially proposed in civil engineering [29]. The con-

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cept was adopted in software engineering subsequently as design patterns [30]. These patterns are descriptions of communicating objects and classes that are customized to solve a general design problem in a particular context [30]. A design pattern promotes design reuse, conforms to a literary style, and defines a vocabulary for discussing design [31]. Modeling patterns are therefore generalizations of frequently occurring system (functional and physical) behaviors which can be applied to solve a generic modeling problem in a specific context.

We propose here a set of modeling patterns dedicated to production availability studies. We formulate these patterns in terms of a simplified version of Guarded Transition Systems (GTS) [32]. GTS both generalize and simplify the mathematical framework of SPN-AP. This generalization is obtained at no computational cost. We show how the model of the particular FPSO we studied is obtained by composing these modeling patterns. Subsequently, based on this model, we discuss the experimental protocol we apply to determine the sensitive parameters and critical components of the FPSO, with respect to production availability.

The remainder of this article is organized as follows. Section 2 discusses some related works. In Section 3, we describe the architecture of a FPSO system. Section 4 recalls basics about guarded transition systems and investigates some modeling patterns used for this study. Section 5 presents the experimental results. Eventually, Section 6 concludes the article.

2. Related works

ISO 20815 [16] and NORSOK Z-016 [15] standards provide a general framework to perform production availability studies. Two categories of methods have used so far: analytical methods and simulation based methods (see [33] for a review).

Most of the analytical methods rely on formulas describing the system failures, typically a fault tree, a block diagram or a Markov chain [18,19,34–36]. These methods are interesting, but limited in terms of size and complexity of the systems.

In general, simulation based studies are performed using discrete events Monte-Carlo simulation, where events such as failures, repairs and reconfigurations are associated with stochastic delays [37–41]. Although nowadays computers are powerful and efficient softwares have been developed, the computational cost remains quite high.

Stochastic Petri Nets (SPN) is the dominant modeling formalism to assess production availability via simulation based methods [22,42]. An international standard (IEC 62551) [43] has been released for SPN which are also among the recommended methods by ISO 20815 standard.

Stochastic Petri Nets with predicates and assertions (SPN-AP), as implemented in the GRIF Workshop modeling and simulation environment[1] have been used by different authors to assess production availability of offshore systems. Ref. [44] studies the European SAFERELNET test case. Ref. [27] studies the subsea part of the FPSO system, which directly obtains the oil and gas from the subsea wellheads and manifolds.

As pointed out in the introduction, there is a strong need for methods to structure simulation/analytical models in order to improve their design and their maintenance. An interesting attempt in this direction is the work by Signoret et al. in [28]. Their approach is related to the use of high-level modeling languages such as AltaRica [45].

[1] http://grif-workshop.com/.

3. The FPSO system

Our case study is a FPSO system serving in an offshore oil field. This FPSO includes the crude oil processing system, a single point mooring system, a crude oil storage and ballast system, a fire protection and lifesaving system, a power and instrumental system [46,47]. In this paper, we focus on the production availability of the crude oil processing system which we refer to as the FPSO system, for the sake of simplicity. Failures of the rest offshore assets can also influence the FPSO production performance. For example, a fire (or an explosion) occurred in the facility, therefore after the failure of the fire protection system, can lead to the suspension of the entire system. The investigation of the leakage points and ignition sources is out of this research scope. In this work, we focus on studying the system reliability issue rather than the safety aspect.

3.1. System overview

The FPSO system consists of four sub-systems: platforms A, B, C and the FPSO subsystem, as shown in Fig. 1. Platform A transfers the oil to a buffer tank in platform B. Together with the output oil of platforms B and C, the overall oil is transported to the heat exchangers of the FPSO subsystem. In Fig. 1, solid arrows represent the crude oil flow, while dashed arrows represent the separated gas or waste water. These three platforms are relatively independent. The unavailability of either platforms A, B, or C cannot lead to the output unavailability of platforms. The unavailability of platforms B and C can result in the output unavailability of platforms. The unavailability of platform B can trigger the closure of platform A.

3.1.1. The platforms

Platform A is in charge of the pre-fractionation and transportation of the oil from well head A (WEA). WEA stands for dozens of production wells under the fixed production platform. There are two main components on platform A: the primary separator A (PSA) and the efflux pump A (EPA). PSA separates the crude oil into three parts: the gas is transported to vent A (VA), the water is delivered to water processing system A (WPSA), and the purified crude oil flow is sent to EPA. The provisional destination of the crude oil from platform A is the crude oil buffer tank (COBT) on platform B.

Platform B purifies preliminarily the crude oil and transports it from Well head B (WEB). Platform B is made of the primary separator B (PSB), COBT, the efflux pumps B1 (EPB1) and B2 (EPB2). PSB separates the crude oil into three parts: the separated gas flows to vent B (VB), the exporting crude oil is carried to EPB1, and the remaining water is delivered to water processing system B (WPSB). The oil temporarily stored in COBT is transferred to platform C through EPB2. The exported oil from EPB1 and EPB2 are integrated into a unique flow to platform C.

Platform C purifies the initial oil flow and transports it from the Well head C (WEC). Like Platform A, Platform C includes two main components: the primary separator C (PSC) and the efflux pump C (EPC). PSC separates the initial crude oil into three parts: the gas is transferred to vent C (VC), the water is delivered to water processing system C (WPSC), and the treated crude oil is transferred to EPC. The oil from EPC joins the flows from EPB1 and EPB2 to the FPSO subsystem.

3.1.2. The FPSO subsystem

The FPSO subsystem processes and stores the crude oil. It consists of two parallel heat exchangers (HEs), a sea water cooler (SWC), three parallel booster pumps (BPs), two parallel pre-heaters (PHs), as well as three processors (TCP, EDHP, EDSP).

The main function of the FPSO subsystem is to process the primarily separated oil so to make it at the standard quality. The overall oil flowing from platforms is initially delivered to HEs to increase

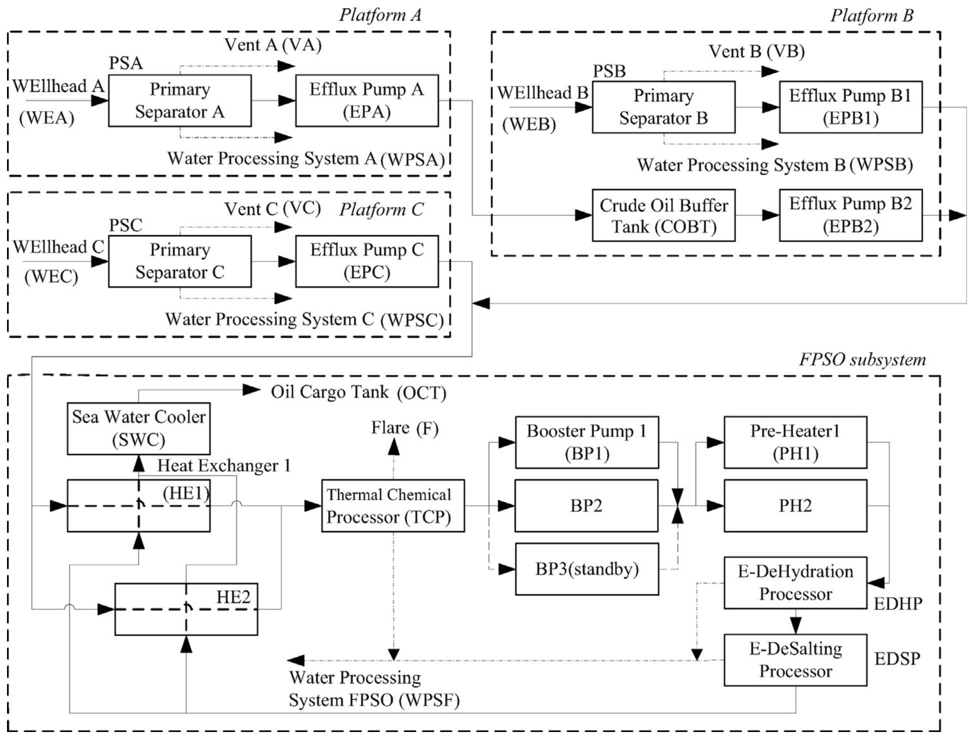

Fig. 1. The flow diagram of the FPSO production system.

its temperature. After HEs, the flow goes to the thermal chemical processor (TCP) that separates the oil from the remaining gas and water. TCP uses chemical agents, the gravity and an internal heater for dehydration. The gas is sent to the flare for burning, and the water is delivered to water processing system of the FPSO (WPSF). Before entering TCP, the crude oil contains around 30% of water. After TCP stage, the water percentage in the crude oil is less than 10%.

Regarding the oil flow, it goes to PHs through BPs. BP3 is a cold standby pump for redundancy. The FPSO subsystem requires that at least two pumps work simultaneously.

After PHs, the oil flow is transferred to the electric dehydration processor (EDHP). The EDHP further dehydrates the oil by using mixed electric field generators with the alternative current (AC) and direct current (DC). After EDHP, the concentration of water in the crude oil is less than 0.47%.

The crude oil from the oil reservoir contains several chemical substances like NaCl, $MgCl_2$ and $CaCl_2$, which are harmful for the onshore refinery. An electro-desalting processor (EDSP) is thus required. The residual water from EDHP and EDSP goes to WPSF. After EDSP, the oil flows into HEs and SWC to decrease its temperature. The oil is then delivered to oil cargo tank (OCT), which is transported periodically (normally around once a week) to the onshore refinery by shuttle tankers.

The maximum oil, gas and waste water processing capacities of the FPSO are 7870 m^3/d, 10,240 m^3/d, and 12,000 m^3/d, respectively.

3.1.3. Expected oil yield

Table 1 describes the evolution of expected crude oil outputs of the platforms, given the predicted capacity of the reservoir [46].

3.2. Reliability data and maintenance policy

The maintenance policy of the FPSO system consists of both corrective and preventive maintenances. The former is implemented right after the failures are detected and when the repair crews are available. The corrective maintenance is only minimal repair. This policy resumes that the system component to work without altering its failure rate [48]. The clock-based preventive maintenance is carried out at predefined dates. The maintenance strategy may include periodic tests and limited maintenance resources, like having only one repair team. Units PSA, PSB, PSC, HEs, and TCP are operated with both the corrective and periodic maintenance. Table 2 sketches the periodic maintenance policy. The other units are operated with the corrective maintenance only. Because the preventive maintenance (PM) here is a clock-based one, and the downtime of the planned PM is often treated as deterministic [49], thus both the intervals and durations of the PM policy are deterministic in this study.

Table 1
Expected crude oil outputs of the platforms.

Year	Crude oil yield/(10^4 m^3/year)		
	Platform A	Platform B	Platform C
1	12.9	16.7	14.0
2	164.2	213.6	178.7
3	153.8	200.1	167.4
4	83.2	108.2	90.5
5	56.9	74.0	61.9
6	44.8	58.3	48.8
7	37.3	48.5	40.6
8	31.4	40.9	34.2
9	27.2	35.4	29.6
10	21.9	28.4	23.8

Table 2
The preventive maintenance policy of the FPSO system.

Components	Interval/h	Duration/h
PSA, PSB, PSC	4380	36
HE1, HE2	8760	36
TCP	17520	72

Table 3
Reliability data and maintenance policy of the FPSO system.

Components	Failure rate/h^{-1}	Repair time/h	Maintenance
PSA,PSB,PSC, TCP	2.63E−4	8.2	CM+PM
EPA,EPB1,EPB2,EPC	5.51E−4	32.7	CM
COBT	1.63E−4	30.3	CM
HE1,HE2	2.00E−4	8.9	CM+PM
EDHP,EDSP	2.63E−4	8.2	CM
BP1,BP2,BP3	1.03E−3	5.0	CM
PH1,PH2	6.96E−5	42.2	CM
SWC	9.78E−5	70.0	CM

The PM policy can lead to the decrease of the system availability and production availability if the constant failure and repair rates are employed [38]. However, in order to keep near to the system specification [46], we model the system by taking the PM policy into consideration. In this study, there is one PM policy for each PM-involved component. The components do not share the same PM interval and duration, as shown in Table 2.

Table 3 tabulates the reliability data [50] and the maintenance policy of the FPSO system. The capacities of TCP, EDHP and EDSP are 219, 102 and 102 m^3, respectively. These three separators share the identical failure rate and repair time. BPs are twin-screw pumps, which belong to the category of rotary pumps. PHs are U-shape tubular heat exchangers, and the SWC and HEs are plate heat exchangers.

3.3. Characteristics of production availability studies of FPSO

The FPSO system has a certain number of characteristics that strongly impact production availability studies.

Their mission time is relative long, ten years in our case. During that time, the expected production first increases, then slowly decreases after a production peak (typically located after two years).

Components of the FPSO system are operated with both corrective and preventive maintenances. The preventive maintenance activities may cover the inspection, adjustments, lubrication, parts replacement, calibration, and repair of items [49]. As preventive maintenance usually turns off the units, most of the production losses are due to these down times. Finding the right balance between potential losses due to unexpected events and actual losses due to preventive maintenance activities is thus a very meaningful and difficult topic. Note that the FPSO architecture also involves hot, warm and cold redundancies.

Standby redundancy can be categorized into hot, warm and cold standby according to different failure rates of unused standby components. Hot standby and cold standby are special cases of warm standby. The "temperature" of the standby indicates whether the unused standby components can fail at their full rates (hot standby), fail at a rate attenuated with a dormancy factor (warm standby), or cannot fail (cold standby) [51,52]. These three types of standby redundancy are applied in different scenarios. The hot standby is usually used when the recovery time is crucial. The cold standby is normally applied when the energy consumption is crucial. The warm standby is typically utilized when a compromise of energy consumption and recovery time is required. The spare components in warm standby are partially powered up when the primary component is operational [53,54].

The FPSO system involves feedback loops. The heat exchanger plays a double role: heating up the mix of oil and water coming from the upstream platforms and cooling down the water issued from the dehydration process taking place downstream. These two operations depend on each other.

Finally, modeling the FPSO production is twofold: first, we have to model the states of the different units and their changes under failures and maintenance actions. Then we have to model the production level which eventually depends on flows of oil circulating amongst the different units. Whether these two layers are considered separately or merged is a very important modeling choice. The more systematic the modeling process is, the less it is prone to errors, and the less difficult are the models to debug and to maintain. Ideally, designing a model should just consists in assembling on-the-shelf modeling components. In practice, we are rather far from this ideal situation.

4. Methodological approach

4.1. Preliminary remarks

Generalized Stochastic Petri Nets (GSPN) [22], extend Petri nets by associating with each transition a random variable representing its duration. This random variable is assumed either to be constantly equal to 0 (immediate transitions) or to be exponentially distributed (with a given transition rate). This leads to a clear relationship between the GSPN framework and continuous-time Markov chains (CTMC): any GSPN can be seen as an implicit representation of a CTMC.

Stochastic Petri nets with assertions and predicates, as implemented in the GRIF environment [28], extend GSPN in several ways. First, random variables associated with transitions can obey many different distributions, e.g. non null Dirac distributions and Weibull distributions. Second, state variables are added to the model with instructions to test and to update their values via so-called messages, assertions and predicates. It results a very powerful modeling formalism which has little to do with original Petri nets and even with GSPN. Unfortunately, the underlying mathematical model is blurred by ad-hoc constructs and a confusion between the actual model and its graphical representation. It remains that the GRIF environment is probably, at the time we write these lines, a very powerful modeling and simulation environment for the assessment of probabilistic risk models via stochastic simulation.

To discuss the model we designed for the FPSO system, we use a simplified version of (stochastic) guarded transition systems (GTS) [32]. The GTS framework is both more expressive than stochastic Petri nets with assertions and predicates and cleaner from a mathematical standpoint. Moreover, this generalization and clarification is obtained at no algorithmic cost.

The model was designed by tailoring and assembling modeling patterns, that is, relatively small generic GTS. The pattern approach makes models not only much easier to design and to debug, but also to share with stakeholders and to maintain throughout the lifecycle of systems. For the sake of the conciseness, we shall present here only a selection of the patterns we employed for our study.

4.2. Formal definition of guarded transition systems

A GTS is a quintuple $\langle V, E, T, A, \iota \rangle$ where V is a finite set of variables, E is a finite set of events, T is a finite set of transitions, A is an assertion and ι is the initial assignment of variables.

Each variable $v \in V$ takes its value into a domain denoted by $domain(v)$. Variables can be Boolean, integers, floating point numbers, members of finite sets of symbolic constants or anything convenient for the modeling purpose. For instance, places of Petri nets are just positive integer variables.

A variable assignment is a function from V to $\prod_{v \in V} domain(v)$. A variable update is a function from $\prod_{v \in V} domain(v)$ into itself, that is a function that transforms a variable assignment into another one.

Each event $e \in E$ is associated with:

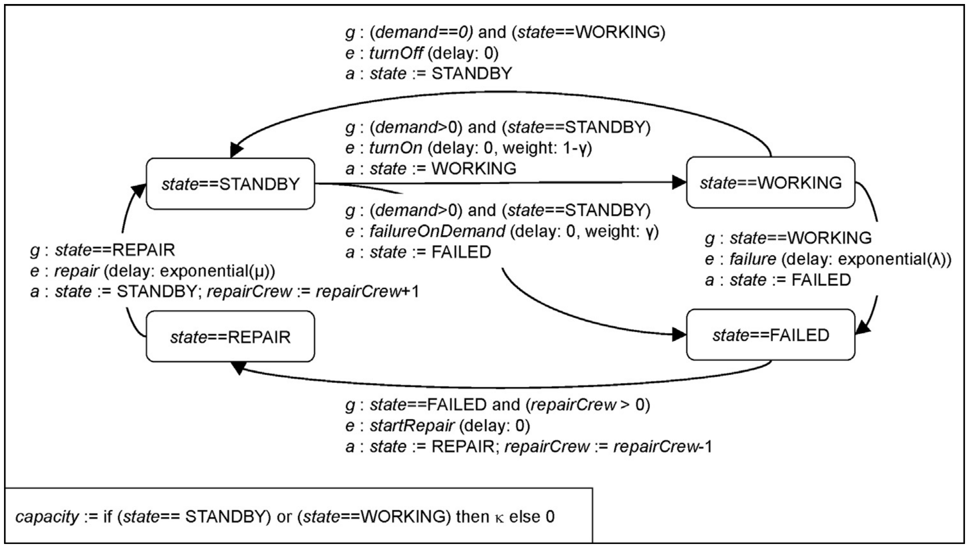

Fig. 2. Modeling pattern for basic components.

– A monotonic, increasing, invertible function $delay_e$ from [0, 1] into $\Re^+$, the set of positive real numbers;
– A priority (an integer) $priority_e$ (by default, $priority_e = 0$).
– A weight (a real number) $weight_e$ (by default, $weight_e = 1.0$.

Each transition $t \in T$ is a triple $\langle e, g, a\rangle$, denoted by $g \xrightarrow{e} a$, where e is an event in E, g is a Boolean condition over the variables in V and a is an instruction over the variables of V, that is a variable update. a is called the action of the transition.

The assertion A is an instruction over the variables of V.

Let σ be a variable assignment and $t : g \xrightarrow{e} a$ be a transition which is potentially fireable in σ, i.e. such that $\sigma(g) = true$. Firing t updates σ into the assignment $\rho = A(a(\sigma))$, that is, it consists in applying on σ first the update a (the action of the transition) and then the update A (the global assertion).

We say that a variable $v \in V$ is impacted by the update of σ into ρ if $\rho(v) \neq \sigma(v)$. By extension, we say that the transition $g' \xrightarrow{e'} a'$ is impacted by this variable update if at least one of the variables occurring in g' is impacted by the update.

Let $t : g \xrightarrow{e} a$ be a transition in T. By extension, we define $priority_t$ as $priority_e$ and $weight_t$ as $weight_e$. If two transitions are potentially fireable at the same time, then the one with the highest priority will be fired. If the two transitions have the same priority, then the weight is used to choose at random among them. This mechanism will be further explained Section 4.4

4.3. The modeling pattern for basic components

As an illustration, consider the modeling pattern for basic components of the FPSO System. Fig. 2 shows a graphical representation of this pattern. It involves four variables: *state*, *capacity*, *demand* and *repairCrew*. The symbolic variable *state* takes its value in the set {STANDBY, WORKING, FAILED, REPAIR}. The real variable *capacity* exports the production capacity of the component, which is its maximal capacity κ if the component is either in state STANDBY or in state WORKING and 0 otherwise. The real variable *demand* represents the actual production of the component. This demand is imported into the component from the sub-system that contains the component. Finally, the integer variable *repairCrew* is shared between all components in competition for the same pool of repair crews.

When the component is in state STANDBY and is demanded to produce a non null quantity, it attempts immediately to turn on. This action may fail, with a probability γ or succeed with a probability $(1-\gamma)$. The two corresponding events (*failureOnDemand* and *turnOn*) are thus associated with a null delay and with respective weights γ and $(1-\gamma)$. When the component is in state WORKING and the demand falls to zero, it is immediately turned off (event *turnOff*).

When the component is in state WORKING, it may fail. The delay associated with the corresponding event (*failure*) is exponentially distributed, with a transition rate λ. It is assumed that the component cannot fail in state STANDBY.

When the component is in state FAILED, a repair is launched as soon as there is an available repair crew (event *startRepair*). It goes then to state REPAIR and the number of available repair crews is decreased by one.

Finally, the repair is completed (event *repair*) after an exponentially distributed delay of parameter μ. Once the repair is completed, the component goes back to state STANDBY and the number of available repair crews is increased by one.

4.4. Semantics

The semantics of a GTS is formally defined as the set of its possible runs (executions).

A schedule is a function from T to $\Re^+ \cup \{+\infty\}$, that is, a function that associates a (possibly infinite) date with each transition. A run of a GTS is a finite sequence of triples $(d_0, \sigma_0, \delta_0), (d_1, \sigma_1, \delta_1), \ldots, (d_n, \sigma_n, \delta_n)$ where the d_i's are dates, the σ_i's are variable assignments and the δ_i's are schedules.

The set of runs of the GTS is defined inductively, starting from date 0, as the smallest set such that:

Initialization: The sequence made of only one triple $(0, \iota, \delta)$ is a run if, for each transition $t : g \xrightarrow{e} a$ in T the following conditions hold:

(i) $\delta(t) < +\infty$ if and only if t is potentially fireable in ι.
(ii) If $\delta(t) < +\infty$, there exists $z \in [0, 1]$ such that $\delta(t) = delay_e(z)$.

Run extension: if $\Gamma = (d_0, \sigma_0, \delta_0), \ldots, (d_n, \sigma_n, \delta_n)$ is a run $(n \geq 0)$, then $\Gamma' = \Gamma, (d_{n+1}, \sigma_{n+1}, \delta_{n+1})$, if there is a transition $t : g \xrightarrow{e} a$ scheduled at date $\delta_n(d) < +\infty$ such that:

(iii) t is potentially fireable in σ_n;
(iv) There is no transition t' such that $\delta_n(t') < d$, or $\delta_n(t') = d$, and $priority_{t'} < priority_t$; We say that such transition t is actually

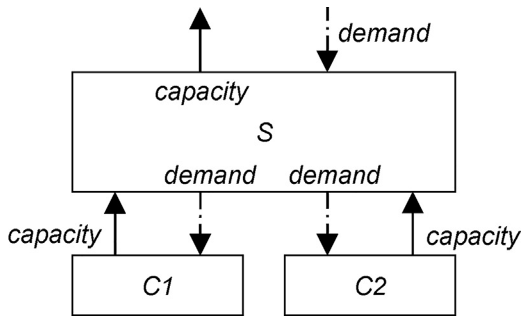

Fig. 3. Modeling pattern for hierarchical composition.

fireable in the run Γ. σ_{n+1} and δ_{n+1} are related to σ_n and δ_n as follows.

(v) $\sigma_{n+1} = A(a(\sigma_n))$, i.e. σ_{n+1} is obtained from σ_n by firing transition t.

(vi) δ_{n+1} is obtained from δ_n by reexamining t and all transitions impacted by the update from σ_n to σ_{n+1}, i.e. for all such transitions $t' : g' \xrightarrow{e'} a'$:
- $\delta_{n+1}(t') < +\infty$ if and only if t' is potentially fireable in σ_{n+1}.
- If $\delta_{n+1}(t') < +\infty$, then there exists $z \in [0, 1]$ such that $\delta_{n+1}(t') = d + delay_{e'}(z)$.

Let Γ be a run. There may be several transitions $t_1, \ldots, t_k$ actually fireable in Γ. During a stochastic simulation, we have to choose which of the t_i's to fire. This choice is done via weights. Namely, the probability $p(t_i)$ to draw the transition t_i is defined as follows:

$$p(t_i) \stackrel{def}{=} \frac{weight_{t_i}}{\sum_{j=1}^{k} weight_{t_j}}$$

4.5. Hierarchical decomposition

In the FPSO, components are assembled in series or in parallel, with possibly some cold redundancy. GTS makes it possible to define modeling patterns for these compositions (series, parallel and cold redundancy), as is sketched in Fig. 3. The idea is to create a component (S) to gather two or more components ($C1$ and $C2$). As basic components, this component exports a capacity (solid line) and imports a demand (dashed line).

Capacity $S.$ *capacity* (exported by S) is calculated from the capacities $C1.$ *capacity* and $C2.$ *capacity* exported by $C1$ and $C2$, respectively. Similarly, the demand $S.$ *demand* imported by S is distributed over $C1$ and $C2$. This distribution depends on the type of composition and the capacities of $C1$ and $C2$.

For parallel composition, we have typically:

$$\begin{aligned} S.capacity &:= C1.capacity + C2.capacity \\ C1.demand &:= S.demand \times \frac{C1.capacity}{C1.capacity + C2.capacity} \\ C2.demand &:= S.demand \times \frac{C2.capacity}{C1.capacity + C2.capacity} \end{aligned}$$

Other distribution policies than the above pro-rata are possible as well.

For a series composition, we have typically:

$$\begin{aligned} S.capacity &:= \min(C1.capacity, C2.capacity) \\ C1.demand &:= \min(C1.capacity, S.demand) \\ C2.demand &:= \min(C2.capacity, S.demand) \end{aligned}$$

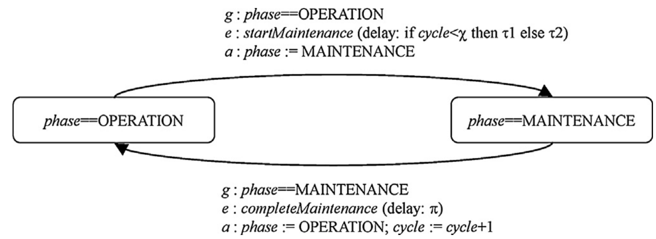

Fig. 4. Modeling pattern for preventive maintenance policy.

For cold redundancy composition, we have typically:

$$\begin{aligned} S.capacity &:= \text{if } C1.capacity > 0 \text{ then } C1.capacity \\ &\quad \text{else } C2.capacity \\ C1.demand &:= \text{if } C1.capacity > 0 \text{ then } S.demand \text{ else } 0 \\ C2.demand &:= \text{if } C1.capacity > 0 \text{ then } 0 \text{else } S.demand \end{aligned}$$

These composition mechanisms used for production availability analysis are generalized by using the idea developed in [52] to give a sound semantics to dynamic fault trees. Note that these mechanisms cannot be implemented directly with stochastic Petri nets with assertion and predicates. Therefore, they have to be simulated by introducing ad hoc immediate transitions.

4.6. Preventive maintenance

Modeling patterns can be composed to give more advanced patterns. As an illustration, we consider the introduction of preventive maintenance. A preventive maintenance policy is an alternating sequence of operation and maintenance phases. The duration of maintenance phases is usually fixed. The duration of operation phases depends in general on the cycle. For instance, offshore systems may be inspected every month the first three months, then every three months in a second period of one year, and finally every six months for the rest of their lifetime. The maintenance periods are common to many components because the installation (or parts of it) has to be stopped during these periods.

Fig. 4 shows the modeling pattern for preventive maintenance policies. This pattern involves two variables: *phase* which alternates between values `OPERATION` and `MAINTENANCE`, and *cycle* that is used to set up the durations of operation phases. All the durations are here deterministic (and non null), which takes the model out of the Markovian framework.

The pattern for maintenance policy can be composed with other patterns to form a pattern for periodically tested components (or sub-systems). It suffices to set the demand of the component to zero (0) during maintenance phases (via the assertion).

5. Experimental results

In terms of issues and problems associated to ocean-related matters, the offshore installations typically confront with the risk of hydrocarbon leaks, fire, explosion, collision, and marine system failures. In the following experimental studies, we assume that the involved equipment to be modeled in FPSO has no hydrocarbon leakage. Since the hydrocarbon leaks are prerequisite to the offshore fire and explosion, we have not considered such incidents/accidents. In addition, since the marine system failures cannot directly impact the production availability, we have not taken such types of failures into consideration.

5.1. Assessment of production availability

The production availability is defined as the ratio of the predicted production to the expected production [15,16]. The expected

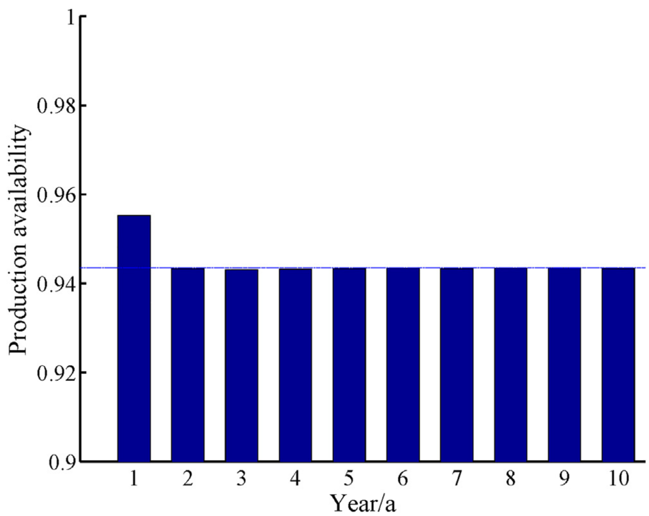

Fig. 5. Production availability of the FPSO system.

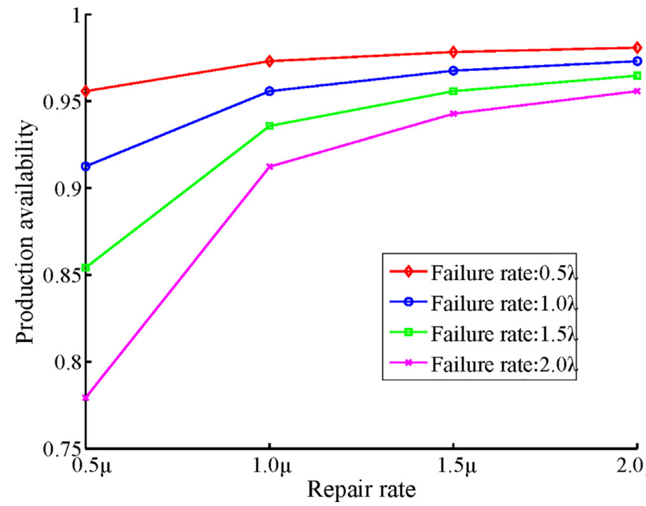

Fig. 7. Production availability.

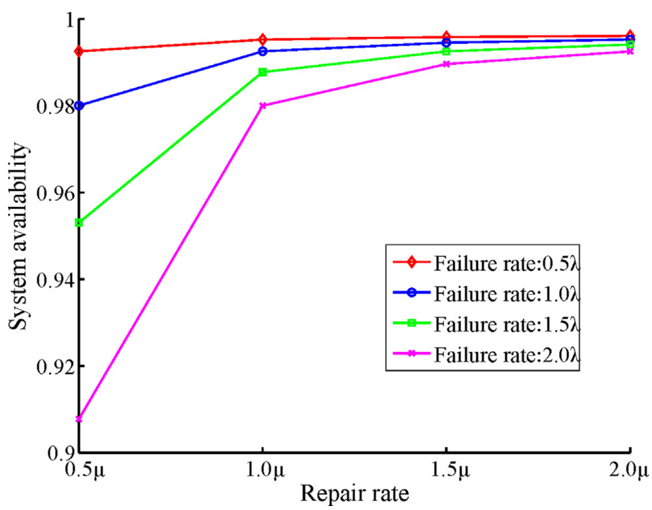

Fig. 6. System availability.

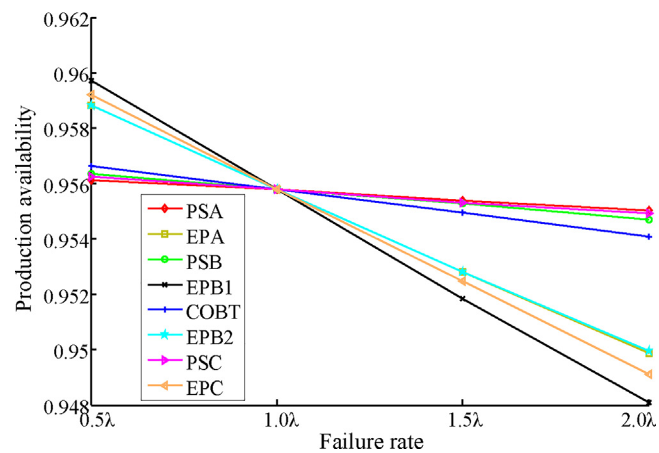

Fig. 8. Production availability-platforms (changing failure rate).

production being provided by the field operators (see Table 1), our main work is to calculate the predicted production.

Fig. 5 depicts the evolution of the production availability of the FPSO system over ten (10) years of production. This figure shows that the production availability changes very little along with the time. Except for the first year, the production availability is stable, that is, a bit above 94%.

5.2. Sensitivity to variations of parameters

We assessed the impact of two types of parameters on the production availability: the failure rate and the repair rate of the components. Figs. 6 and 7 show the system availabilities and production availabilities we obtained for different values of the failure rates. The considered values were obtained by multiplying the initial values in Table 3 with a coefficient in {0.5, 1.0, 1.5, 2.0}. In Figs. 6 and 7, μ is the repair rate, which is the reciprocal number of the repair time in Table 3.

These experiments indicate that relatively small variation on failure rates and repair rates may have significant influence on the production availability of the FPSO system. They show also that this impact decreases in region where the production availability is very high.

5.3. Critical components

In order to determine which components contribute the most to variations of production availability, we ranked the components with the Birnbaum's measure [55]:

$$I(i|t) = \frac{\partial h(p(t))}{\partial p_i(t)} \quad \textit{for} \quad t > 0 \tag{1}$$

In our case, $\partial p_i(t)$ stands the variation of the failure/repair rate of component i and $\partial h(p(t))$ is corresponding modification of the production availability or system availability.

Fig. 8 shows the impact of variations of the failure rates of platforms components on the production availability. Clearly, the efflux pumps (*EPB*1, *EPC*, *EPA*, *EPB*2) are more critical than the other platform components. This is due to their role in the process as well as their failure rates which are higher than those of the separators (*PSA*, *PSB*, *PSC*) and tank *COBT*.

Fig. 9 shows the impact of variations of failure rates of the components on FPSO subsystem. Clearly, *TCP*, which has a higher failure rate than *HEs* and *BPs*, is more important than the other components. In Figs. 8 and 9, λ is the failure rate in Table 3.

Aggregating the results in Figs. 8 and 9, we can conclude that the components having a higher influence on the production availability of the FPSO system are mainly the efflux pumps (*EPA*, *EPB*1, *EPB*2, *EPC*) and the processor *TCP*, in this order.

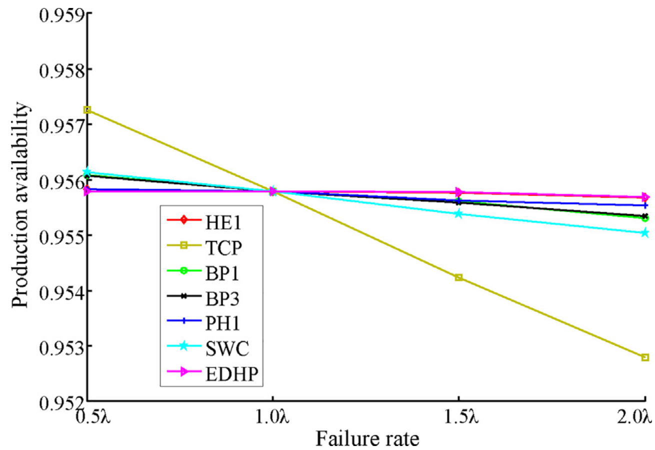

Fig. 9. Production availability-FPSO subsystem (changing failure rate).

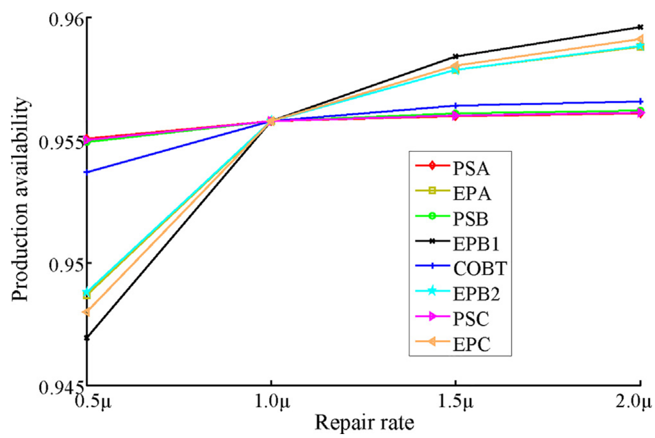

Fig. 10. Production availability-platforms (changing repair rate).

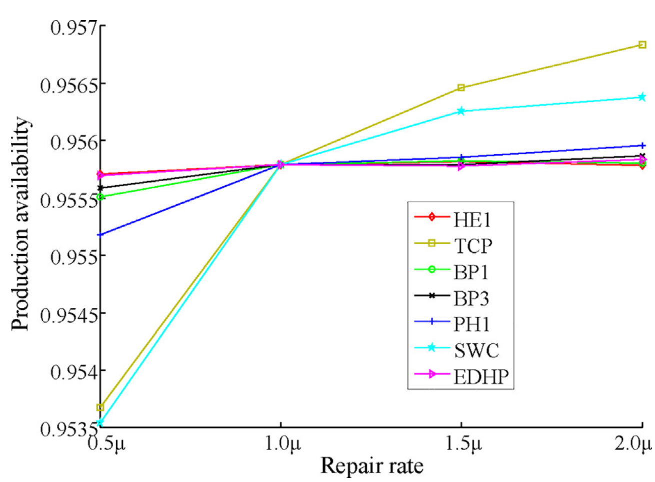

Fig. 11. Production availability-FPSO subsystem (changing repair rate).

Figs. 10 and 11 show the sensitivity of production availability to variations of repair rates of platform and FPSO subsystem components respectively. Critical components of platforms with respect to repair rates are, in the decreasing order, the efflux pumps (*EPB*1, *EPC*, *EPA*, *EPB*2), the oil tank *COBT* and the primary separators (*PSB*, *PSA*, *PSC*). *EPB*2 and *EPA*, on the one hand, and *PSA*, *PSB* and *PSC*, on the other hand, have the same importance. Critical components of the FPSO subsystem *TCP* and the sea water cooler *SWC*. The variation of the repair rates of other components of the subsystem has little effect.

From these results, we can conclude that the most critical components with respect to repair rates, are *EPB*1 (*EPC*), *EPB*2 (*EPA*), *TCP*, *COBT* and *SWC*, in this order, the last three components showing less significant influence.

The four pumps are the most critical components because they have a high failure rate (5.51E−4 h^{-1}) and long repair time (32.7 h). Moreover, they govern the outputs of the three platforms, thus the input of the FPSO subsystem, which contribute directly to the final production availability.

6. Conclusion

In this article, we analyzed the production availability of a Floating Production Storage and Offloading (FPSO) system. More specifically, we propounded a set of modeling patterns devoted to production availability analysis. We formulated these patterns in the light of a simplified version of Guarded Transition Systems. We demonstrated how the model of a FPSO is obtained by assembling these modeling patterns. We discussed the experimental studies we apply to identify the sensitive parameters and critical components, with reference to the production availability. Regarding the experimental results, the study showed that at least for the system and mission time we considered in this article, system availability and production availability are strongly linked. As a consequence, the latter can be accurately estimated by averaging the former. Finally, Birnbaum's importance measure seems to be a good indicator of component criticality, in view of the production availability.

In terms of the production availability of FPSO, the most important factors are the efflux pumps (i.e., EPB1, EPC, EPB2, and EPA), thermal chemical processor (i.e., TCP), and sea water cooler (i.e., SWC). Various measures can be carried out to improve their availabilities. For example, we can decrease the repair time by improving the accessibility to the failed equipment and increasing the number of repair crew.

Lessons related to modeling methods have been learned. This study showed that stochastic simulation is a very powerful tool to assess production availability. It showed also that stochastic Petri nets with assertions and predicates, as implemented in the GRIF environment, are the very powerful modeling formalism. However, they are quite difficult to master when the system under study gets complex. Models tend to be hardly readable. A way to improve the modeling methodology is to design models by tailoring and composing modeling patterns. Stochastic guarded transition systems provides a clear and powerful mathematical framework for that purpose. The next step in that direction will be to use them directly, via the development of a dedicated library of the AltaRica 3.0 language [56].

Offshore and onshore production systems have similarities and differences. On the one hand, both systems are deployed to receive, process, and (temporarily) store hydrocarbons. It is therefore they have some similar equipment (e.g., separators, pumps, compressors, and heat exchangers). On the other hand, the offshore installations are costly and complex to be installed and maintained and the onshore facilities are relatively economical and convenient to be repaired. Accordingly, the lessons learned in this study can also be beneficial to the production performance analysis of onshore facilities.

As another future work regarding the experimental experiments we conducted, we plan to investigate other types of offshore systems (e.g., subsea production systems) and to develop experimental protocols so that production availability can be assessed in a systematic way.

Furthermore, the current manuscript is restricted to conduct production performance analysis in the field of system reliability. This work can be more comprehensive by taking the structural reliability into account. For example, it would be of great interest to study the equipment corrosion, hot work, and structural cracks to be repaired, which can show a negative effect on the production performance. It is beneficial to assess the production availability by integrating system reliability and structural reliability. This is therefore another topic for further research.

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References

[1] L.W. Lake, K.E. Arnold, Petroleum Engineering Handbook: Facilities and Construction Engineering, Society of Petroleum Engineers, Richardson, TX, USA, 2007.
[2] C. Barton, H. Hambling, E.K. Albaugh, B. Mahlstedt, D. Davis, 2016 Worldwide Survey of Floating Production, Storage and Offloading (FPSO) Units, 2016, , (accessed 10.06.17) http://www.offshore-mag.com/.
[3] V. Tam, R. Lee, Gas explosion modelling of FPSO, J. Loss Prev. Process Ind. 11 (1) (1998) 67–73.
[4] M. Muncer, Analysis of accident statistics for floating monohull and fixed installations, Health and Safety Executive, Aberdeen, UK, 2003, Tech. rep.
[5] H. Chen, T. Moan, Probabilistic modeling and evaluation of collision between shuttle tanker and FPSO in tandem offloading, Reliab. Eng. Syst. Saf. 84 (2) (2004) 169–186.
[6] J.A. Suardin, A.J.M Jr., A. Sipkema, M. Childs, M.S. Mannan, Fire and explosion assessment on oil and gas floating production storage offloading (FPSO): an effective screening and comparison tool, Process Saf. Environ. Protect. 87 (3) (2009) 147–160.
[7] F. Silva-González, A. Vázquez-Hernández, L. Sagrilo, R. Cuamatzi, The effect of some uncertainties associated to the environmental contour lines definition on the extreme response of an FPSO under hurricane conditions, Appl. Ocean Res. 53 (2015) 190–199.
[8] J.E. Vinnem, I.B. Utne, I. Schjølberg, On the need for online decision support in FPSO-shuttle tanker collision risk reduction, Ocean Eng. 101 (2015) 109–117.
[9] X. Zhang, L. Sun, C. Ma, E. Fassezke, H. Sun, A reliability evaluation method based on the weakest failure modes for side-by-side offloading mooring system of FPSO, J. Loss Prev. Process Ind. 41 (2016) 129–143.
[10] K.-Y. Kang, K.-H. Choi, J.W. Choi, Y.H. Ryu, J.-M. Lee, Explosion induced dynamic responses of blast wall on FPSO topside: blast loading application methods, Int. J. Naval Archit. Ocean Eng. 9 (2) (2017) 135–148.
[11] J.E. Vinnem, FPSO Cidade de S ao Mateus gas explosion – lessons learned, Saf. Sci. 101 (2018) 295–304.
[12] S. Mannan, Lees' Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control, Elsevier Butterworth-Heinemann, Waltham, MA, USA, 2005.
[13] T. Aven, L.M. Pedersen, On how to understand and present the uncertainties in production assurance analyses, with a case study related to a subsea production system, Reliab. Eng. Syst. Saf. 124 (2014) 165–170.
[14] J. Barabady, T. Aven, A methodology for the implementation of production assurance programmes in production plants, J. Risk Reliab. 222 (2008) 283–290.
[15] NORSOK, Z-016 Regularity Management and Reliability Technology, 1998.
[16] ISO 20815, Petroleum, Petrochemical and Natural Gas Industries: Production Assurance and Reliability Management, 2008.
[17] T. Aven, Availability evaluation of oil/gas production and transportation systems, Reliab. Eng. 18 (1) (1987) 35–44.
[18] P. Hokstad, Assessment of production regularity for subsea oil/gas production systems, Reliab. Eng. Syst. Saf. 20 (1988) 127–146.
[19] Y. Kawauchi, M. Rausand, A new approach to production regularity assessment in the oil and chemical industries, Reliab. Eng. Syst. Saf. 75 (2002) 379–388.
[20] Y.-F. Li, R. Peng, Availability modeling and optimization of dynamic multi-state series-parallel systems with random reconfiguration, Reliab. Eng. Syst. Saf. 127 (2014) 47–57.
[21] E. Zio, The Monte Carlo Simulation Method for System Reliability and Risk Analysis, Springer Series in Reliability Engineering, Springer London, London, England, 2013.
[22] M. Ajmone-Marsan, G. Balbo, G. Conte, S. Donatelli, G. Franceschinis, Modelling with Generalized Stochastic Petri Nets, Wiley Series in Parallel Computing, John Wiley and Sons, Bognor Regis, West Sussex, England, 1995.
[23] M. Talebberrouane, F. Khan, Z. Lounis, Availability analysis of safety critical systems using advanced fault tree and stochastic Petri net formalisms, J. Loss Prev. Process Ind. 44 (2016) 193–203.
[24] O. Grunt, R. Briš, SPN as a tool for risk modeling of fires in process industries, J. Loss Prev. Process Ind. 34 (2015) 72–81.
[25] O. N‘yvlt, S. Haugen, L. Ferkl, Complex accident scenarios modelled and analysed by stochastic Petri nets, Reliab. Eng. Syst. Saf. 142 (2015) 539–555.
[26] Z. Liu, Y. Liu, B. Cai, X. Li, X. Tian, Application of Petri nets to performance evaluation of subsea blowout preventer system, ISA Trans. 54 (2015) 240–249.
[27] H. Zhang, F. Innal, F. Dufour, Y. Dutuit, Piecewise deterministic Markov processes based approach applied to an offshore oil production system, Reliab. Eng. Syst. Saf. 126 (2014) 126–134.
[28] J.-P. Signoret, Y. Dutuit, P.-J. Cacheux, C. Folleau, S. Collas, P. Thomas, Make your Petri nets understandable: reliability block diagrams driven Petri nets, Reliab. Eng. Syst. Saf. 113 (2013) 61–75.
[29] C. Alexander, A Pattern Language: Towns, Buildings, Construction, Oxford University Press, 1977.
[30] E. Gamma, R. Helm, R. Johnson, J. Vlissides, Design Patterns: Elements of Reusable Object-Oriented Software, Addison-Wesley Professional, 1995.
[31] E. Gamma, Design patterns – ten years later, in: Software Pioneers, Springer, 2002, pp. 688–700.
[32] A. Rauzy, Guarded transition systems: a new states/events formalism for reliability studies, J. Risk Reliab. 222 (4) (2008) 495–505.
[33] A.H. Vesteraas, Comparison of Methods and Software Tools for Availability Assessment of Production Systems, Norwegian University of Science and Technology, Trondheim, Norway, 2008 (Master's thesis).
[34] M.M. Cowing, M.E. Paté-Cornell, P.W. Glynn, Dynamic modeling of the tradeoff between productivity and safety in critical engineering systems, Reliab. Eng. Syst. Saf. 86 (3) (2004) 269–284.
[35] R. Eymard, S. Mercier, Comparison of numerical methods for the assessment of production availability of a hybrid system, Reliab. Eng. Syst. Saf. 93 (2008) 168–177.
[36] X. Gao, J. Barabady, T. Markeset, An approach for prediction of petroleum production facility performance considering arctic influence factors, Reliab. Eng. Syst. Saf. 95 (2010), 873–846.
[37] E. Borgonovo, M. Marseguerra, E. Zio, A Monte Carlo methodological approach to plant availability modeling with maintenance, aging and obsolescence, Reliab. Eng. Syst. Saf. 67 (2000) 61–73.
[38] E. Zio, P. Baraldi, E. Patelli, Assessment of the availability of an offshore installation by Monte Carlo simulation, Int. J. Press. Vessels Pip. 83 (4) (2006) 312–320.
[39] E. Zio, M. Marella, L. Podofillini, A Monte Carlo simulation approach to the availability assessment of multi-state systems with operational dependencies, Reliab. Eng. Syst. Saf. 92 (2007) 871–882.
[40] E. Zio, Reliability engineering: old problems and new challenges, Reliab. Eng. Syst. Saf. 94 (2) (2009) 125–141.
[41] M. Naseri, P. Baraldi, M. Compare, E. Zio, Availability assessment of oil and gas processing plants operating under dynamic arctic weather conditions, Reliab. Eng. Syst. Saf. 152 (2016) 66–82.
[42] F. Bause, P.S. Kritzinger, Stochastic Petri Nets: An Introduction to the Theory, Vieweg+Teubner Verlag, Wiesbaden, Germany, 2002.
[43] IEC 62551, Analysis Techniques for Dependability – Petri Net Techniques, 2012.
[44] R. Briš, M. Kochaníčková, Stochastic Petri net approach to production availability evaluation of special test case, in: C.G. Soares, E. Zio (Eds.), Safety and Reliability for Managing Risk, Three Volume Set: Proceedings of the 15th European Safety and Reliability Conference (ESREL 2006), CRC Press, Estoril, Portugal, 2006, pp. 1569–1575.
[45] M. Boiteau, Y. Dutuit, A. Rauzy, J.-P. Signoret, The AltaRica data-flow language in use: modeling of production availability of a multi-state system, Reliab. Eng. Syst. Saf. 91 (7) (2006) 747–755.
[46] FPSO project group, FPSO manual for operation and maintenance, CNOOC, Shenzhen, China, 2007, Tech. rep.
[47] H. Meng, L. Kloul, A. Rauzy, Production availability modelling of FPSO system using stochastic Petri nets, in: L. Podofillini, B. Sudret, B. Stojadinovic, E. Zio, W. Kröger (Eds.), Safety and Reliability of Complex Engineered Systems: ESREL 2015, CRC Press, Zurich, Switzerland, 2015, pp. 2271–2279.
[48] R. Peng, M. Xie, S.H. Ng, G. Levitin, Element maintenance and allocation for linear consecutively connected systems, IIE Trans. 44 (11) (2012) 964–973.
[49] M. Rausand, A. Høyland, System Reliability Theory: Models, Statistical Methods, and Applications, John Wiley and Sons, Hoboken, NJ, USA, 2004.
[50] SINTEF, NTNU, Offshore Reliability Data Handbook, 6th ed., 2015.
[51] D. Coppit, K.J. Sullivan, J.B. Dugan, Formal semantics of models for computational engineering: a case study on dynamic fault trees, in: ISSRE 2000. Proceedings. 11th International Symposium on Software Reliability Engineering, 2000, IEEE, 2000, pp. 270–282.
[52] A. Rauzy, Towards a sound semantics for dynamic fault trees, Reliab. Eng. Syst. Saf. 142 (2015) 184–191.
[53] O. Tannous, L. Xing, R. Peng, M. Xie, S.H. Ng, Redundancy allocation for series-parallel warm-standby systems, in: IEEE International Conference on

Industrial Engineering and Engineering Management (IEEM), 2011, IEEE, 2011, pp. 1261–1265.

[54] Q. Zhai, R. Peng, L. Xing, J. Yang, Binary decision diagram-based reliability evaluation of k-out-of-(n + k) warm standby systems subject to fault-level coverage, Proc. Inst. Mech. Eng. O: J. Risk Reliab. 227 (5) (2013) 540–548.

[55] Z. Birnbaum, On the importance of different components in a multicomponent system, in: P. Krishnaiah (Ed.), Multivariate Analysis, Academic Press, 1969, pp. 581–592.

[56] T. Prosvirnova, M. Batteux, P.-A. Brameret, A. Cherfi, T. Friedlhuber, J.-M. Roussel, A. Rauzy, The AltaRica 3. 0 project for model-based safety assessment, in: Proceedings of 4th IFAC Workshop on Dependable Control of Discrete Systems, DCDS'2013, International Federation of Automatic Control, York, Great Britain, 2013, pp. 127–132.