Probabilistic analysis of risk and mitigation of deepwater well blowouts and oil spills

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Abstract

The development of robust risk assessment procedures for offshore oil & gas operations is a major element for the assessment of the potential feedback between planned activities and the environment. We illustrate a methodological and computational framework conducive to (*i*) a quantitative risk analysis of deepwater well barrier failures and subsequent hydrocarbon release to the environment and (*ii*) the analysis of the value of the deployment of conventional and/or innovative mitigation measures. Our methodological framework is grounded on historical records and combines the use of Dynamic Event Trees and Decision Trees from which we estimate probability of occurrence and impact of post-blowout events.

Each sequence of response actions, which are undertaken immediately after the event or in the subsequent days, is considered within the context of appropriately structured event paths. This approach is conducive to an estimate of the expected value of key decisions and underlying technologies, with an emphasis on their potential to reduce the oil spill volume, which can critically impact the environment. Our study yields an original comparative analysis of diverse intervention strategies, and forms a basis to guiding future efforts towards the development and deployment of technologies and operating procedures yielding maximum benefit in terms of safety of operations and environmental protection.

LIST OF ABBREVIATIONS

A	Annulus
BO	Blow Out
BOEMRE	Bureau of Ocean Energy Management, Regulation and Enforcement
BOP	Blow Out Preventer
BOPD	Barrel of Oil Per Day
BP	British Petroleum
BS	Blowstop
BS-PI	Blowstop (Primary Intervention)
BS-SI	Blowstop (Secondary Intervention)
CS	Capping stack
CUBE	Containment of Underwater Blowout Events
DNV	Det Norske Veritas
DPS	Dynamic Positioning System
DR	Debris Removal
DS	Drill String
DSL	Damage to Surface Mud Lines
DT	Decision Tree
DTA	Decision Tree Analysis
EMV	Expected Monetary Value
ERA	Environmental Risk Assessment
ESP	Electrical Submersible Pump
ET	Event Tree
ETA	Event Tree Analysis
FLOAT	Rig Floating
FMEA	Failure Modes and Effects Analysis
FTA	Fault Tree Analysis
HAWK	Hampering Active Wellbore Kit
IPR	Inflow Performance Relationship
LEP	Loss of Electric Power
LMRP	Lower Marine Riser Package
LMRP TH#4	LMRP Top Hat #4
NPV	Net Present Value
OA	Outer Annulus
OC	Outside Casing
OGP	International Association of Oil and Gas Producers
OLF	Oljeindustriens Landsforening
OSCAR	Oil Spill Contingency And Response
OSS	Oil Spill Scenario
OSV	Oil Spill Volume
PDF	Probability Density Function
PI	Productivity Index
PRA	Probabilistic Risk Analysis
PSA	Probabilistic Safety Analysis
QRA	Quantitative Risk Analysis
R&D	Research & Development
RC	Rapid CUBE
RIS	Marine Riser Sinking
RITT	Riser Insertion Tube Tool

ROV	Remotely Operated Vehicle
RW	Relief well
SEP	Start of Evacuation of rig Personnel
SINK	Rig Sunk
SINTEF	Stiftelsen for INdustriell og TEknisk Forskning
ST	Stock Tank conditions
TH	Top Hat
TOW	Rig Towed
VEC	Valued Ecosystem Component
VoO	Vessel of Opportunity

1. INTRODUCTION

The development and implementation of robust risk assessment procedures for offshore oil & gas operations is a cornerstone of the activities of the major oil companies and a critical element in the interplay between the ensuing anthropogenic actions and environment preservation. The recent increase of the level of awareness of environmental protection has favored the competitiveness for the development of risk-related studies and risk-reduction measures aimed at minimizing the environmental footprint of exploration and production in these challenging environments (Vinnem 2007). In this broad context, lessons learned from the Macondo well blowout (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling 2011a) have spurred a significant body of activities geared towards the assessment of innovative risk reduction technologies. Amongst these, we recall, as surface interventions on a wild well: (*i*) subsea capping stack (OGP 2011); (*ii*) Riser Insertion Tube Tool (RITT) and (*iii*) Lower Marine Riser Package (LMRP) Top Hat #4 (United States District Court 2015); (*iv*) a secondary intervention for Blow Out Preventer (BOP) (Klassen 2013); (*v*) a new dual Remoted Operately Vehicle (ROV) - assisted well killing system for deep water blowout (Ferrara et al. 2014); and (*vi*) the Hampering Active Wellbore Kit (HAWK) (Rojas and Slocum 2016). Risk assessment approaches need to be continuously updated, in line with modern industrial and environmental research and experience, to be able to support key scientifically-based practical recommendations aimed at defining effective planning and regulation, as well as addressing public concerns about the possibility of releasing potentially harmful substances to the environment.

Our study is framed in the context of the existing literature about offshore blowout risk analysis, which is often associated with a subsequent Environmental Risk Assessment (ERA). Among the most recent works on the subject, we refer here to Brude (2007), Brandt et al. (2010), Kruuse-Meyer et al. (2011), Rasmussen (2011), Ji et al. (2012), Dyb et al. (2012), Johnsen (2012), Jouravel (2013), Vandenbussche et al. (2012, 2014), Ahluwalia and Ruochen (2016), and Ruochen et al. (2016) and references therein.

Most of the above studies have been performed in compliance with OLF (Oljeindustriens Landsforening, i.e., Norwegian Oil and Gas Association) guidelines for ERA (Brude 2007). As such, all of them share a common structure for the adopted blowout risk analysis approach. Elements of these works which are relevant to our study are summarized as follows:

(i) the probability of an accident is quantified on the basis of historical data (SINTEF Offshore Blowout Database, and Scandpower reports, in the works mentioned above);

(ii) diverse blowout and oil spill scenarios are characterized on the basis of well flow paths, release points, flow restriction in the BOP, and well penetration depth inside the reservoir;

(iii) the duration of the blowout is calculated relying on historical data associated with documented occurrences and intervention practices;

(iv) the flow rate of hydrocarbons for each scenario is analyzed by way of transient fluid dynamic simulators (e.g., OLGA 5.3 in Rygg et al. 1992; BlowFlow in Karlsen and Ford 2014) as a function of physical and geometrical properties of the reservoir and the well;

(v) common and well established intervention techniques are considered (e.g., subsea capping stack, or relief well), their probability of success and intervention time being the elements driving their potential to stop the blowout depends.

Even in the presence of all of the above advancements, currently available studies on blowout risk assessment suffer from a number of limitations, including:

(i) approaches and procedures illustrated in these studies are typically confined to some aspects of the blowout scenario; for example, while the four classical blowout paths are considered (i.e., drill string, annulus, outer annulus and outside casing), important elements such as the rig conditions and the

occurrence of significant events after the blowout are not embedded in the analysis;

(ii) they lack a systematic comparison between diverse sets of intervention measures, the only notable exception being the work of Vandenbussche et al. (2014), where measures based on capping stack and relief well are compared;

(iii) they do not incorporate analyses of the most recent intervention techniques, of the kind developed after the Macondo blowout;

(iv) they lack a quantification of the contribution of any of the considered techniques to the mitigation of blowout consequences or risk.

The inclusion of all of the above aspects in a clear conceptual and operational framework is precisely the objective of our work. We pursue this by presenting an original probabilistic risk analysis of deepwater drilling blowouts focused on the major role of both common and innovative intervention technologies in the context of major oil spills. Our main results are expressed in terms of oil spill volumes derived from probabilities of occurrence of oil spill scenarios, blowout flow rates and event durations. Note that a complete ERA is outside the scope of the present contribution.

Our work aims at defining in a modern context the applicability of a variety of intervention techniques throughout the duration of the blowout event. The proposed methodology includes the study of the propagation of uncertainties to risk and mitigation results through a suite of Monte Carlo simulations. These could form the input to oil spill modeling software (e.g., OS3D/OSCAR - SINTEF and DNV 2009) so that environmental impacts can be assessed for the target Valued Ecosystem Component (VEC) affected by the spill.

The work is structured as follows. Section 2 illustrates the structure and content of the database available for the risk analysis. Section 3 details our methodology for risk assessment, focused on the analysis of consequences of a deepwater oil well blowout. Section 4 is devoted to the illustration of the set of results stemming from our analysis.

2. INPUT DATA FOR RISK ANALYSIS

The input data which are used in our risk analysis can be classified according to three major areas: (*i*) the top event, described in terms of possible blowout scenarios, their probability of occurrence and associated spill rates; (*ii*) the events following the blowout, with their probability and temporal sequence of occurrence; (*iii*) the intervention actions, characterized by their conditions of applicability, documented success rate, effect on the released flow rate and required time of implementation. All of these components are described in the following.

2.1 Top event

The analysis of the top event is grounded on the definition of initial blowout scenarios and the characterization of their probability of occurrence and associated flow rates. The probability of blowout occurrence, P_{BO} is defined as

$$P_{BO} = AF_{BO} / n_w \tag{1}$$

where AF_{BO} is the absolute frequency documented in the available database for oil and gas blowouts initiated from deep formations, both in shallow and deep water settings, during drilling phase; and n_w is the total count of offshore well drilled recorded up to the present day. These data are here inferred from the SINTEF Offshore Blowout Database (Holand 2014). Note that documented underground blowouts are not included in our analysis, which is specifically targeted to surface and subsea releases. As such, we consider two release points, i.e., a surface and a subsea point, respectively related to spills on the floating rig and on the seabed.

The initial blowout scenarios are characterized on the basis of blowout flow paths and release points. Flow paths inside the well have been classified by Holand (1997) and Petersen et al. (2011) with two slightly different approaches. We rely here on the terminology used in the SINTEF Database, which is the one proposed by Holand (1997). Fig. 1 depicts these flow paths in the context of deepwater drilling with riser. Dark red areas in the figure represent possible paths for formation fluids. These paths are termed Drill String (DS), Annulus (A), Outer Annulus (OA) and Outside Casing (OC).

Probabilities P_p associated with a given flow path p are expressed as:

$$P_p = AF_{BO,p} \big/ n_w \tag{2}$$

$AF_{BO,p}$ being the absolute frequency of blowouts having taken place through flow path p.

The initial point of fluid release to the environment is defined according to the initial flow path, i.e., fluids flowing through drill string, annulus and outer annulus are always conducive to a surface release, outside casing flow being associated with a subsea release. Flow paths and release points could evolve during the spill. This aspect will be further explored in Section 3.1.

The potential blowout flow rates for each path depend on the well and reservoir characteristics. The quantitative analyses illustrated here consider the Macondo case as a representative setting. Forensic evidence confirmed that fluids remained confined inside the production casing of the Macondo well (National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling 2011b), so that the Macondo path is of the Annulus type (see Fig. 1). Diverse values are reported in the literature for the Macondo blowout flow. For the purpose of comparison of final results of blowout risk and mitigation, we ground our analyses upon two different values of the flow rate ($Q_{BO, A}$) associated with the Annulus flow path, i.e., $Q_{BO, A}$ = 60000 bbl/day (= 9539 Sm^3/day), or 38000 bbl/day (= 6041 Sm^3/day), which are respectively inferred from the estimates of cumulative volume of oil released by Macondo well given by Pooladi-Darvish (2013) and Blunt (2013), divided by the total blowout duration (i.e., 85.8 days - United States District Court 2015). For the remaining flow paths, which are associated with higher frictional pressure losses than the annulus path, we assume a flow rate which is approximately equal to 50% of $Q_{BO, A}$, i.e., $Q_{BO, DS} = Q_{BO, OA} = Q_{BO, OC} = Q_{BO, A} / 2$ = 30000 bbl/day (= 4769.5 Sm^3/day), or 19000 bbl/day (= 3020.5 Sm^3/day).

Note that these assumptions are used only for the sake of exemplifying our procedure, appropriate estimates being required for the analysis of a specific case. Here and in the following we denote the blowout flow rate associated with path p as $Q_{BO, p}$ (p = DS, A, OA, and OC, respectively indicating Drill String, Annulus, Outer Annulus, and Outside Casing, consistent with Fig. 1).

2.2 Subsequent events

Here, we discuss possible events taking place after the top event and unrelated to the interventions undertaken for spill reduction.

The literature for risk assessment typically considers the blowout extinction by *external causes* (i.e., well bridging, coning, natural depletion, possibly combined) as the only possible set of subsequent events, which could occur after a blowout. Vinnem (2007) was the first to consider diverse events in addition to these. These also include the possibility of (immediate, delayed, or significantly delayed) ignition of spilled fluids and the ensuing presence of fire, both on the rig and/or on sea.

Here, we focus on the following set of events: (*i*) loss of electric power on the rig (LEP); (*ii*) start of evacuation of rig personnel (SEP); (*iii*) damage to surface mud lines (DSL); (*iv*) sinking of the marine riser (RIS); and (*v*) final rig condition, expressed as sunk (SINK), towed (TOW), or still floating (FLOAT).

These events have not been taken into account by previous literature, the only exception being the sinking of riser and/or rig (which is considered with its probability of occurrence, no information about the time of occurrence being given). Considering the events illustrated above is relevant because they affect the outcome of the interventions. We illustrate in the following our analyses aimed at estimating both the probability and timing of occurrence of such events.

2.2.1 Estimation of probability and timing of subsequent events

Our study relies on a considerable number of documents and reports regarding past offshore blowouts. Amongst these, we selected only those related to surface and subsea offshore blowouts with floating rig. These include the works of Westergaard (1987), Marquin (2014), Williams (1972), Myer (1984), Gill et al. (1985), PSA (2007), COWI A/S (2003), Miller (2001), Transocean (2015), and BOEMRE (2011).

A total of 13 past offshore blowouts have been identified and analyzed. We list these in the following by considering the floating rig and year of occurrence as identifiers: Sedco 135G 1969; Sedco 135F 1979; Sea Quest 1980; Petromar V 1981; Vinland 1984; Treasure Seeker 1984; West Vanguaard 1985; Ocean Odissey 1988; Treasure Saga 1989; Actinia 1993; Jim Cunningham 2004; Sedco 700 2009; Deepwater Horizon 2010. The method we employ to assess time and probability of occurrence of subsequent events is equivalent to the so-called *well-specific risk assessment* used to assign a risk level to each well type considered in the study of Vandenbussche et al. (2012).

We start by defining a binary indicator of occurrence, $O_{b,\,e}$, which is either unit or zero depending on whether an event *e* after blowout *b* has occurred or not. The results of our analysis are listed in Table 1. Note that here and in the following we base our results on 9 accidents out of the 13 above identified, because the available data about Sea Quest 1980, Petromar V 1981, Treasure Saga 1989, and Sedco 700 2009 did not contain sufficient information.

Next, we associate each event in Table 1 with its probability of occurrence and timing. To project historical documented data into a future setting, we introduce *risk factors f* (Vandenbussche et al. 2012). These are: (*a*) year of occurrence of the blowout (connected to technology and procedural advancements); (*b*) formation type (shallow gas pockets vs productive formations, following the terminology proposed by Holand (2014)); (*c*) fluid type (gas, condensate, oil); (*d*) water depth; and (*e*) availability of information regarding the accident. These elements are employed to emphasize the relative importance of diverse aspects associated with each case, including technological advances in safety, well barriers installed at the time of accident, risk of ignition, drilling equipment complexity and reliability of information.

A score $S_{b,\,f}$ is then assigned to each risk factor *f* of blowout *b*. Table 2 lists the criteria of scoring risk factors *f*. We subdivide these into three classes (1-3) according to an increasing risk level. We weight each risk factor *f* by a weight w_f, which quantifies the relative impact of

f on time and occurrence of the events. Values of the weights employed rely on in-house evaluations performed by focused groups of Eni deepwater drilling experts and are listed in Table 2. Clearly, the use of diverse sets of weights, which might arise from a diverse pool of experts, would not affect the overall methodological approach.

An overall blowout score S_b is then calculated as

$$S_b = \frac{\sum_f w_f S_{b,f}}{\sum_f w_f} \tag{3}$$

The overall probability P_e of occurrence of an event e has been obtained as a weighted average of the associated value of the occurrence indicator $O_{b,e}$ for each event e between blowouts b, i.e.,

$$P_e = \frac{\sum_b S_b O_{b,e}}{\sum_b S_b} \tag{4}$$

Along the same lines, the mean time of occurrence of an event e since the occurrence of a blowout, Δt_e, is calculated as the weighted average

$$\Delta t_e = \frac{\sum_b S_b \Delta t_{b,e}}{\sum_b S_b} \tag{5}$$

where $\Delta t_{b,e}$ is the time at which event e takes place after blowout b. The latter is defined and considered only if $O_{b,e} = 1$.

2.3 Intervention technologies

Previous studies about blowout risk analysis rely on estimates of blowout duration obtained according to two different ways. An approach is grounded on SINTEF and/or Scandpower historical statistics, that include the extinction of the release by external causes (i.e., well bridging, coning, natural depletion). Most of the recent works published after the Macondo accident (Rasmussen 2011; Dyb et al. 2012; Johnsen 2012; Vandenbussche et al. 2012, 2014; Jouravel 2013) follow a different approach, i.e., the complete blowout extinction (with no possibility of partial flow reduction) is related to: (*a*) the bridging of the well (with probability and occurrence time estimated from historical data) and/or (*b*) the application of blowout stopping techniques available at the time of the accident (surface killing methods, subsea capping stack, killing by relief well), each with its probability of success and intervention time calculated according to a series of assumptions. Neglecting the possibility to consider partial reductions of blowout flow rate is a notable limitation. This is particularly evident when one considers intervention technologies such as RITT, Top Hat, HAWK (United States District Court 2015; Rojas and Slocum 2016) and the two innovative technologies we analyze here and introduce in the following.

In the context of our analyses, we assume that the blowout duration can be modified solely by the application of intervention measures and not by other factors. The effects of interventions are analyzed not only with respect to their potential to fully stop the blowout, but also to the extent by which they can reduce the flow of hydrocarbon released to the environment.

We study the effect of both conventional and innovative intervention technologies. Amongst the conventional technologies, we consider: (*a*) the well shut-in by the application of a subsea capping stack (CS), together with debris removal (DR), which is necessary to the application of the subsea capping stack; and (*b*) the dynamic killing of the well through a relief well (RW).

We also include in our study the application of two very recent and innovative techniques, developed in-house at Eni, i.e., the Blowstop (BS) and Rapid CUBE (RC) technologies. The former relies on the injection of high density solids inside the well, with the aim of creating a plug at the well bottom, resulting in a large pressure loss along the blowout path. This effect is enhanced by a swelling reaction that is associated with a polymeric layer coating the solids and is activated following contact with hydrocarbons. Rapid CUBE (Containment of Underwater Blowout Events) is a no-seal technology for hydrocarbon collection and quick separation from a subsea release (Andreussi and De Ghetto 2013). This system is based on the use of an open-sea containment system, formed by a small subsea separator and a marine riser. The former enables a rapid gas/liquid separation, while the latter allows evacuating the liquids up to surface. The whole system is designed to contain the overall residence time within the separator, hence ~~remarkably~~ reducing the risk of system clogging due to hydrate formation.

The Blowstop technology can be applied right after the blowout, when the equipment required to perform the well kill is still on site and operating after the accident. We denote this application as Blowstop Primary Intervention (BS-PI). Alternatively, one could resort at a later time to a Vessel of Opportunity (VoO) with the equipment needed for the intervention. We refer to this practice as Blowstop Secondary Intervention (BS-SI). Rapid CUBE is supposed to be deployed on site by a VoO, in almost the same way as the subsea capping stack, but requiring a shorter deployment time, due to reduced dimensions and weight of the subsea equipment.

All of the above mentioned intervention techniques are here analyzed in relation to their: (*i*) applicability for each scenario; (*ii*) success of application; (*iii*) effect on blowout flow rate; and (*iv*) time required for intervention.

2.3.1 Applicability of intervention

Conditions for applicability of subsea capping stack are fulfilled in scenarios where (*a*) the release point is subsea; (*b*) debris removal activities have been completed successfully; and (*c*) fluid flow takes place inside the drill string or the annulus. With reference to the latter point and consistent with previous studies about the Macondo blowout (Hickman 2012), we assume that in all other cases the tubular elements within the well cannot withstand the pressure levels induced by the capping stack shut-in.

The possibility to perform well killing with a relief well is considered to be feasible in all scenarios, consistent with recent advances in relief well technologies. The applicability of debris removal activities is satisfied in all scenarios that require this type of intervention, which are those associated with riser and/or rig sunk.

The conditions of applicability of Blowstop differ when considering primary or secondary intervention. Assuming Blowstop equipment to be already on site when the accident occurs, its deployment requires pumping power for a water-based carrier and the availability of 3” service lines to the BOP (an automatic injection system has been recently developed to guarantee the continuity of the injection also in case of rig personnel evacuation). In this work, we assume that such facilities are still available in the context of the Primary Intervention. Therefore, both the riser and the offshore rig should not be sunk and the BOP should be in place. Another condition of applicability of the technology is that the solids injected into the wellbore must intercept the formation fluids rising upwards. This condition can be satisfied only for blowout taking place through the well annulus. For the Secondary Intervention (i.e., BS-SI), the latter condition is required for applicability, together with successful debris removal to restore BOP connection with a service line.

Rapid CUBE is considered to be applicable in almost all of the scenarios related to a subsea release, a notable exception being a case with very high flow rates of gas release, due to the limited subsea separator capacity. For this reason and to streamline our analysis, we assume that Rapid CUBE can be applied for gas flow rates values whose upper limit is about 80% of the largest value of admissible gas flow rate considered.

2.3.2 Success of intervention

We define PS_t as the probability of success of a given technology of intervention t (t = RW, CS, DR, RC, BS-PI, BS-SI). In the case of conventional technologies, such probability is assigned the value which is most frequently used in the literature (Johnsen 2012; Vandenbussche et al. 2012, 2014), i.e., PS_{CS} = 0.9 is assumed for capping stack; PS_{RW} = 1 for relief well; PS_{DR} = 1 for debris removal activities.

The probability of success of emerging technologies such as Blowstop and Rapid CUBE is assessed on the basis of in-house evaluations. The purpose of our current analysis is not to qualify such technologies for application (thus demonstrating the probabilities of success), but to show the impact of such technologies if reasonable probabilities of success are achieved.

Both primary and secondary Blowstop intervention require several conditions for success. The probability of success of Blowstop is calculated as

$$PS_{BS} = PS_{BS\ -\ inject\ solids} \times PS_{BS\ -\ solids\ reach\ bottomhole} \times PS_{BS\ -\ plug} \tag{6}$$

According to in-house evaluations, the probability of success of injecting solids is estimated $PS_{BS\text{-}inject\ solids}$ = 0.85, while the probability of success of the solids reaching the bottomhole is $PS_{BS\text{-}solids\ reach\ bottomhole}$ = 0.76, and 0.82, respectively for surface and subsea releases (ENI E&P 2016); and $PS_{BS\text{-}plug}$ is the probability of success in creating a low-permeability plug at the bottomhole. In our analyses we assume that $PS_{BS\text{-}plug}$ = 1 with a minimum differential pressure ΔP_{BS} = 40 bar across the plug (a lower pressure drop would be considered as a failure, a higher pressure drop being typically achievable).

Since Rapid CUBE is a no-seal technology, its major cause of failure is clogging due to hydrate formation. This is consistent with the observation that all failed attempts to collect hydrocarbons flowing from the Macondo wellhead (Cofferdam, Riser Top Hat) were associated with a stop of the collected flow due to hydrate nucleation and growth. The Rapid CUBE technology has then been designed with the objective of minimizing the risk of hydrate obstructions inside of the subsea capturing device and the riser. On the basis of the analysis of a series of failure modes of the system (ENI E&P 2016), the failure of Rapid CUBE intervention is assessed in terms of a cumulative temporary down time of the overall system, rather than through a value of probability.

2.3.3 Effects of intervention on flow rate reduction

Previous works about blowout risk analysis consider a constant flow rate throughout the duration of the release, until a sudden downturn to zero takes place when the control of the well is restored. All conventional techniques examined in this work (i.e., subsea capping stack and relief well) adhere to this concept. Otherwise, Blowstop and Rapid CUBE might be effective also by reducing (significantly) the overall spill volume.

The amount of oil collected by Rapid CUBE depends on the fluid dynamics and the dimensions of the system (subsea separator volume, flow lines diameters), the total amount of gas released by the well being evacuated subsea.

Given a generic blowout flow rate $Q_{o,BO}$, the deployment of Rapid Cube can lead to the potential collection of (*a*) fraction of the oil spill rate, here termed as $Q_{o,RC}$, which is then sent to offloading facilities at the surface, and (*b*) a certain amount of water, with a flow rate $Q_{w,RC}$. The total flow rate of liquids captured via this technology is then $Q_{liq,RC} = Q_{o,RC} + Q_{w,RC}$. Results of flow rate tests of subsea separator are graphically reported in Fig. 2a through values of $Q_{o,RC}$, $Q_{w,RC}$ and $Q_{liq,RC}$ versus $Q_{o,BO}$, up to $Q_{o,BO}$ = 50000 BOPD (Barrels of Oil Per Day). For higher values of $Q_{o,BO}$, all other fluid flow rates are supposed to remain constant at their largest values of $Q_{liq,RC}$ = 12000 BOPD, $Q_{o,RC}$ = 12000 BOPD and $Q_{w,RC}$ = 0 BOPD.

Blowstop has a high potential for flow rate reduction. By creating an additional pressure drop along the blowout path, its effect is to reduce the blowout flowrate from its original value to a lower (or residual) value. The estimation of the residual oil spill rate ($Q_{o,residual}$) is connected to the well Productivity Index *PI*:

$$Q_{o,residual} = Q_o - \Delta p_{BS} \times PI \tag{7}$$

For example, the minimum Blowstop performance required to qualify the application as successful with for a PI = 60 Sm^3/day/bar would be a spill reduction of about 2400 Sm^3/day = 15000 BOPD. In case of complete success, the additional pressure drop would be sufficient to bring the spill rate down to zero.

Fig. 2b depicts the blowout flow rate $Q_{o,residual}$ [%] (in percentage of the annulus blowout flow rate $Q_{BO,A}$) versus the resulting pressure losses, Δp, in the case of deployment of the blowstop technology. These results indicate that a value of Δp = 40 bar is associated with a value of about $Q_{o,residual}$ = 30%, which represents a safe condition for the low-permeability plug at the bottomhole described in Section 2.3.2. We note that this latter condition would be achievable only if the solid injection lasts for about 10 hours (pressure loss rate is typically evaluated as = 4 bar per hour of solids injection). That is a critical point, which highlights the importance of analyzing the rig conditions after the accident in these settings.

2.3.4 Time required to intervention

Deployment and application of an intervention technology t require a series of activities a, each associated with a given duration $\Delta t_{t,a}$. The total time needed to document an effect on blowout flow rate is termed intervention time Δt_t. The latter is a function of durations $\Delta t_{t,a}$ of all of the necessary activities, which include consecutive or simultaneous actions. We examined duration of activities associated with each of the secondary intervention technologies t (i.e., CS, RW, DR, RC, BS-SI) and assigned realistic values on the basis of typical technical procedures and reasonable assumptions. All of the activities associated with secondary interventions are outlined in Appendix A together with the corresponding estimated $\Delta t_{t,a}$. From these, we obtain: (*a*) Δt_{CS} = 24 days; (*b*) Δt_{RW} = 71 days; (*c*) Δt_{DR} = 16 days; (*d*) Δt_{RC} = 17 days; and (*e*) $\Delta t_{BS\text{-}SI}$ = 22 days.

The value associated with Blowstop Primary Intervention, instead, is much shorter, i.e., of the order of hours, being assessed by considering: (*i*) time to set-up and activate the injection system; (*ii*) time for the solids to reach bottomohole; (*iii*) time for solids to settle in front of the blowout depth; (*iv*) time for the plug to form and consolidate. With a proper setup, (*i*) and (*ii*) can be reduced to minutes, while (*iii*) and (*iv*) can be globally estimated in 4-5 hours, thus yielding $\Delta t_{BS\text{-}PI}$ = 0.2 days.

3. METHODOLOGY FOR PROBABILISTIC RISK ANALYSIS

The Probabilistic Risk Analysis (PRA) we perform rests on the terminology of Vinnem (2007) for offshore risk assessment. This choice is consistent with prior literature studies on blowout risk.

Dealing with risk always requires a complete view of causes and consequences of the undesired event. These are typically connected in a logical and consequential way through a bow-tie diagram (an exhaustive example is given by Shan et al. 2017), which includes the analysis of causes leading to the top event, also known as (Fault Tree Analysis, FTA) and the analysis of its consequences (Event Tree Analysis, ETA). The probabilistic approach considered in this study has also been adopted in diverse areas of engineering, management, and risk assessment (e.g., Shan et al. 2017; Tartakovsky 2012; Fukutani et al. 2014). A variety of methodologies for probabilistic risk analysis are discussed in the literature. These include, e.g., the application of the Failure Modes and Effects Analysis (FMEA) method for the identification of risk factors in gas refineries for insurance purposes (Ghasemi et al. 2015), or analyses aimed at assessing estimates of the emission frequency of pollutants (Shahriar et al. 2014) or pipeline failures (Alzbutas et al. 2014). In this broad context, the most distinctive aspects of our work are (1) the quantification of the value of the mitigation actions undertaken in the presence of a non-negligible environmental risk and (2) an original comparative analysis between diverse conventional and innovative intervention technologies. To this end, we employ a probabilistic approach to risk assessment that is grounded on a well-defined series of event and decision trees and is mainly keyed to the analysis of consequences of a deepwater oil blowout during drilling operations.

3.1 Event Tree Analysis

We present here the Event Tree Analysis (ETA) associated with the investigated settings. When viewed in the context of other studies embedding event or logic trees in probabilistic approaches to environmental risk assessment (e.g., Vinnem 2007; Fukutani et al. 2014; Shan et al. 2017), we note that our model for ETA introduces risk mitigation actions, together with their potential for applicability and success of intervention. Due to its complex structure, we start from the illustration of the streamlined overall event tree depicted in Fig. 3. The well blowout is the initiating event, with probability of occurrence P_{BO}. The first branches lead to the diverse flow paths inside the well. These are considered as independent events.

Flow paths and events are framed in a so-called flow-path event tree ET_p (p being DS (Drill String), A (Annulus), OA (Outer Annulus), or OC (Outside Casing)). Each event tree is characterized by a given applicability of interventions. In this work we build two different overall event trees, respectively devoted to moored and dynamically positioned rigs.

We exemplify our procedure by detailing the key elements of the Annulus event tree (ET_A) for a moored rig. We subdivide it into two trees, which we respectively term Primary and Secondary event tree, according to the terminology used for the two categories of interventions.

Fig. 4 depicts an example of primary event tree for ET_A. The initiating event is characterized by probability P_A. Interventions are included within the tree only if they are applicable in the given scenario. Two branches depart from the node representing their applicability, i.e., a branch labeled *Yes* and associated with a probability of success PS_t and a branch labeled *No* and associated with probability of failure $(1 - PS_t)$. Subsequent event nodes are labeled *Yes* if the event occurs (with probability P_e) and *No* in case of non-occurrence (with probability $(1 - P_e)$).

We label as k each branch of the event tree which starts from the initiating event (defined in Fig. 3 by flow path and initial release point) and leads to each of the end points (corresponding to the final release point). Each branch is associated with a unique sequence of events which have taken place and successful interventions. We term as k,e the nodes representing an intersection point of branch k, at the time of the event e. For simplicity, all nodes k,e with an associated probability $P_e = 1$ have been reported only with the branch *Yes*, as in the case of starting evacuation of rig personnel in Fig. 4.

We note that while the chronological order of events and interventions could change, the approach we follow is compatible with the construction of dynamic event trees. All examples we illustrate here are grounded on average times of occurrence of events and average times of intervention.

We denote the end points of the event tree as final scenarios ω. Each of these final scenarios is characterized by a probability P_ω that depends on the nodes k,e intercepted. Note that here and in the following we term e both events and interventions, k,e being a node of the event tree with an associated probability $P_{k,\,e}$. The probability associated with a final scenario is expressed as the product of the sequence of conditional probabilities, $P_{k,\,e}$, i.e.,

$$P_{\varpi} = \prod\nolimits_{e} P_{k,e} \qquad (8)$$

Formulation (8) is consistent with the assumption that all events in the event tree of Fig. 4 are independent. The mutual exclusivity of the final rig conditions is an exception to this. A primary event tree for dynamically positioned rigs does not contemplate riser sinking and rig towing, riser and platform being supposed to be always joined together and rig sinking being considered as an event dependent on the electric power loss. The latter observation follows from the presence of the Dynamic Positioning System (DPS, consisting in propellers and thrusters being operational only if electric power is available on the rig) as the only equipment capable of preventing the rig from drifting away from the target point and consequently sinking. The probability of proceeding along branch *Yes* from node *k,SINK* is then taken to be $P_{k,SINK}$ = 1 along all event tree branches k for which there is power loss on the rig. Otherwise, we take $P_{k,SINK}$ = 0.0 along all branches k for which power loss on the rig does not occur.

Fig. 5 depicts an example of a secondary event tree for Annulus blowout (ET_A) and moored rigs, where secondary interventions and their success (or lack of) are considered. Final scenarios of secondary event trees are defined as oil spill scenarios *OSS* and are located at the end of each branch of secondary event trees.

We note that, for simplicity, we consider that (*a*) each final scenario of the primary event tree is the initiating event of a secondary event tree, and (*b*) the set of secondary interventions (and their success probabilities) are independent.

Note that the escalation of interventions in a real blowout is more complex. On one hand, the complete success of primary interventions would make secondary interventions unnecessary. On the other hand, the repeated failure of interventions affects the probability of success of subsequent ones, not only because of technical reasons, but also because of human and organizational factors, such as the intensification of efforts (as in the case of Macondo). We are not including this complex interplay in our analysis.

3.2 Decision Tree Analysis

Embedding a Decision Tree Analysis in a risk analysis approach has been traditionally employed in the oil&gas industry to support decision making. Examples of application include: (*i*) the definition and maximization of Net Present Value (NPV) for an oil&gas field development (Coopersmith et al. 2001); (*ii*) the analysis of risk for directional drilling operations (Thorogood et al. 1991); and (*iii*) the coordination and execution of oil spill response measures in a contingency plan (Abel 1993).

An appropriate Decision Tree Analysis (DTA) enable us to define in a clear and schematic way the final targets of a set of operations. This objective is achieved by obtaining values of risk for several drilling and blowout scenarios and its mitigation associated with a variety of possible response actions.

We start by calculating the consequences of each final oil spill scenario, expressed as Oil Spill Volume OSV_{OSS} or $OSV_{p,k}$, as given by

$$OSV_{OSS} = OSV_{p,k} = \sum_{e} \left(OSV_{p,k}\right)_e = \sum_{e} Q_{p,k,e}\left(\Delta t_{p,e+1} - \Delta t_{p,e}\right) \quad (9)$$

Here, $(OSV_{p,k})_e$ is the partial oil spill volume which flows through well path p and is released between the event e and $e+1$ of the branch k of the ET_p; $Q_{p,k,e}$ is the flow rate of oil following occurrence of event e; and $\Delta t_{p,e+1}$ and $\Delta t_{p,e}$ respectively are time of occurrence of events e+1 and e subsequent to a blowout inside the well flow path p.

Our DTA is performed with two different types of decision trees, examples of which are depicted respectively in Fig. 6 and Fig. 7. This methodology gives the possibility of analyzing two diverse situations, corresponding to scenarios for which the analysis starts while drilling the well or at the moment of the blowout. The major innovation here introduced is the assessment of risk and mitigation values for each of these two initial situations, as described in the following.

Fig. 6 depicts a decision tree built on the basis of a non-negligible risk of occurrence of a potential blowout during well drilling. Before the start of drilling operations (a phase which is known as well spud), all solutions available for intervention in case of blowout are included in the Drilling Plan. Here, we associate a decision j with the choice of starting the drilling activities jointly with the availability of deploying a defined set of intervention measures, in case of blowout of the well. Each decision is followed by two possibilities: (*a*) all drilling operations continue with no delays and no accidents, so that no spill occurs and no interventions are needed; or (*b*) a blowout occurs during drilling activities, so that all of the available intervention measures are undertaken, with the aim of reducing the total impact of the accident. In the latter case, all possible combinations of subsequent events and consequences are analyzed in the context of an overall event tree of the kind depicted in Fig. 3. The event trees ET_p are built differently for each decision j, consistent with the associated set of techniques being available for the deployment.

Fig. 7 depicts the structure of the decision tree we propose when considering an initial condition corresponding to a blowout which takes place during the well drilling phase and continues during the response phase. In this context, a decision j expresses the choice of undertaking a given action to mitigate the blowout consequences, by deploying a specific set of technologies. Each decision is accompanied by the associated overall event tree.

It is possible to associate a blowout risk value with each decision taken and for a given initial situation considered, the drilling of the well and the response phase. Consistent with standard practice, we choose to calculate an expected value of blowout risk for each decision j, termed R_j, by weighing oil spill scenarios consequences ($OSV_{p,k}$) through the associated probability, $P_{p,k}$, as

$$R_j = \left(\sum_p \sum_k P_{p,k} OSV_{p,k} \right)_j \qquad (10)$$

We present in Appendix B a schematic flow chart exemplifying risk calculation through (8), (9) and (10). For ease of illustration, the example targets a given branch of the overall event tree of Fig. 3 and enables us to single out the contribution of the various model component.

Formulation (10) enables us to compare diverse initial situations in terms of expected blowout risk. Other types of comparisons could obviously be performed, depending on the criteria underpinning the definition of decisions j, leading to consequent values of R_j. For the purpose of our analysis, we associate each decision j with a precise historical period in which a well-defined set of techniques is available to be deployed in case of subsea blowout. This framework is consistent with the development over time of technologies and best practices. Decisions j and the sets of associated intervention techniques are listed in Table 3 and termed as Risk Scenarios.

A main aspect is the recognition that blowout intervention technology is continuously evolving, so that the tools available in the pre-Macondo context are solely a subset of what is available nowadays and what will be, predictably, available in the short and medium term future. This concept is illustrated in Table 3, where each technological context (here called Risk Scenario, or Decision) leads to a diverse set of intervention technologies among which one can select.

The first two rows of Table 3 list the standard equipment available for subsea intervention before and after the Macondo blowout. Various experts stated that a relief well was, before and at the time of the accident, the only available and tested technique to stop a subsea blowout (5 May 2010, National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling 2011a). The subsequent development of a subsea capping stack technology is here considered in the Post Macondo scenario, together with the use of a relief well.

It is noted that Rapid CUBE is currently available for deployment within the expected time frame. The Blowstop technology is currently in the development stage. As a consequence, we could define a present-time scenario with the addition of Rapid CUBE to capping stack and relief well and two future scenarios (see Table 3). In the scenario termed Short Term Future, Blowstop is expected to be available in its secondary intervention configuration (BS-SI). The Long Term Scenario considers both configurations of Blowstop (BS-SI and BS-PI) to be available.

We then define an expected risk mitigation value M_t for each intervention technology t, with the only exception of relief well. Expected risk mitigation values are expressed as

$$M_t = \Delta R_j = R_j - R_{j-1} < 0, \qquad j = 2, ..., 5 \tag{11}$$

where expected values M_{CS}, M_{RC}, $M_{BS\text{-}SI}$ and $M_{BS\text{-}PI}$ are calculated via (11), with j = 2, ... 5, respectively. Use of (11) enables us to assess risk mitigation potential in terms of expected reduction of oil spill volume, as a result of the addition of a given technology to a new risk scenario. For example, M_{CS} represents the expected reduction of oil spill volume following by the addition of subsea capping stack to the set of technologies of Pre Macondo Scenario.

3.3 Assessment of a complete risk distribution

The assessment of uncertainties and the way they could propagate to results is a key point of PRA and ERA approaches. OLF (Oljeindustriens Landsforening, i.e., Norwegian Oil and Gas Association) has issued guidelines on how to calculate flow rates and durations in an ERA (Nilsen et al. 2004) and emphasizes that the results should be presented in a probabilistic context (Brude 2007). Some works illustrate a blowout duration distribution through a set of 4 discrete values, with their associated probabilities taken from historical data (e.g., Roald 2000; Brandt et al. 2010; Rasmussen 2011; and Kruuse-Meyer et al. 2011). Intervention measures and their time of application are associated with probability distributions based on realistic assumptions in the works of, e.g., Dyb et al. (2012), Johnsen (2012), or Vandenbussche et al. (2012, 2014). These authors employ either a uniform or a triangular distribution for the time associated with each activity when considering the technology of capping stack and relief well.

Here, we model the probability of each event time, Δt_e, through a triangular distribution. The support of the latter ranges between a minimum and maximum value of time respectively corresponding to minimum and maximum values of all of the $\Delta t_{b,e}$ taken from documents and reports listed in Section 2.2.1 for each specific blowout. A triangular distribution is also used for the time of duration ($\Delta t_{t,a}$) of each activity, which is needed for the deployment and application of a given intervention. The parameters of these distributions are selected on the basis of realistic assumptions, as detailed in Appendix C.

To assess the complete distribution of quantitative risk values, PRA studies typically rely on a Monte Carlo framework, examples being reported in the works of Benekos (2007), Qin (2012), Shahriar (2014), or Mumford (2015). Here, the final probability distributions of risk and mitigation values, respectively denoted as R_j and M_t, are calculated via Monte Carlo simulations. We do so by considering Δt_e and $\Delta t_{t,a}$ as the only random quantities in (8) and (9). A preliminary study on the convergence of the statistics of R_j and M_t has been performed by considering up to 100,000 Monte Carlo samples. These results reveal that an acceptable convergence of the main statistics and distribution quantiles is attained for about 10,000 Monte Carlo samples. As such, all results presented in Section 4 are based on a collection of 10,000 Monte Carlo realizations.

4. RESULTS AND DISCUSSION

This Section is devoted to the illustration of the set of results stemming from our analysis. We present results related to (*a*) the probability of occurrence of blowout scenarios and subsequent events (Section 4.1), (*b*) the expected temporal evolution of blowout flow rates for each risk scenario, together with expected values of blowout risk mitigation for each technique of intervention (Section 4.2), and (*c*) values of risk of blowout for each risk scenario (Section 4.3).

4.1 Subsequent events and final release points

Regarding blowout scenarios, we report here probabilities of surface and subsea release point of final oil spill scenarios. Starting with an initial probability of surface blowout of $P_{in,surf} = 1$ and using the event trees approach described in Section 3.1, our results reveal that a final subsea release point is associated with a probability of $P_{fin,\,sub,\,MR}$ = 0.814 for moored rigs and $P_{fin,\,sub,\,DPR}$ = 0.829 for dynamically positioned rigs. These results are consistent with corresponding values found by, e.g., Dyb et al. (2012), Johnsen (2012), and Jouravel (2013) which are comprised in the range [0.73, 0.90].

Values of P_e and Δt_e for subsequent events e are listed in Table 4 for mooring rigs and rigs with a Dynamic Positioning System (DPS). Our results suggest that probability values are rather high for all events (with the exception of the event associated with sinking of moored rigs). The first three events listed in Table 4 (i.e., Lost of electric power supply, Emergency evacuation, and Damage of surface mud lines) occur, on average, shortly after the blowout. Otherwise, the sinking of the riser or of the rig or the towing of the rig tend to occur on average between one and two days after the blowout.

4.2 Temporal dynamics of blowout flow rates and risk mitigation values

A first analysis about risk scenarios and their consequences involves the assessment of blowout flow rates and their temporal evolution. Each final oil spill scenario OSS is associated with a characteristic evolution and duration of the blowout flow rate. These flow rate profiles could be condensed into a single expected evolution of blowout flow rates, calculated for each risk scenario. We follow the same approach used to calculate R_j (10), and weigh flow rates $Q_{p,k,e}$ by the associated probability, $P_{p,k}$, through

$$Q_{o,\exp,j,e} = \left(\sum_p \sum_k P_{p,k}\, Q_{p,k,e} \right)_j \qquad (12)$$

where $Q_{o,\exp,j,e}$ is an expected oil flow rate at the time of occurrence of event e and for decision j leading to the corresponding risk scenario.

Fig. 8 depicts temporal evolutions of blowout flow rates associated with each of the five risk scenarios considered (see Table 3), with the assumption of $Q_{BO,\,A}$ = 60000 BOPD. Note that results depicted in Fig. 8 and in the following figures are obtained as the arithmetic mean between values obtained for moored rigs and dynamically positioned rigs, except when otherwise specified.

By making use of (9), (10) and (12) it is possible to express R_j as a function of $Q_{o,\exp,j,e}$ through

$$R_j = \sum_e Q_{o,\exp,j,e}\left(\Delta t_{p,e+1} - \Delta t_{p,e}\right) \tag{13}$$

According to formulation (13), the five areas subtended by flow rate curves in Fig. 8a, b, c and d coincide with expected values of R_j (R_1, R_2, R_3, R_4 and R_5, respectively).

The shadowed area in each of the plots in Fig. 8 represents the difference between values of R_j and R_{j-1}, (j = 2, 3, 4, 5, respectively for Fig. 8a, b, c, and d). According to (11), each shadowed area corresponds to the absolute value of the expected mitigation $|M_t|$ for technology of intervention t = CS, RC, BS-SI, BS-PI, and resulting in M_{CS} = -1183 kbbl (= -188 kSm^3); M_{RC} = -196kbbl (= -31 kSm^3); $M_{BS\text{-}SI}$ = -208 kbbl (= -33 kSm^3); and $M_{BS\text{-}PI}$ = -401 kbbl (= -64 kSm^3). These results highlight the relative importance of the applicability and of the expected success of each technique. The major conclusions that can be drawn from Fig. 8 are: (*i*) the intervention based on the use of a relief well always leads to the blowout extinction when the dynamic kill is performed; (*ii*) application of capping stack in the Post Macondo scenario yields a notable difference in the expected blowout risk as compared to the Pre Macondo scenario, albeit significant limitations due to its applicability can be observed, the expected value $Q_{o,\,exp,\,j,\,e}$ still remaining high at about ≅ 20000 BOPD the days after *CS* application; (*iii*) Rapid CUBE and Blowstop (secondary intervention) are conducive to a moderate spill mitigation, with a positive, synergic effect, rendered by their abilities to intercept diverse blowout flow paths (also in relation to the capping stack) and reducing $Q_{o,\,exp,\,j,\,e}$ values from 20000 BOPD to 15000 BOPD and less, after 25 days of spilling; and (*iv*) an interesting and significant potential is evidenced for BS-PI for early spill reduction, suggesting a maximization of its mitigating effect when coupled with the other secondary interventions.

Temporal evolutions of blowout flow rates (such as those depicted in Fig. 8) provide insights on the implications of our results within the context of a complete Environmental Risk Assessment (ERA). We note that a variety of methods for ERA have been presented with the aim of evaluating the exposure of ecosystems to potentially harmful events. Probabilistic risk linked to industrial activities is typically assessed in terms of the probability of a pollutant concentration exceeding some set environmental standards (e.g., Agwa et al. 2013; Mumford et al. 2015). Vandenbussche et al. (2014) address ERA of blowouts and oil spills and suggest an approach based on (*a*) evaluating the probability for coastal and pelagic resources (e.g., seabirds, marine mammals and shoreline habitats) to be reached by the spill and (*b*) inferring the ensuing damage. Considering the blowout flow rate reduction associated with each of the available technologies, as we do in our work, has a natural feedback on modeling techniques to be employed to characterize the fate of the oil spill and its resulting impact on Valued Ecosystem Components (VECs). Mitigation effects could be assessed through the same DTA-based approach we propose in our study. Finally, we note that our approach can seamlessly embed analysis frameworks targeting estimated oil spill remediation costs (Jouravel 2015) to then allow associating an Expected Monetary Value (EMV) with each of the available mitigation technologies.

4.3 Risk values

We now present results condensing all the information given in the previous Sections into expected values of risk and its mitigation. Expected values of R_j are depicted in Fig. 9 through histograms. These refer to the drilling and response phase and are associated with the set of five risk scenarios considered. Results are illustrated for the two values of $Q_{BO,A}$ analyzed and are expressed in two ways, i.e., (*a*) through (10) in bbl and (*b*) as a percentage of Pre Macondo risk values $R_{\text{Pre Macondo}}$.

Most of the results associated with the drilling phase are characterized by an expected risk value between 0.5 and 1.5 thousand of bbl of potential oil spill per well drilled, with small differences among the three values denoted as Post M, Pres, and LT Fut, in comparison with Pre Macondo and Long Term Future scenarios. Values of R_j calculated as percentage of $R_{\text{Pre Macondo}}$ suggest no visible differences between the results stemming from the two values $Q_{BO,\,A}$ employed in the analysis, a slight increase in the effectiveness of interventions being noticed for the setting characterized by $Q_{BO,\,A} = 60$k BOPD.

An interesting comparison can be done between values of R_j for the response phase (depicted in Fig. 9b) and the actual volume of oil spilled into the environment from the Macondo well, here termed $OSV_{Macondo}$. Before the well was capped, two successful interventions made through the Riser Insertion Tube Tool (*RITT*) and the LMRP Top Hat #4 (*LMRP TH#4*) collected a considerable amount of oil above the subsea wellhead (Lehr et al. (2010) assess an expected value of $V_{RITT+LMRP\ TH\ \#4}$ = 818 kbbl). Subtracting this quantity from the assumed value of 5.15M bbl of cumulative oil released from the Macondo wellhead (Pooladi-Darvish 2013), one obtains $OSV_{Macondo}$ = 4.33M bbl. All values of R_j in Fig. 9b are considerably smaller than $OSV_{Macondo}$, almost all of them being included between 1 and 2 million of bbl.

Sample relative frequencies of R_j are shown in Fig. 10 for the five risk scenarios, during the response phase and considering $Q_{BO,\,A} = 60$k BOPD. One can observe: (*i*) the Pre Macondo scenario is associated with the widest sample distribution, encompassing a broad range of R_j values, in contrast with the compact distributions associated with the other scenarios; (*ii*) mean values $\mu(R_2) > \mu(R_3) > \mu(R_4)$ (respectively for Post Macondo, Present and Short Term Future scenarios) suggesting the effectiveness (on average) of Rapid CUBE and Blowstop (Secondary Intervention) in terms of oil spill volume reduction. We note that the frequency distributions R_2, R_3 and R_4 in Fig. 10 are not well separated, thus allowing for some ambiguities in the evaluation of the actual order of effectiveness of these technologies.

5. CONCLUSIONS

Our study is chiefly aimed at illustrating a methodology we developed for risk analysis and mitigation of deepwater drilling blowouts and major oil spills in the context of an ever increasing technological evolution. We do so upon relying on a probabilistic approach. Probability of top event (the blowout event) and subsequent events are assessed from historical data. The parameters of the intervention techniques are obtained from technical and realistic assumptions. Specific event trees and decision trees are constructed and employed to assess the applicability and degree of success of diverse technologies. This is achieved in the context of multiple risk scenarios and through the quantification of a risk mitigation value for each technology.

Elements of innovation of our Probabilistic Risk Assessment approach include: (*a*) the possibility of embedding events occurring after the blowout; (*b*) the quantification of the applicability and success of interventions; and (*c*) the final Decision Tree Analysis, according to which risk scenarios and diverse sets of interventions are identified in a consistent conceptual and operational framework and values of risk and risk mitigation are assessed for the diverse operational phases taking place.

The deployment of several blowout intervention technologies is here compared for the first time and within a probabilistic approach. Additional considerations about blowout risk mitigation should be made when considering the simultaneous effect of more technologies on the same well. Our analysis clearly underlines the high mitigation potential of capping stack, when firstly introduced in addition to the relief well. On the contrary, expected values of blowout risk do not show sensible declines for present and future scenarios. Dealing with major disasters as deepwater subsea blowouts could probably cause, each contribution (even as small) to oil spill reduction should be considered as a success. Rapid CUBE shows a moderate effect on spill reduction, its potential for intercepting and capturing subsea releases from all well flow paths and its short intervention time being elements deserving highest consideration. Future additions of Blowstop to the currently available technologies is suggested as a valuable asset for blowout risk reduction.

Our results show the positive and complementary contribution of all of the considered technologies. Future studies should provide in-depth analyses to improve our understanding of the major risks and to optimize a global response action, rather than a single intervention. Within this context, future technologies should be optimized to maximize their added value to existing sets of technologies. As such, the application of the methodology we present is conducive to the appraisal of the effect of a given technology in the context of existing ones.

Albeit of definite interest, detailed studies about initial blowout scenarios, blowout flow rate modeling and phenomena of natural extinction of the flow are outside the scope of our work, as well as oil spill modeling and the assessment of the ensuing environmental impacts. Possible steps for future developments and improvements foresee the integration of these aspects within the illustrated methodology, together with the analysis of additional deepwater intervention technologies not yet considered, such as the innovative Eni dual ROV killing system for deepwater well blowout (Ferrara et al. 2014) or crew interventions techniques (momentum kill, dynamic kill) operated with the available equipment on the rig.

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APPENDIX A

Duration of activities and interventions (Part 1)

Interventions and activities	Mean ≡ Mode [d]	Min [d]	Max [d]
Site Preparation	**11**	**5**	**17**
Mobilize Intervention Workover Control System Hardware	3	1	5
Mobilize IWOCS Vessel	3	1	5
IWOCS System and Vessel in Field	8	4	12
Debris Removal	**16**	**8,5**	**23,5**
Mobilize Debris Removal Hardware	5	3	7
Transport Debris Removal Hardware to Field	8	4	12
Mobilize Vessel with ROV and Construction Support	3	1	5
Vessels in Field	8	4	12
Debris Removal Plan developed	2	2	2
Debris Removal Activities	5	3,5	6,5
Rapid CUBE	**17**	**11**	**23**
Mobilize CUBE and Necessary Equipment	3	1	5
Transport CUBE by Airplane	1	1	1
Mobilize Support Vessels and Well Testing Equipment	5	3	7
Preparation for Offshore Transportation	1	1	1
Transport CUBE on Site	8	4	12
Mobilize required consumables (chemicals)	2	0	4
Mobilize MODU and arrival to Location	11	5	17
Make Up and Run CUBE on Riser	1	1	1
Position Acquisition and Flow Rate Adjustment	1	1	1
Early Capture to the Intervention Vessel (Drilling Rig)	1	1	1

Duration of activities and interventions (Part 2)

Interventions and activities	Mean ≡ Mode [d]	Min [d]	Max [d]
Well Capping (Shut Only Scenario)	**24**	**18**	**30**
Mobilize Tested Well Cap System	7	5	9
Transport Well Cap System by Airplane	1	1	1
Transport Well Cap System to Dock	2	2	2
Mobilize Intervention Vessel	5	3	7
Preparation for Offshore Transportation	1	1	1
Transport Well Cap to Site	8	4	12
Offload Well Cap and Prepare for Deployment	1	1	1
Deploy Well Cap in Safe Zone	2	2	2
Position, Land and Test Well Cap	1	1	1
Shut In Well	1	1	1
Monitor Well for Stability	1	1	1
Preparatory activities for Well Kill (BSSI, CS)	**18**	**10**	**26**
Mobilize Pumping Services and Equipment	3	1	5
Mobilize MODU and arrival to Location	11	5	17
Mobilize Test package to the drilling rig and Test	4	2	6
Approach the well head with the auxiliary line	2	2	2
Debris Removal (BOP choke/kill line inlet)	2	2	2
Connect the Auxiliary Line with Pumping Unit	1	1	1
Blowstop (Secondary Intervention)	**21**	**13**	**29**
Wait for the auxiliary line	0	0	0
Debris Removal (BOP choke/kill line inlet)	2	2	2
Mobilize Blowstop Equipment	5	3	7
Mobilize Blowstop equipment to dock	5	3	7
Mobilize Blowstop equipment on site	8	4	12
Prepare the Injection System on MODU	1	1	1
Bullets Injection	0	0	0
Coating Swelling	1	1	1
Static Well Killing (Well Capped)	**28**	**22**	**34**
Mobilize Pumping Services and Equipment	3	1	5
Mobilize MODU and arrival to Location	11	5	17
Mobilize Test package to the drilling rig and Test	4	2	6
Perform Well Kill after Capping Stuck Shut In	4	4	4
Relief Well and Dynamic Killing	**71**	**49,5**	**92,5**
Mobilize Drilling Equipment	9	7	11
Mobilize MODUs and arrival to Location	13	7	19
Drilling Relief Well	45	31,5	58,5
Perform Well Kill and Abandonment Scope	4	4	4

APPENDIX B

Flow chart for risk evaluation methodology and factors contributing to expected blowout risk

We illustrate here the main steps leading to expected blowout risk evaluation with the aim of evidencing the contribution of the various model components.

We do so by considering in Fig. 11 an exemplary setting corresponding to the decision of deploying all intervention techniques in case of occurrence of the top event (well blowout). We illustrate the example of the Event Tree for the Annulus flow-path in case of dynamically positioned rigs. We consider one given path inside the event tree for which the applicability of all techniques (at the moment of their application) is consistent with the actual conditions of the spill and the rig. Note that probability values shown in the grey circles of Fig. 11 are solely to be considered as representative of the actual statistics associated with given events.

All of the events, each with its probability of occurrence, are listed on the left hand side of the chart in Fig. 11. Cause-effect relationships between events, applicability of interventions and their success are displayed following the assumptions considered in Sections 2.3.1 and 2.3.2.

The right hand side of the diagram is devoted to the calculation of the impact in terms of blowout flow rates, their duration and of their final product, leading to quantifiable oil spill volumes (OSV). Figure 11 only shows the events that cause a modification of blowout flow rate, either increasing or decreasing it (i.e., post blowout interventions). Oil spill volumes are then summed up to obtain an overall final spill volume for the considered branch of the Event Tree. The resulting value of the expected blowout risk for the considered decision is hence calculated as a sum of probabilities associated with each branch, multiplied by the corresponding oil spill impact. Note that the value included in the diagram necessarily coincides with the expected value for Long Term Future scenario shown in Figure 9a with a blue bar.

APPENDIX C

Assumptions considered on mode, minimum and maximum values of times of activities

Interventions and activities	Mean ≡ Mode [d]	Min [d]	Max [d]
Mobilization of equipment or VoO (fast)	1	3	5
Mobilization of equipment or VoO (medium)	3	5	7
Mobilization of equipment or VoO (slow)	5	7	9
Arrival of VoO to incident site	4	8	12
Debris removal activities on site	3,5	5	6,5
Relief well drilling activities	31,5	45	58,5

Table 1. Values of the indicator $O_{b,e}$ denoting occurrence of subsequent events *e* after blowout *b* included in the dataset analyzed. The associated rig names are abbreviated: TS (Treasure Seeker); WV (West Vanguard); A (Actinia); S 135G (Sedco 135G); JC (Jim Cunningham); V (Vinland); OO (Ocean Odissey); S 135F (Sedco 135F); DH (Deepwater Horizon).

Event *e*	**TS**	**WV**	**A**	**S 135G**	**JC**	**V**	**OO**	**S 135F**	**DH**
LEP	0	1	1	0	1	1	1	1	1
SEP	0	1	1	1	1	1	1	1	1
DSL	0	1	1	1	0	0	1	1	1
RIS	0	0	1	1	0	0	0	1	1
SINK	0	0	1	0	0	0	0	0	1
TOW	0	1	0	1	0	0	1	1	0
FLOAT	1	0	0	0	1	1	0	0	0

Table 2. Scores $S_{b,f}$ and weights w_f for blowout risk factors f and their classes.

Risk factors *f*	$S_{b,f}=1$	$S_{b,f}=2$	$S_{b,f}=3$	w_f [%]
Year	1969 - 1982	1983 - 1999	2000 - 2010	40
Formation	Shallow gas	-	Deep	5
Fluids	Gas	Gas and condensate	Oil	30
Sea depth	<500 m	$500\ m \leq H < 1000\ m$	$\geq 1000\ m$	5
Information	Low	Medium	High	20

Table 3. Risk scenarios (decisions *j*) with associated technologies. Decisions *j* are numbered from $j = 1$ to $j = 5$. Green check marks (✓) indicate technologies available to be deployed in each risk scenario; red crosses (✗) represent technologies that are not already developed or not ready to be deployed on site.

Risk Scenario (Decision *j*)	**RW**	**CS**	**RC**	**BS-SI**	**BS-PI**
"Pre Macondo" ($j = 1$)	✓	✗	✗	✗	✗
"Post Macondo" ($j = 2$)	✓	✓	✗	✗	✗
"Present" ($j = 3$)	✓	✓	✓	✗	✗
"Short Term Future" ($j = 4$)	✓	✓	✓	✓	✗
"Long Term Future" ($j = 5$)	✓	✓	✓	✓	✓

Table 4. Probability and weighted-averaged time of occurrence of blowout subsequent events for mooring rigs and dynamically positioned rigs.

		Loss of electric power supply	**Emergency evacuation starting**	**Surface mud lines damaged**	**Riser sinking**	**Rig sinking**	**Rig towing**
Mooring system	P_e	0.83	1	0.66	0.54	0.11	0.49
	Δt_e [hh:mm]	00:35	01:07	01:47	19:34	40:24	40:37
DPS	P_e	0.83	1	0.66	0.83	0.83	-
	Δt_e [hh:mm]	00:35	01:07	01:47	36:15	36:15	-

Figure Captions

Fig. 1. Possible blowout flow paths for offshore deepwater wells (Holand 1997). Red/darker areas represent possible release paths for formation fluids.

Fig. 2. (*a*) Flow rates of water ($Q_{w,RC}$), oil ($Q_{o,RC}$) and total flow rate of liquids ($Q_{liq,RC}$) flowing inside the Rapid CUBE system as a function of oil spill flow rate ($Q_{o,BO}$); (*b*) residual blowout flow rate $Q_{o,BO}$ [%] after Blowstop success, as a function of pressure losses Δp.

Fig. 3. Layout of the overall event tree for well blowout and subsequent events.

Fig. 4. Example of primary event tree of ET_A for moored rigs and blowout inside the Annulus flow path.

Fig. 5. Secondary event tree of ET_A for moored rigs and blowout inside Annulus flow path.

Fig. 6. Decision tree for possible decisions and related scenarios considering a non-negligible risk of occurrence of a potential blowout during the well drilling phase.

Fig. 7. Decision tree for possible decisions and consequent scenarios during response phase when considering an initial condition corresponding to a blowout that takes place during the well drilling phase and continues throughout the response phase.

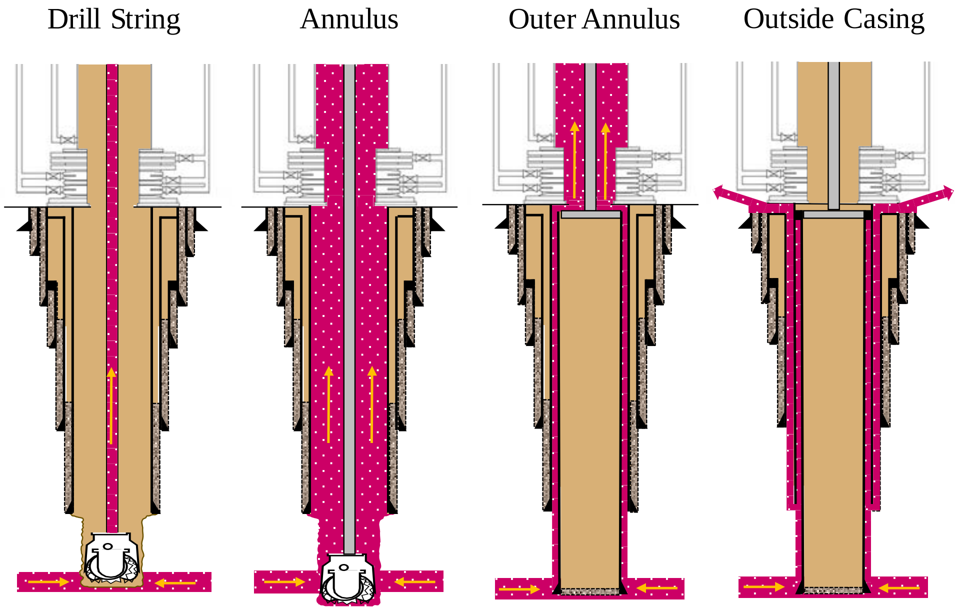
Fig. 8. Expected evolution of flow rates through time for the five risk scenarios and expected blowout risk mitigation (M_t) of the four intervention technologies considered (t = CS, RC, BS-SI, BS-PI). *a*) The red curves refer to Pre Macondo expected flow rate evolution, where only relief well was available; the orange curves are related to Post Macondo scenario, where capping stack is applied at day 24; the shadowed area represents the expected spill reduction of capping stack (termed as M_{CS}); *b*) yellow curves are associated with Present scenario, the effect of the use of Rapid CUBE being represented by the shadowed area (termed as M_{RC}); *c*) light green curves represent Short Term Future scenario, the effect of the use of Blowstop secondary intervention being represented by the shadowed area (termed as M_{BSSI}); *d*) dark green curves represent

Long Term Future scenario, the effect of the use of Blowstop primary intervention being represented by the shadowed area (termed as M_{BSPI}).

Fig. 9. Histograms for expected blowout risk R_j for the five risk scenarios, here abbreviated Pre M (Pre Macondo), Post M (Post Macondo), Pres (Present), ST Fut (Short Term Future), LT Fut (Long Term Future). Yellow bars express values stemming from the use of $Q_{BO,A}$ = 38k BOPD, while considering $Q_{BO,\,A}$ = 60k BOPD leads to values of R_j depicted as blue bars. *a*) Histograms depict expected values of risk of blowout R_j during drilling phase, while percentages values refer to values of R_j [%] with respect to Pre Macondo scenario, during drilling phase. *b*) Yellow and blue histograms refer to expected values of R_j during the response phase.

Fig. 10. Sample relative frequencies of expected blowout risk R_j during response phase, for the five risk scenarios, Pre Macondo (black), Post Macondo (brown), Present (orange), Short Term Future (yellow), Long Term Future (light green).

Fig. 11. Flow chart for risk evaluation methodology and factors contributing to expected blowout risk in an exemplary setting.



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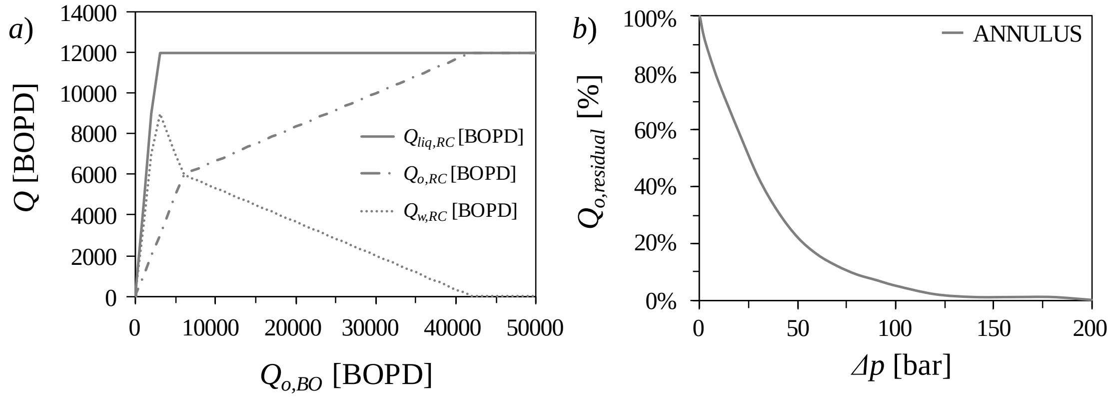

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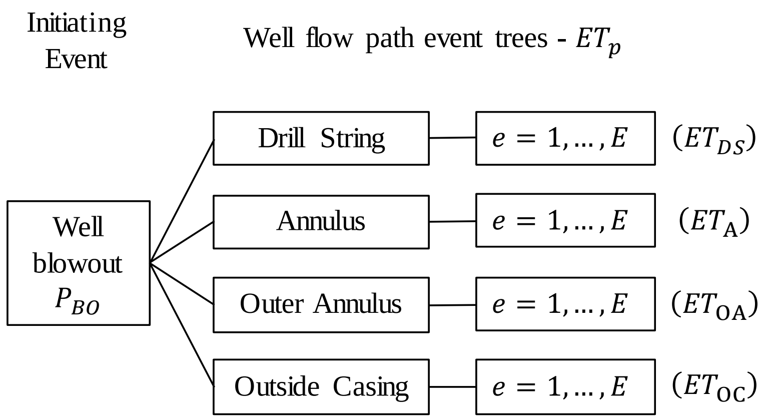

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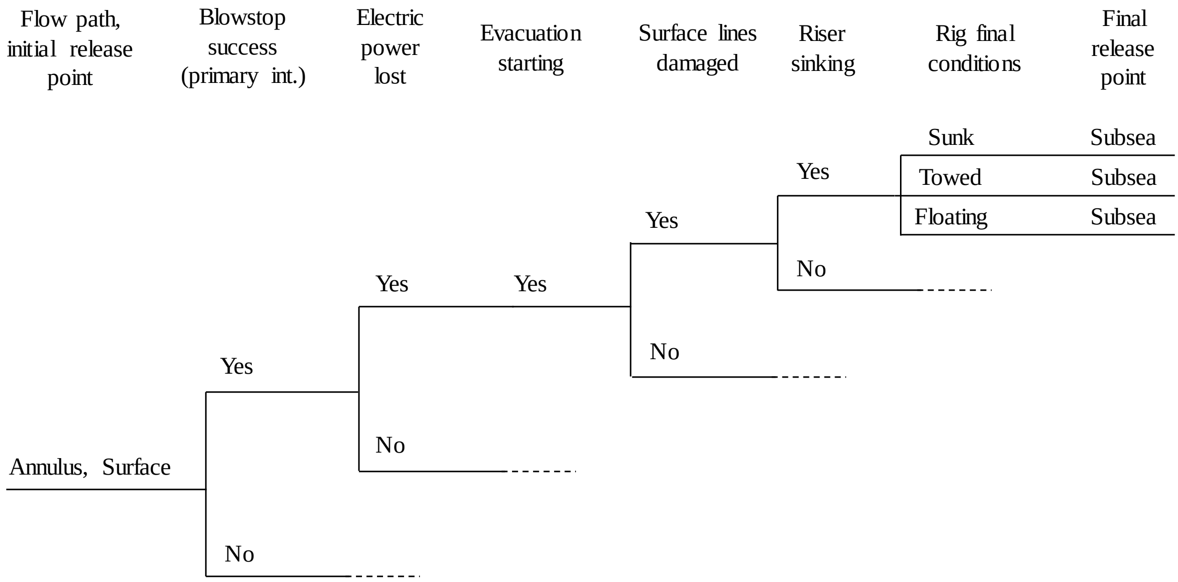

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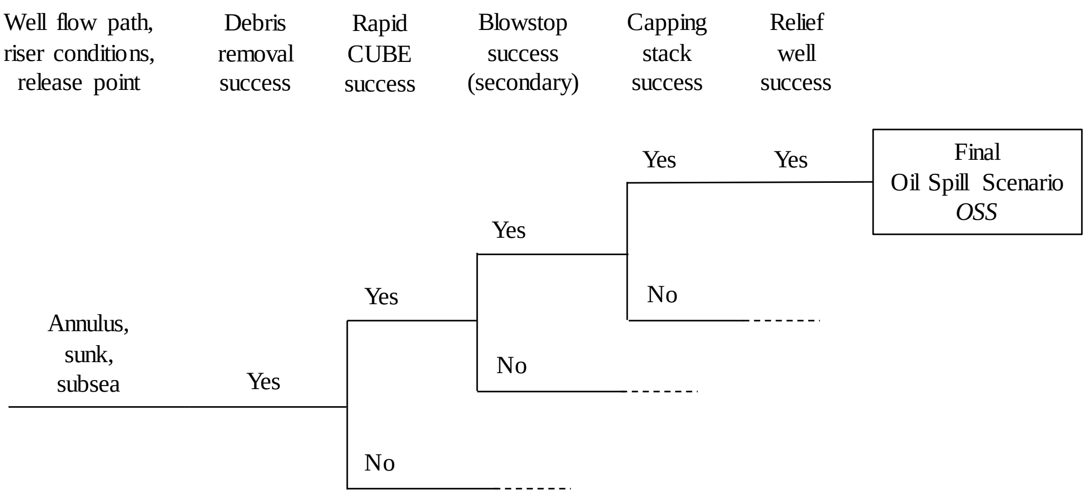
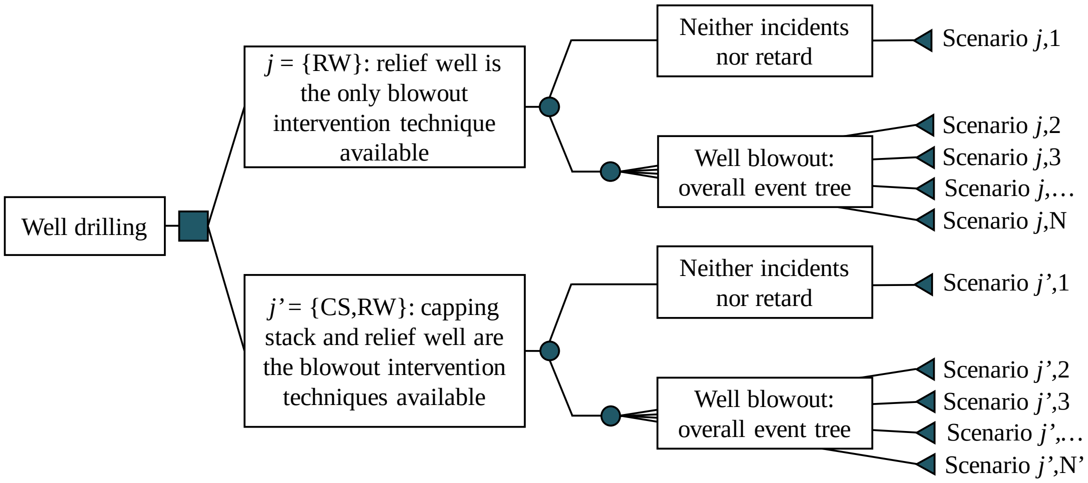


Fig. 5. Secondary event tree of ET_A for moored rigs and blowout inside Annulus flow path.



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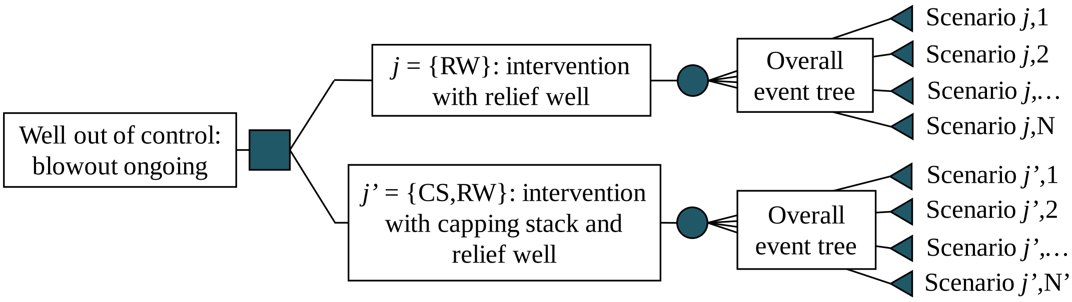

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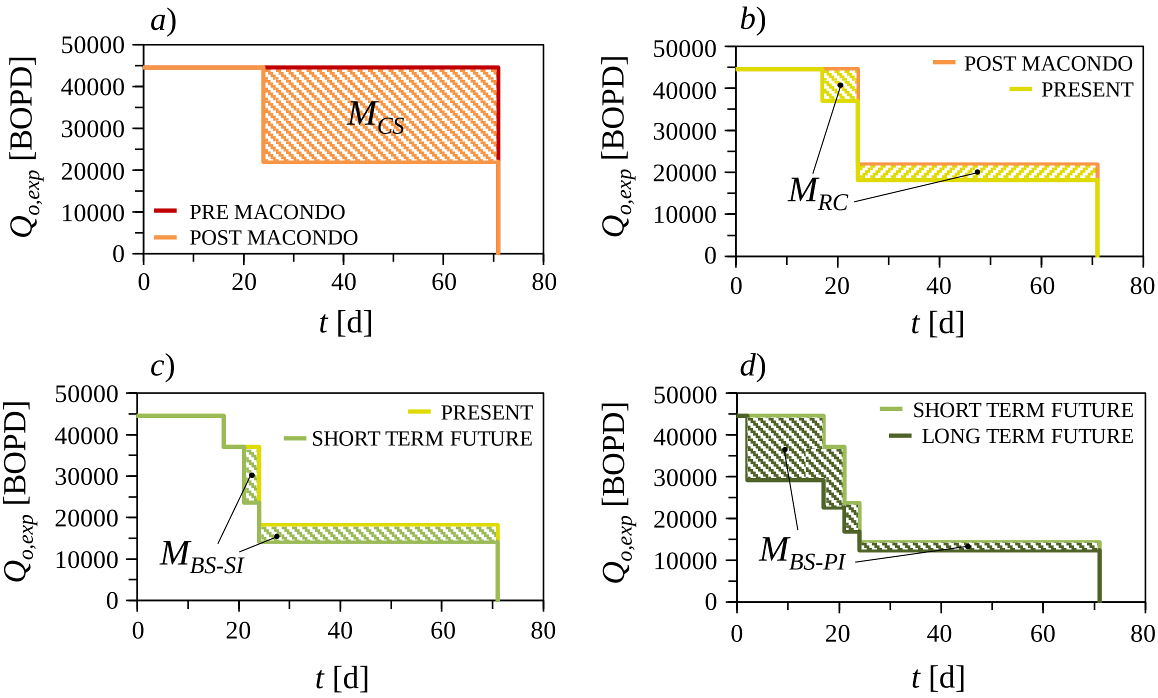

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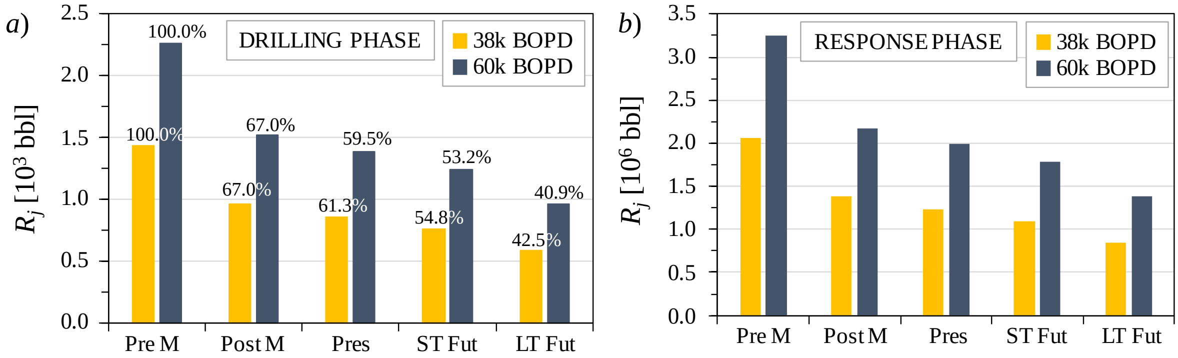

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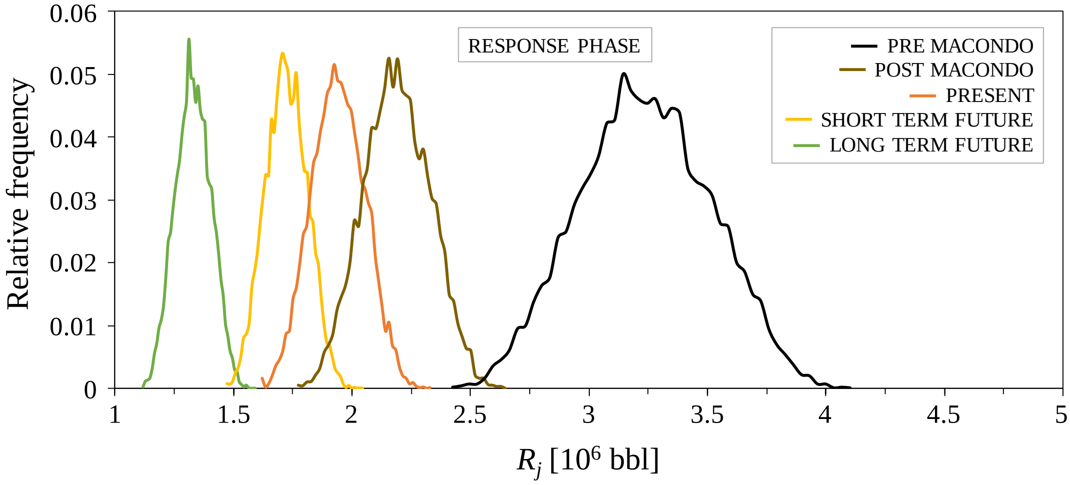

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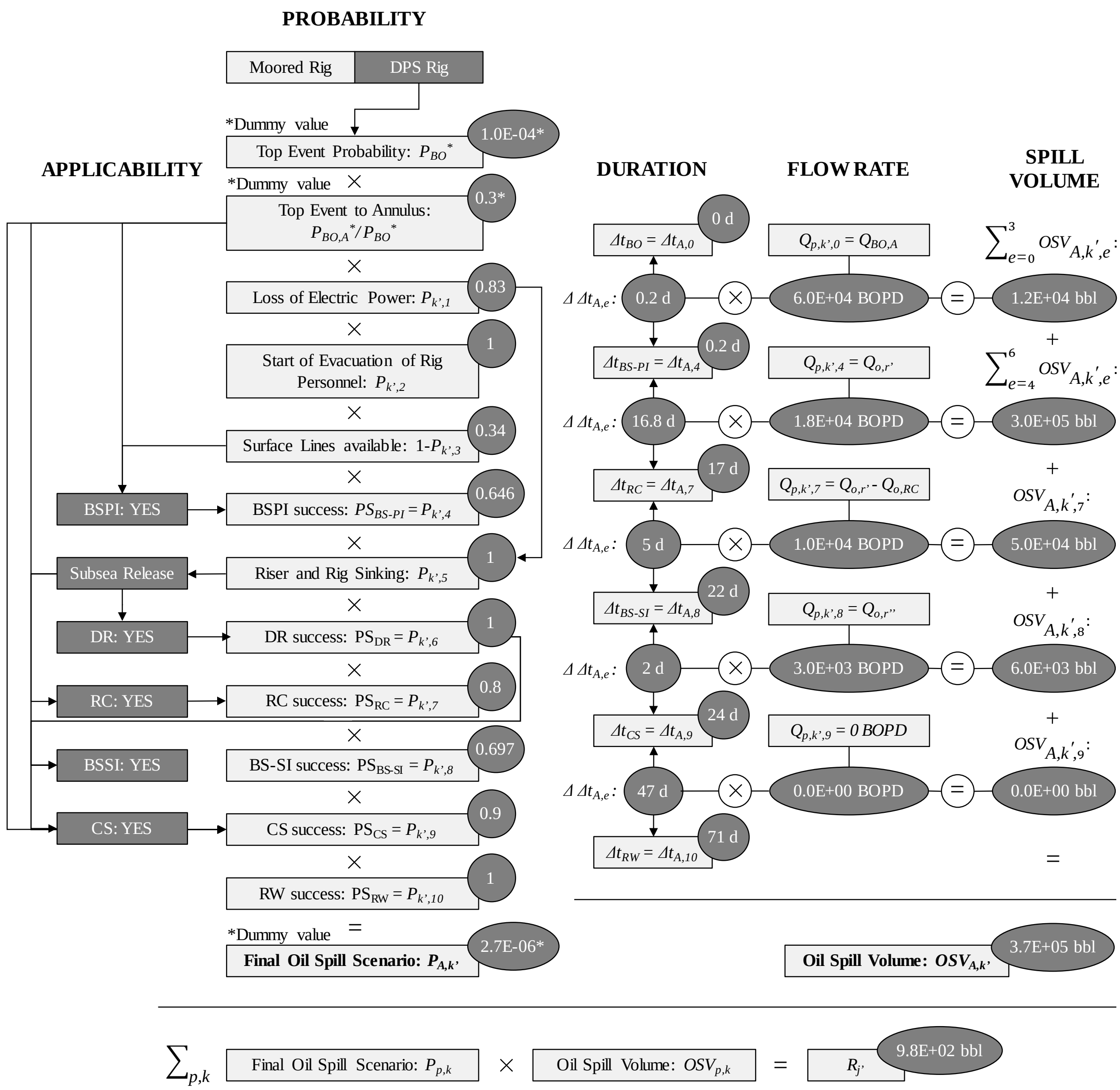

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