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Dynamic assessment of safety barriers preventing escalation in offshore Oil&Gas

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ABSTRACT

Oil&Gas activities in the arctic and subarctic regions are characterized by several challenges related to the harsh but sensitive environment in which they are carried out. The weather may deteriorate facility components at a higher rate, and delay operations, emergency and evacuation procedures. Moreover, these regions host unique ecosystems, and their preservation is a worldwide priority. For this reason, a comprehensive and systematic approach for risk analysis is necessary to prevent major accidents and comply with Arctic pollution control. A novel approach for dynamic risk assessment and management, based on Bayesian Networks and safety barrier assessment, is suggested. The method is applied to the Goliat Oil&Gas platform located in the Barents Sea and risk data on the Norwegian petroleum activities are used as evidence to simulate continuous update of risk assessment throughout the years. The case study shows the benefits and limitations of such approach. Accurate modelling of potential accident scenarios is possible through BNs, but time-consuming. The approach allows for drill-down capabilities, which enhance support of operations and definition of risk mitigating measures. However, the data used for dynamic risk assessment has a pivotal role, as data quality and quantity sensibly affect the outcome. Fortunately, the Oil&Gas industry is committed to improving collection of field data for the assessment of safety barrier performance. This approach represents a strategy to process deviations and resilient reactions, regularly iterating dynamic risk assessment to support risk management of critical systems, such as the Oil&Gas production in the arctic and sub-arctic regions.

1. Introduction

Despite the constant growth within the field of renewable energy (Granata et al., 2016; The solar foundation, 2016), as of today, the world energy demand is mainly fulfilled by fossil fuels (IEA - International Energy Agency, 2016). While energy consumption in western countries is bounded by uncertain economic growth (US Energy Information Administration, 2018), countries with strong economic growth, particularly in Asia, account for more than 60% of the world total projected increase in energy consumption from 2015 through 2040 (US Energy Information Administration, 2017). Increasing Energy demand drives oil & gas (O&G) exploration companies to search for novel reservoirs within the Arctic and sub-Arctic regions, along Norwegian, American and Russian continental shelves. However, this explorations bring also a series of critical challenges to address.

1.1. Oil&Gas production in the arctic and subarctic regions and related risks

The interest of oil and gas (O&G) industry on arctic and subarctic regions is driven by promising resources (Barabadi et al., 2015; Bercha et al., 2003; Gao et al., 2010; Musharraf et al., 2013; Song et al., 2016). The United States Geological Institute estimates 22% of world hydrocarbon reserves within these areas and approximately 84% of such sources is expected to be found in offshore areas (Bird et al., 2008; Bucelli et al., 2018, 2017b). Despite the fact that low oil prices have recently clouded the overall industry focus on these regions (Gulas et al., 2017), the slow price resurgence is set to reverse this trend. In fact, decreasing production of a Nordic country such as Norway has increased the national attention in Arctic Oil&Gas (Gulas et al., 2017). In 2016, the platform on Goliat field started production. The field is located 85 km Northwest of Hammerfest, North of Russia and Norway,

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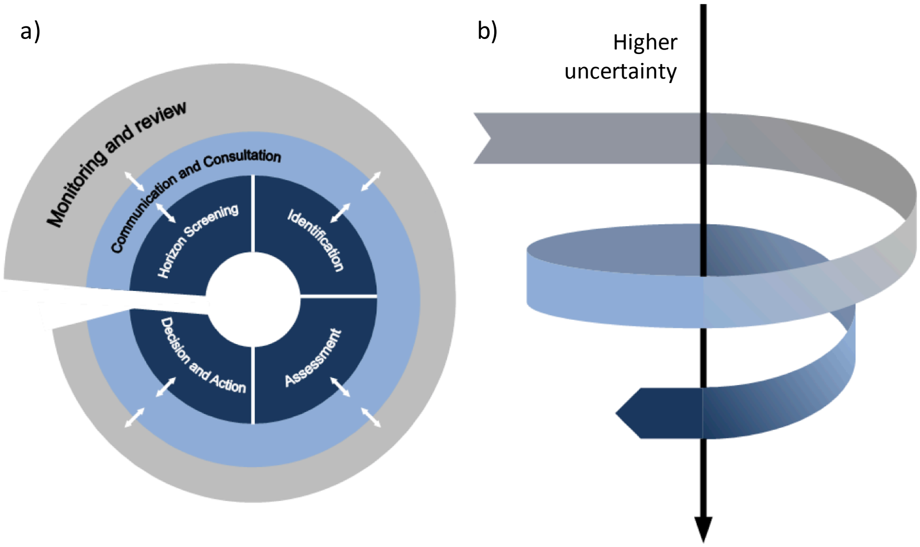

Fig. 1. Dynamic risk management framework: (a) two-dimensional version, and (b) three-dimensional version. Adapted from (Grøtan and Paltrinieri, 2016).

and is the first oil field to be developed in the Barents Sea (Eni Norge, 2015). The production license is owned by ENI Norge, with 65%, and by Statoil, with 35%. The Goliat field has two separate main reservoirs, Kobbe and Realgrunnen, characterized by low pressure. The recoverable reserves amount to 174 million barrels (28 Mm^3). The field is expected to be in production for fifteen years, but field life may be extended with new discoveries (Eni Norge, 2015).

However, one of the challenges of arctic and subarctic regions is represented by their climate, characterised by long, usually very cold winters, and short, cool to mild summers (Bucelli et al., 2017b, 2017a; Paltrinieri et al., 2017). Snow and ice are often present in many different forms. Such harsh climate is associated with remoteness, long distances from customer and supplier's markets. Climate has considerable influence on the choice of design, operations, and maintenance (Barabadi et al., 2015), as operations may be delayed by harsh weather, and maintenance would have to focus on components that are quickly deteriorating due to severe conditions (Barabadi et al., 2015; Gao et al., 2010; Landucci et al., 2017). In particular, special attention is needed due to the uncertainty on the influence of Arctic low temperature on offshore platform mechanical properties, which represents a topic for further investigation (Yan et al., 2016). On the other hand, in case of loss of integrity and, consequently, oil spill, its spreading and weathering would be substantially reduced in cold and icy conditions (Nevalainen et al., 2017). As oil decomposes slowly in cold latitudes, the recovery rate in Arctic regions sensibly decreases (Brandvik et al., 2006). Harsh weather intensifies the uncertainty on the response to such major events. As stated by Nevalainen et al. (2017), an oil spill in these regions is likely to remain in the environment for a relatively long time, prolonging the related environmental harm (Arctic Council, 2007).

Rich and important ecosystems are located in the Arctic and sub-Arctic regions (Barabadi et al., 2015; Gao et al., 2010). The Barents Sea, located off the northern coasts of Norway and Russia, is relatively shallow and free from ice during the year, due to high salt level and warm Gulf Stream currents from the Atlantic Ocean. This improves its biodiversity and supports abundant fish stocks as well as high concentration of nesting seabirds and a diverse community of sea mammals (Larsen et al., 2004). Such characteristics make the Barents Sea (together with the Kara Sea) one of the World Wildlife Fund (WWF) marine ecoregions for global conservation (Olson and Dinerstein, 2002), and its coast a high priority area for biodiversity maintenance (Larsen et al., 2004). These ecosystems consist of relatively short food webs making trophic interactions comparatively simple (Kaiser et al., 2011). This implies that population changes in just one key species may have strong cascading effects in the entire ecosystem (Hop and Gjøsæter, 2013; Palumbi et al., 2008).

A number of authors discuss risk-based design enhancing safety of operations in harsh environment (Gao et al., 2010; Paik et al., 2011; Vinnem, 2014). Other works suggest relatively more advanced approaches for the assessment of safety barriers within harsh environment (Bucelli et al., 2018, 2017a; Paltrinieri et al., 2017), where safety barriers are defines as "technical, operational and organizational elements intended individually or collectively to reduce the possibility for a specific error, hazard or accident to occur, or limit its harm/disadvantages" (Petroleum Safety Authority, 2013). As reminded by Bucelli et al. (2017a), releases of flammable hydrocarbons on an Oil& Gas Arctic platform have the potential to escalate into major events with serious multiple consequences for operators, environment and asset. Within this context, a comprehensive and systematic approach for risk analysis, which can rely on a robust modelling basis, is still missing. In addition, it should not be forgotten that another purpose of risk analysis is demonstrating the compliance with Arctic governance and environmental pollution control, which are rightfully strict and are set to further strengthen, as invoked by Gulas et al. (2017).

Quantitative Risk Assessment (QRA) is the most common approach to assess the risk of oil loss of containment. However, criticisms have directed towards this approach. Creedy (2011) states that the estimation of event frequencies, such as releases, still appears to be largely based on values from several decades ago, while Apostolakis (2004) underlines that probabilities of these events cannot be realistically calculated. Moreover, such uncertainties have little chance of being overcome as this approach is intrinsically static (Villa et al., 2016a, 2016b). In fact, it precludes possible updates and integrations of the overall risk figures on a frequent basis. For this reason, in the last years, several studies have been devoted to the development of novel approaches for dynamic risk assessment and management (Paltrinieri et al., 2014b, 2013, 2011, 2010; Paltrinieri and Hokstad, 2015).

Fig. 1 shows the two- and three-dimensional versions of the framework developed to support dynamic risk management (Dynamic Risk Management Framework – DRMF) (Grøtan and Paltrinieri, 2016; Paltrinieri et al., 2019). The two-dimensional version has a characteristic shape, showing an iterative risk management process that is open to the outside, opposing self-sustained processes by including external experience and early warnings through monitoring and review activities. DRMF suggests communication of this new information, with possibly the support of experts (communication and consultation), for:

(i) improved investigation of overall issues (horizon screening), (ii) delineation of related hazards (identification), (iii) assessment of associated risk (assessment) and, (iv) ultimately, support for risk-informed decision-making and focused safety operation (decision and action). Such a process would not only continuously improve the current risk picture, but also limit uncertainties in its management, as represented by the three-dimensional version of DRMF. A centripetal iteration from the external phase of monitoring and review (represented in grey in Fig. 1) to the final phases of assessment and decision (represented in blue in Fig. 1) implies an additional transition along a third dimension, which may be identified as the increment of knowledge for risk analysis (Aven and Krohn, 2014), or, as shown in Fig. 1, the decrease of uncertainty about potential unwanted scenarios (Grøtan and Paltrinieri, 2016; Paltrinieri et al., 2017).

Technical and operational performance of safety barriers on Oil&Gas facilities is a critical aspect to continuously monitor and assess, not only within sensitive areas (Bercha et al., 2003; Gao et al., 2010). The Norwegian Petroleum Safety Authority (PSA) requires yearly performance assessment of safety barriers on all the Norwegian Oil&Gas installations (PSA, 2018). The present study is aimed at providing a methodology for dynamic risk assessment based on the variation in safety barrier performance, which will be dedicated to offshore Oil&Gas facilities in sensitive areas. Such method is inspired by previous relevant studies (Paltrinieri and Khan, 2016), and it integrates the Bayesian theory for the barrier management and, ultimately, risk assessment. In fact, the use of Bayesian networks for barrier management is a relatively innovative way to evaluate probabilities of possible barrier failures. This approach can take advantage of model flexibility and possibility to update with new available data. It allows updating barrier probability of failure and, in turn, frequency of outcoming events, based on incidents and near misses occurred within the system (Paltrinieri et al., 2014a). This allows investigating how barrier performance influences the overall level of risk during the lifecycle of the facility, considering the information present in literature and collected by the national authorities.

2. Safety barriers in offshore Oil&Gas

Sklet (2006) defines a safety barrier as a physical and/or non-physical means planned to prevent, control or mitigate undesired events or accidents. It may range from a single technical unit or a single action to a complex and structured socio-technical system.

Each barrier is characterized by one or more specific functions. Delvosalle et al. (2006) summarises barrier functions as follows:

- Avoidance. Removing all potential causes of accidents by changing design.
- Prevention. Reducing probability of a hazardous event or reducing its consequences.
- Control. Limiting deviations from the normal operation and also delimiting emergency situations.
- Protection. Protecting assets from consequences of hazardous event.

The barrier function may be considered as the purpose of the safety barrier. This function is realized by several measures or solutions which are defined as barrier elements. Every element by itself is not able to reduce the overall risk, but it performs a specific role within the barrier system. Barrier elements could be divided in three categories: technical, operational and organizational. A technical element is an equipment or a system (sensor, a transmitter or a valve). An operational element is an action or activity to be carried out by personnel. An organizational element is a role or functions attributed to personnel (Petroleum Safety Authority, 2013).

A barrier system is a structured collection of barrier elements designed and implemented to perform one or more barrier functions. Often “barrier system” and “safety barrier” are two different words for the same meaning. Barrier systems may be decomposed in elements. Every element perform a certain sub-function. If a barrier system reduces the probability of a hazardous event, it is named frequency-reducing barrier or proactive barrier. If a barrier system reduces the consequence of a hazardous event, it is named consequence-reducing barrier or reactive barrier (Sklet, 2006).

Barrier systems can be classified as passive, if they do not require any solicitation in terms of human activation, information signals or energy source. Passive barriers must be inspected routinely in order to monitor their state and their capability to respond to the identified hazards. On the contrary, they can be defined active, if they need at least one among human activation, information signals or any energy source, to perform their protective function. In case of active barriers, all the necessary signals must be detectable when activation is required. Active barriers must be fail-safe and tested, by either self-testing or regular function testing (Sklet, 2006). Human actions is another kind of barrier. The effectiveness of this barrier relies on the knowledge of the operator in order to reach the purpose. Human actions include the use of senses, communication, thinking, physical activities and also rules, guidelines and emergency plans (Delvosalle et al., 2006).

According to PSA, performance requirements shall be established for the safety barriers on an Oil&Gas installation (Petroleum Safety Authority, 2013). According to Sklet (2006) and relevant standards, the performance of a safety barrier may be defined by three parameters:

- Probability of failure on demand (PFD), for which special reference is made to IEC 61,508 (International Electrotechnical Commission, 2010) and NOGA 070 (Norwegian Oil Industry Association, 2004), as the recommended standards for specification, design and operation of Safety Instrumented System (SIS).
- Functionality/effectiveness, which is the ability to perform a specified function under given technical, environmental, and operational conditions. The barrier effectiveness addresses the effect that the barrier has on the event or accident sequence. The potential degree of fulfilment may be expressed as the probability of successful function execution or the percentage of successful function execution (Sklet, 2006).
- Time to respond, which is the time from solicitation of the barrier to the end of the response (Sklet, 2006).

2.1. Safety barriers against escalation

One of the main events triggering escalation is primary fire (Landucci et al., 2015). For this reason, the study focuses on technical safety barriers related to fire scenarios.

Barriers used to prevent escalation in process plants can be divided in active barriers, passive barriers, and human actions (Hourtolou and Bernuchon, 2004). Active barriers require a sequence of detection, diagnosis, decision, and action. The sequence is performed by a detection system, a logic solver or an electro-mechanical device, and a mechanical or instrumented system – or alternatively a human (Hourtolou and Bernuchon, 2004).

The main scopes of active fire protection systems are (Landucci et al., 2015):

- To mitigate fire exposure of target that could be equipment or structures. It can be done keeping a water film on exposed surfaces to cool them and absorb radiant heat preventing material loss of strength.
- To isolate and empty the target vessel, reducing the potential loss and consequent damages due to release of inventory in undesirable locations.
- Control of the primary fire and prevention of fire spread in nearby units.

On the basis of these scopes, active fire protection systems can be divided in two categories (Landucci et al., 2015):

1. Systems for the delivery of fire-fighting agents such as water or foam. They can be fixed, semi-fixed, mobile and portable systems.
2. Emergency Shutdown (ESD) Systems and Blowdown (BD).

The most common way to deliver fire-fighting agents (usually simply water or water with some additives) is by means of the deluge system. The effect of this barrier system is multiple. It can reduce likelihood of escalation by controlling fires dimensions, providing cooling of equipment near to the fire, and reducing consequences of a gas explosion if activated before the ignition (van Wingerden, 2000). The deluge system can be used to cover a whole process area providing non-specific coverage of pipework and equipment; it can protect a specified equipment or structural elements providing a dedicated coverage, or it can be used to form a water curtain that can reduce thermal radiation and control smoke and dangerous gasses dispersion.

The purpose of the ESD system is to prevent escalation of abnormal conditions into a major hazardous event and to limit the extent and duration of any such event that may occur. To perform this safety function, ESD valves shall isolate and sectionalise the installations in a fast and reliable manner, in order to reduce the total amount of released hydrocarbons in the event of a leakage (NORSOK, 2008). ESD valves are actuated valves which are closed when triggered by a signal during emergency conditions. ESD can also command the execution of other automatic actions, for instance main power generator shut down and possible ignition sources isolation (NORSOK, 2008), in order to avoid more severe consequences.

The BD drains liquid from the vessels by opening a certain number of blowdown valves (BDVs). Its main purposes are (NORSOK, 2008):

- in the event of fire, to reduce the pressure in process segments, reducing the risk of rupture and escalation;
- to reduce the leak rate and leak duration and thereby ignition probability;
- in some cases, to avoid leakage at process upsets;
- to route gases from atmospheric vent lines.

The BD is considered the primary means of protection and its intervention time should be reduced as much as possible to limit the need for passive fire protection.

Natural and mechanical ventilation can also be considered a preventing fire escalation measure (NORSOK, 2008). In fact, it dilutes flammable gas concentrations and reduces the size of flammable gas clouds. In case of fire, it dilutes harmful concentration of smoke and toxic gasses, ensuring acceptable environment for evacuation or intervention. Natural ventilation can be considered a passive protection. On the contrary, mechanical ventilation is an active measure as it is activated by engines triggered by fire and gas detection.

In offshore platforms also passive barriers have a key role in preventing escalation due to fire. In particular we can mention passive fire protection (PFP) system. For instance, the objective of passive fire protection is to reduce heat transfer to equipment, structures, and enclosures, while limiting escalation (ISO, 2015). Fire division is used to avoid that fire and explosion escalade into surrounding areas. Fire divisions are made by fire walls and blast walls, ensuring that thermal effects, propagation of fire and explosion overpressure are prevented. Critical structures, piping and equipment components shall have adequate fire resistance with regard to load bearing properties, integrity and insulation properties during a dimensioning fire and contribute in reducing consequences in general (NORSOK, 2008). Containment basins can be also considered barrier elements preventing escalation. They can be located under one or more vessels to contain potential liquid releases, preventing propagation into other areas. A drainage system is often connected to basins. Pressure Safety Valves (PSVs) and rupture disks are considered passive barriers because they open only by the energy of the fluid to be released. They prevent vessel rupture caused by overpressure. Another escalation preventing measure is ignition source control (ISC) that shall minimize the likelihood of ignition of flammable liquids and gases following a loss of containment.

Human barriers are organizational and operational measures aiming to prevent escalation. These barriers include specific procedures during both normal operations and emergency response, and can be divided in two categories (Hauge et al., 2016):

- Procedures to be activated in order to prevent failure or an unwanted event to occur. In this case, the time to perform the procedure is not critical.
- Procedures to be activated after the occurrence of a failure event. In this case, time is critical for the success of the barrier element.

2.2. *Data collection in Oil&Gas*

Most of the conventional Health, Safety and Environment (HSE) management approaches and hazard identification systems in the Oil&Gas are incapable of agile and automated data integration in decision making (Tarrahi and Shadravan, 2016). Application of data analytics in the Oil&Gas industry is in an experimental stage, with much of the early work focused on data-intensive computing and how Input/Output data loading can be managed efficiently. The challenging physical environment in the Arctic and the need to limit the number of personnel in hazardous and remote locations led to the development of some degree of automation within the Oil&Gas rigs (Feblowitz, 2012). In this context sophisticated sensors technologies coupled with powerful data-analytics can be used for early detection of anomalies and malfunctions. In fact, a possible alternative to curative maintenance can be the preventive maintenance, consisting in detecting anomalous behaviour and prevent further consequences. To this end, monitoring equipment is needed and it is possible using data from sensors. Nevertheless, data collected are often difficult to exploit in order to generate relevant information.

Tools for collecting, systematizing and presenting critical information on safety barrier performance are operative only on the most advanced Oil&Gas platforms (Eni Norge, 2018; Paltrinieri et al., 2017). Several Oil&Gas companies operating on the Norwegian continental shelf (NCS) have developed such concepts, but only a few have implemented them (Hauge et al., 2016). For instance, the system used on the Goliat platform measures and monitors over 10 600 technical components in real time, in order to outline the status of major accident-critical barriers for use in daily priorities (Eni Norge, 2018). The barrier panel provides data from the maintenance management system and control system. The information can be aggregated in several different views, tailored to different user groups. The barrier status panel contributes to increased risk awareness, both in daily status meetings, and as decision support during work planning and approval (Eni Norge, 2018; Paltrinieri et al., 2017).

3. Method

Several techniques are available for accident scenario modelling and safety assessment. For instance, a review of 62 risk analysis methodologies for industrial plants is provided by Tixier et al. (2002). As discussed, traditional techniques may not be suitable for dynamic risk management. They are incapable to manage multi-state variables, which are often encountered in process system modelling, or do not take into account the variability of risk level over time. For this reason, attention has been recently focused on dynamic techniques. As clarified by Yang et al. (2017), dynamic approaches are addressed by research on:

1. real-time risk analysis, focusing on real-time input data and high-frequency update;

2. dynamic risk analysis, focusing on the methodologies of risk analysis designed to be dynamic and updatable; and
3. operational risk analysis, focusing on the continuous support to safety-critical operations provided by risk analysis.

Given that dynamic risk analysis deals with the methodological perspective of the issue (Paltrinieri and Khan, 2016) regardless of the specificities of its use, the related literature has been reviewed to identify a suitable technique for this work. Several approaches aim to comprehensively describe socio-technical systems. In this regard, system dynamics was used by Garbolino et al. (2016) for risk assessment of industries dealing with hazardous substances. In addition, preliminary methodologies are developed in collaboration with industry, such as the Risk Barometer (Hauge et al., 2015). Other methods are defined based on the API 581 standard on risk based inspection (American Petroleum Institute, 2016), such as the Frequency modification methodology based on Technical Operational and Organizational factors (TEC2O) (Landucci and Paltrinieri, 2016). The mentioned approaches are defined as proactive by Scarponi and Paltrinieri (2016) and include in the analysis early deviations from the optimal condition also in terms of operational and organizational factors, which have a lower degree of causality on a potential accident and, thus, a relatively uncertain connection. On the other hand, reactive approaches, mainly focusing on technical factors, respond to an event that is directly associated with the overall risk picture and is presumably closer in time to a potential accident, if not to an accident itself (Scarponi and Paltrinieri, 2016). For instance, contributions to dynamic risk analysis by means of the Monte Carlo method can be found in literature (Noh et al., 2014). The Petri nets method is also used to improve risk analysis and capture dynamic sequences (Zhou et al., 2017; Zhou and Reniers, 2017). The application of Bayesian networks (Lee et al., 2017) also falls in the group of reactive approaches and provides sound statistical theories to dynamic risk analysis. Moreover, it allows updating the risk picture of the system by considering information on past events that indicate failure or success of safety barriers (Scarponi and Paltrinieri, 2016), as the barriers can be modelled by network nodes. For this reason, the application of Bayesian networks is considered for this study.

3.1. Bayesian networks

Bayesian networks represent a useful formalism in the risk analysis domain due to their ability to model probabilistic data with dependencies between events (Weber et al., 2012). The Bayes theorem has the advantage to use new evidence to update probabilities of events deviating from normal operations, physical phenomena and, in particular, failure of safety barriers in an accident scenario. Prior probability is estimated in several ways, such as statistical analysis of historical data or data collected from inspection/condition monitoring, deductive reasoning by means of quantitative risk analysis techniques, or expert judgment (Khakzad et al., 2016). On the other hand, relevant information used to update prior probabilities become available during the plant lifecycle, such as deviations from design parameters, near misses, or incidents.

For instance, a safety barrier failure θ_f is updated considering evidence E and the likelihood function $L(E|\theta_f)$ (probability distribution of evidence given that θ_f has occurred) as follows:

$$P(\theta_f|E) = \frac{P(\theta_f)L(E|\theta_f)}{\sum_{\theta_f} P(\theta_f)L(E|\theta_f)} \tag{1}$$

where the safety barrier failure θ_f is a discrete random variable, $P(\theta_f)$ is its probability distribution, and $P(\theta_f|E)$ is the updated (posterior) probability distribution given the evidence E. An example evidence can be represented by the occurrence of an early warning of the safety barrier failure (Paltrinieri et al., 2014a; Scarponi et al., 2016). However, an early warning does not provide complete certainty for barrier failure.

BNs have two types of items to represent the uncertainty of evidence (Fenton et al., 2016):

- virtual evidence that uses the likelihood function to represent the uncertainty of evidence; and
- soft evidence that uses likelihood ratio as the target posterior distribution.

This work generally uses virtual evidence. However, considered the philosophical concern about whether soft evidence has any rational meaning in the real world (Pearl, 2014) and that the two types of evidence are often confused with each other (Fenton et al., 2016), their distinction is excluded from the scope of this work, which will refer to the more generic term of “uncertain evidence”. Evidence imposed on the events of barrier failure θ_f and success θ_s (but independent from them) can be specified by the weights w_f and w_s such that:

$$L(E|\theta_f) = w_f; \quad L(E|\theta_s) = w_s; \quad w_f + w_s = 1 \tag{2}$$

This can be extended to other events θ_i for $i = 1,\ldots,n$.

Uncertain evidence is implemented in many commercial BN software packages, such as AgenaRisk® (Agena Ltd, 2019). The latter is used for this study and only requires to set appropriate weights w_i to describe the likelihood function of uncertain evidence.

Multiple pieces of evidence, causes and effects are correlated within a single potential accident scenario. Bayesian networks can graphically represent such interactions, as it explicitly describes dependencies between a set of variables through an acyclic graph. Uncertain variables (deviating events, physical phenomena, or safety barrier failures) are represented as nodes, while causation or influential dependence is depicted by an arrow between them, denominated *edge*. A *parent node* affects a *child node*. A *root node* has no parent nodes (root cause), while a *leaf node* has no child nodes (final accident outcome). Considering n variables θ_i, such as the sequence of unwanted events and failed safety barriers leading from the root cause θ_1 to a final accident outcome θ_{n+1}, the probability distribution of the final outcome $P(\theta_{n+1})$ is expressed by the chain rule, as follows:

$$P(\theta_{n+1}) = \prod_{i=1}^{n} P(\theta_i|Parents(\theta_i)) \tag{3}$$

For this reason, the update based on new evidence of any probability distribution $P(\theta_i)$ along the chain leads to an updated probability distribution of the final outcome.

4. Case study

The methodology was applied to a real reference case study in the Goliat oil field (Norway), which represents a relevant example of innovative facility operating offshore in the Arctic sensitive region. The information about this platform is gathered exclusively from public sources and the results obtained are derived from theoretical simulations.

4.1. Characteristics of the installation

Goliat installation is a circular geostationary Floating Production Storage and Offloading (FPSO) unit. It is the largest and most complex of its kind and it was specifically designed to ensure safe and reliable production in the harsh conditions of the Barents Sea (Eni Norge, 2016). It is possible to identify seven main areas on the FPSO, as depicted in Fig. 2. Production is supported by a subsea system of 22 wells: 12 production wells, 7 water injectors and 3 gas injectors.

The extracted crude oil is processed, stabilized, stored and then directly offloaded from the FPSO to shuttle tankers through the

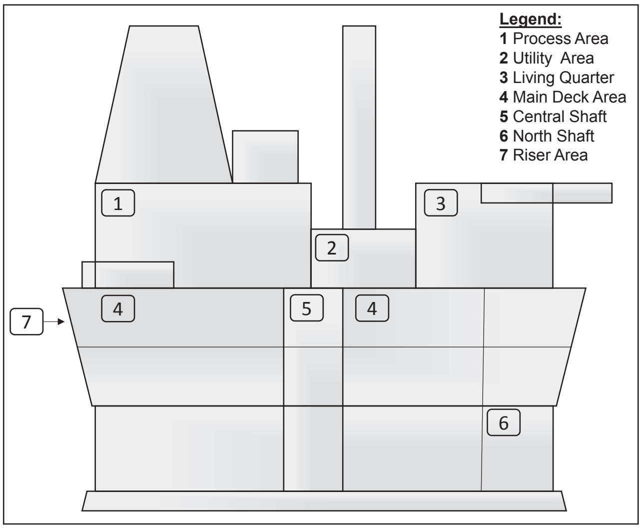

Fig. 2. Main areas on Goliat FPSO (adapted from Rekdal and Hansen, 2015).

offloading station (Bjørnbom, 2011). The offloading system is one of the safest and most reliable offloading system ever fabricated for offshore operations. The distance between the shuttle tanker and the platform is greater than in similar installations and video cameras and a light system are in place for frequent status monitoring of the offloading hose (Eni Norge, 2015).

4.2. *Analysis*

A specific Bayesian network is created for the case study. Relevant data from the yearly PSA reports on performance of safety barriers in the Norwegian Oil&Gas sector (“Trends in risk level in the petroleum activity” (PSA, 2018)) are used to update prior probabilities. A period from 2010 to 2016 was considered. The reports use one or more risk indicators to measure the status of most defined hazard and accident conditions. This shows how the various contributors to risk are developing, both collectively and for the individual defined hazard and accident conditions (PSA, 2018).

The analysis focuses on one of the most critical accident scenarios for an offshore platform with limited space for escape (Bucelli et al., 2018): the scenario of escalation due to fire in the process area. Bayesian networks theory is implemented to calibrate and update the scenario frequency during the years by means of the AgenaRisk® software (Agena Ltd, 2019). The escalation initiating event considered within the Bayesian network is the hydrocarbon leak. Such event is particularly important for the Goliat platform also due to the environmental impact it may lead to, even without ignition. Moreover, information on hydrocarbon leaks are relatively available on scientific literature, as it is possible to rely on a considerable amount of data (Fossan and Opstad, 2016), while escalations are rare events for which probabilistic analysis is challenging. For this reason, modelling escalation from leak events may be beneficial. Furthermore, an analysis of leaks causes would have required specific information about the process area of Goliat, which are not publicly available.

The analysis considers the safety barriers and related barrier elements depicted in Fig. 3, derived from previous studies of safety barriers on the Goliat platform (Bucelli et al., 2017a; Hansen, 2015). As the focus is on escalation, the safety barrier on escalation prevention is broken down into its barrier elements.

The escalation probability due to fire or explosion is estimated based on the probabilities of failure on demand of the considered safety barriers. Eq. (3) is used to obtain frequencies of escalation in Goliat.

$$f_{esc} = f_{ie} \ \ p_{esc} \tag{3}$$

where f_{esc} is the escalation frequency, f_{ie} is the frequency of the initiating event, and p_{esc} is the probability of escalation obtained from the Bayesian network.

The unwanted events and safety barriers considered in the case study (Fig. 3) are further discussed in the following.

4.2.1. *Process leak*

PSA records leaks with minimum flow rate of 0.1 kg/s and classifies them in three categories (Carlsen, 2015):

- Small, from 0.1 to 1 kg/s,
- Medium, from 1 to 10 kg/s, and
- Large, higher than 10 kg/s.

Leak data considered are only from the NCS offshore platforms. Hydrocarbon leaks may be gas or liquid. Moreover, partial vaporization may occur during a liquid release. For this reasons, three possible leak states should be considered: gas, liquid, and two-state. The case of two-state leak is often complex to analyse from a statistical point of view, mostly because the gas and liquid fractions are uncertain as they depend on a number of factors typical for each accidental scenario. The PSA reports (Carlsen, 2015; Tuntland, 2011) classify leaks in two categories: Liquid, and Gas/two-state. Also the ARAMIS project main deliverable (Delvosalle et al., 2004) shows a correspondence between gas and two-state categories, suggesting the same types of consequences after their occurrence: toxic cloud, environmental damage, and jet fire.

In case of delayed ignition, an aerosol puff can turn into a gas puff. As mentioned by the Health and Safety Executive (Health and Safety Executive, 2014), the airborne liquid particles receive energy from the external environment to transit from liquid phase to vapour or gas state. Moreover, the phenomenon of rainout (generation of a pool caused by condensation of little drops from a two-state cloud) is not considered in this model. However, further evaluation is needed to understand whether the release conditions in subarctic climate would anyway favour significant airborne dispersion over rainout.

4.2.2. *Leak detection*

Leak detection is necessary to mitigate leak potential consequences. The probability of failure on demand of appropriate detectors is calculated based on the relevant Norwegian standard (Norwegian Oil Industry Association, 2004) and appropriate assumptions on the leak size in accordance with PSA leak categories.

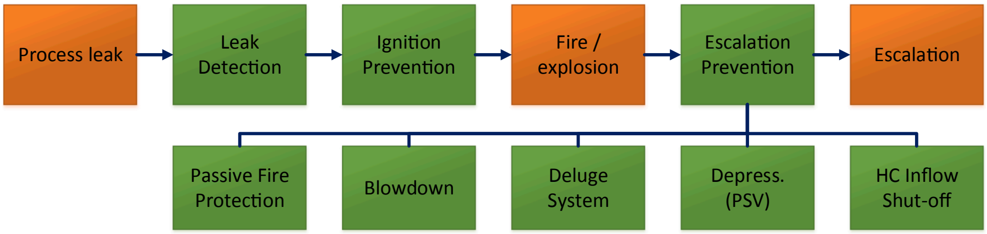

Fig. 3. Scenario considered in the case study. Unwanted events in orange and safety barrier elements in green. PSV and HC stand for, respectively, Pressure Safety Valve and hydrocarbon. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2.3. Ignition prevention

The most common ignition sources in Offshore Oil&Gas platforms are (Eckhoff and Thomassen, 1994): open flames, hot surfaces, metal particle sparks from impact or manual works, electric sparks and arcs, electrostatic discharges, and jet of hot gases.

Different preventing measures can be adopted to contrast such ignition sources, such as connection to the grounding system, isolation, and shields. However, for the sake of simplicity, specific correlations between leak rate and probability of ignition (Lund et al., 2007) were used for this barrier.

4.2.4. Fire/explosion

The unwanted fire and explosion events considered are: jet fire, flash fire, pool fire, and vapour cloud explosion (VCE). Jet fire is a flammable gas leak from pressurized equipment or pipeline that is ignited immediately after the release starts. If the ignition is not immediate, a flammable cloud is generated, leading to flash fire or VCE in case of delayed ignition. Flash fire occurs when the flammable cloud burns in an open space, generating only a radiating and convective heat flux. Due to its short duration, no damages to structures and equipment are assumed to occur. On the contrary, VCE may occur in case of confinement of the burning flammable cloud, and this may affect structures and equipment by means of the overpressure it generates.

The occurrence of these fire and explosion events depends on several conditions specific of a certain accident mechanism and event (Uijt de Haag and Ale, 1999). The occurrence probabilities used for this event refer to the *Guidelines for quantitative risk assessment (Purple Book)* (Uijt de Haag and Ale, 1999).

4.2.5. Passive fire protection

It is one of the barrier elements of escalation prevention. It shall ensure that relevant structures, piping and equipment components have adequate fire resistance with regard to load bearing properties, integrity and insulation properties, and contribute in reducing the consequences in general (NORSOK, 2008). Cott (1994) reports an inventory of PFD values for these barriers.

4.2.6. Blowdown

Blowdown is the main measure to avoid an equipment catastrophic collapse due to a process fire scenario. It allows pressure relief avoiding exceeding maximum design load of the equipment and reduces inventory inside the vessel or equipment involved in a certain fire scenario. Reduction of hydrocarbon inventory prevents severe consequences in case of rupture of equipment lapped by flames or stroke by a burst overpressure avoiding ignition of further flammable substances. Blowdown is considered to be the primary means of protection. Blowdown time should be reduced as much as possible to limit the need for passive fire protection, which are only to be considered as a supplement to blowdown (NORSOK, 2008). According to the IEC 61508 Standard (International Electrotechnical Commission, 2010), the maximum PFD for a blowdown valve is 0.01. To correctly perform the blowdown function, we need a series of n valves and a logic unit to succeed. The number of valves n depends on the extent of fire or explosion event, which is in turn affected by the leak dimension. An updated value for the blowdown valve PFD is reported every year in the PSA reports (PSA, 2018). Probability of failure of the logic unit can be found in NOGA 070 (Norwegian Oil Industry Association, 2004) and it is equal to 0.0044.

4.2.7. Deluge system

The deluge system is an active protection measure that has the task to reduce fire heat loads on equipment and structures. In this way, it can reduce probability of escalation and can be considered a barrier element of escalation prevention. Its failure modes can be failure in the pump activation, failure to open deluge valves and clogged deluge system, due to, for example, ice. According to the IEC 61508 Standard (International Electrotechnical Commission, 2010), the maximum deluge system PFD should be equal to 0.1. The system includes logic unit, fire water pump, fire water diesel engine, electric generator, electric motor, and deluge valve (Norwegian Oil Industry Association, 2004). NOGA 070 (Norwegian Oil Industry Association, 2004) estimates the PFD for a single deluge valve equal to 0.01. PSA also provides a yearly updated PFD values for the deluge valve (PSA, 2018).

4.2.8. Depressurization

This barrier element of escalation prevention is intended to be performed by PSVs. When, for any reason, vessel pressure increases without control, the first depressurization safety function is performed by one or more PSVs. According to ISO 4126 (ISO, 2013) a safety valve is a valve which automatically discharges a quantity of the fluid in case of overpressure. After restoring normal pressure conditions, the PSV shall close automatically. In this model, only fire scenarios are considered and the cause of overpressure is due to the increasing internal temperature of the vessel affected by a fire. A PSV can fail for different reasons, such as clogging. We can consider that a single PSV is installed for each piece of equipment. This hypothesis is conservative as it does not take into account the possibility of redundancy. Also in this case, the number of PSVs and the overall depressurization PFD depend on the extent of fire or explosion event, which is in turn affected by the leak dimension. The PFD of a PSV can be found in PSA reports (PSA, 2018).

4.2.9. Hydrocarbon inflow shut-off

The purpose of the ESD system is to prevent escalation of abnormal conditions into a major hazardous event and limit its extent and duration (NORSOK, 2008). The escalation prevention barrier element is performed by ESD valves that isolate the affected equipment. The system is activated by the detection of hydrocarbon leak on installation (Norwegian Oil Industry Association, 2004). In FPSO units, such as Goliat, riser emergency shutdown valves (RESDV) are an essential risk reduction measure. They isolate the topside from well and subsea pipeline, reducing the potential for loss of containment. The main failure mode is related to imperfect closure of the valve. PSA reports (PSA, 2018) provide the yearly probability to fail the closure test.

4.2.10. Escalation

This event represents the scope of the analysis performed through the Bayesian network. In this case, we consider part of escalation every damage to equipment, physical passive barriers, firewalls and structures caused by fire and explosion events. This may lead to propagation of fire and explosions and further catastrophic events, such as Boiling Liquid Expanding Vapour Explosions (BLEVEs) and fireballs. The main mechanisms causing escalation to other areas are (Vinnem, 2014):

- Heat impact from external flames;
- flames passing through penetrations and openings in the floor, walls or roof; and
- failure of segregating walls.

In the analysis of this case study, the escalation event is considered to happen if a relevant fire or explosion event occurs and the escalation prevention function fails, i.e. none of the escalation prevention barrier elements succeeds.

4.3. Evidence

Specific data for the Goliat platform are not available due to a twofold reason: it recently started its production (March 2016) and specific data on its safety barriers are not public. For this reason, production start for Goliat is assumed in 2010. This allowed using the PSA reports on trends in risk level from 2010 to 2016 (PSA, 2018), reporting relevant evidence for the BN nodes. However, such evidence is uncertain as it is referred to the whole petroleum activity in Norway.

Table 1
Evidence weights for the considered hydrocarbon leak sizes, based on (PSA, 2018).

Leak size (kg/s)	Leak size probability						
	2010	2011	2012	2013	2014	2015	2016
0.1–1	7.20E-01	7.21E-01	7.17E-01	7.22E-01	7.22E-01	7.18E-01	7.08E-01
1.0–10	2.46E-01	2.47E-01	2.44E-01	2.40E-01	2.37E-01	2.43E-01	2.54E-01
> 10	3.39E-02	3.24E-02	3.94E-02	3.80E-02	4.07E-02	3.93E-02	3.78E-02

Table 2
Evidence weights for the considered safety barrier PFDs (success = 1 − PFD), based on (PSA, 2018). HC stands for hydrocarbon.

Safety Barrier	Leak size (kg/s)	PFD						
		2010	2011	2012	2013	2014	2015	2016
Leak detection	0.1–1	1.44E-02	1.44E-02	1.44E-02	1.64E-02	1.64E-02	1.64E-02	1.84E-02
	1.0–10	4.48E-03	4.48E-03	4.48E-03	4.51E-03	4.51E-03	4.51E-03	4.55E-03
	> 10	4.40E-03	4.40E-03	4.40E-03	4.40E-03	4.40E-03	4.40E-03	4.40E-03
Blowdown	0.1–1	2.34E-02	4.84E-02	3.34E-02	2.14E-02	2.54E-02	1.94E-02	2.24E-02
	1.0–10	9.59E-02	2.06E-01	1.41E-01	8.66E-02	1.05E-01	7.72E-02	9.12E-02
	> 10	1.79E-01	3.67E-01	2.59E-01	1.62E-01	1.96E-01	1.45E-01	1.71E-01
Deluge system	/	7.69E-03	1.87E-01	6.69E-03	3.22E-02	1.57E-02	1.37E-02	8.19E-03
Depressurization	0.1–1	1.50E-02	1.40E-02	1.50E-02	2.00E-02	1.70E-02	2.30E-02	1.80E-02
	1.0–10	7.28E-02	6.81E-02	7.28E-02	9.61E-02	8.22E-02	1.10E-01	8.68E-02
	> 10	1.40E-01	1.32E-01	1.40E-01	1.83E-01	1.58E-01	2.08E-01	1.66E-01
HC inflow shut-off	/	2.25E-02	3.25E-02	2.10E-02	1.70E-02	1.25E-02	1.30E-02	2.00E-02

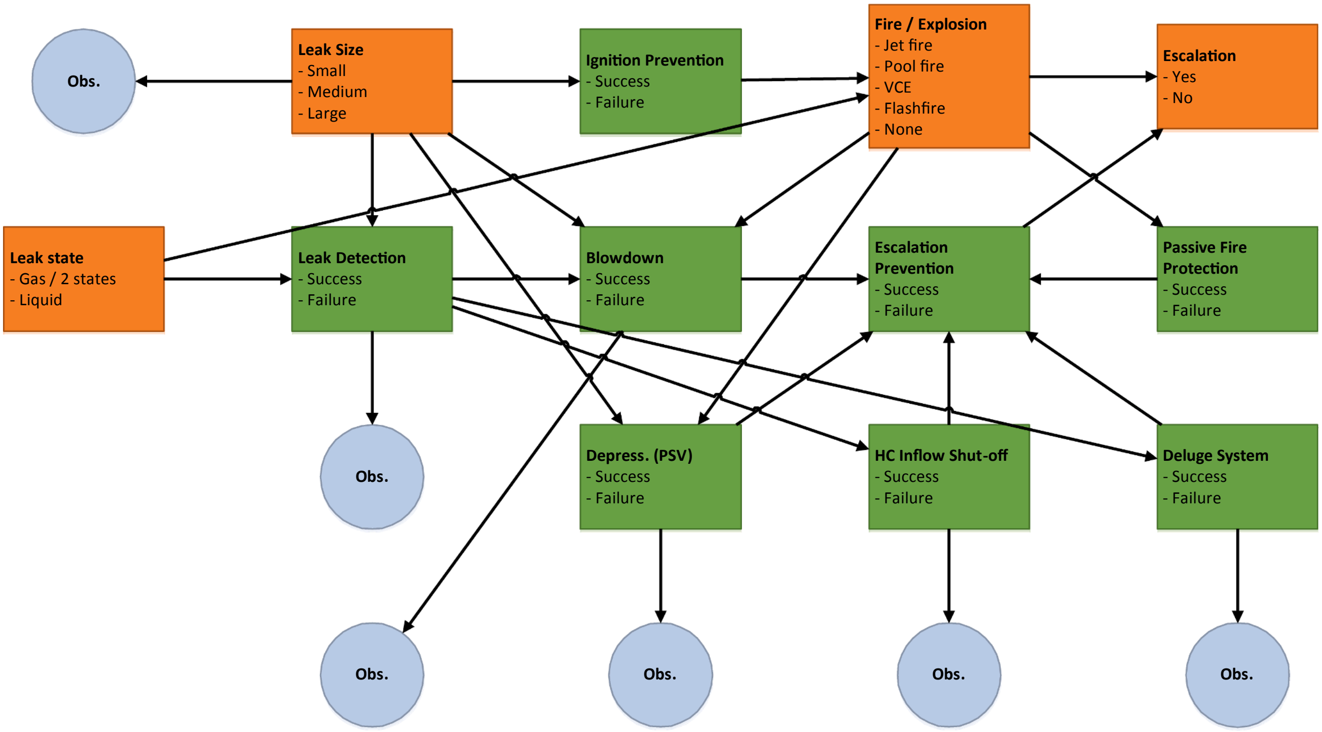

Fig. 4. Bayesian network for the case study. Unwanted events in orange and safety barrier elements in green. PSV and HC stand for, respectively, Pressure Safety Valve and hydrocarbon. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Tables 1 and 2 report the uncertain evidence weights used to yearly update the respective BN nodes.

5. Results

Fig. 4 depicts the Bayesian network defined for the case study, representing the relationships among the scenario events and safety barriers discussed in Section 4.2. Fig. 5 shows the calculated escalation frequencies and probabilities for the period 2010–2016. Frequencies are obtained from equation 3, using the event probabilities from the Bayesian network and the related yearly leak frequencies from (PSA, 2018) averaged by the number of production units surveyed every year. 2011 shows the highest frequency of escalation, which is demonstrated by the associated probability net of the yearly leak frequency values. Fig. 6 allows understanding that Escalation Prevention is the safety barrier that affects the most the final event of escalation, as it generally

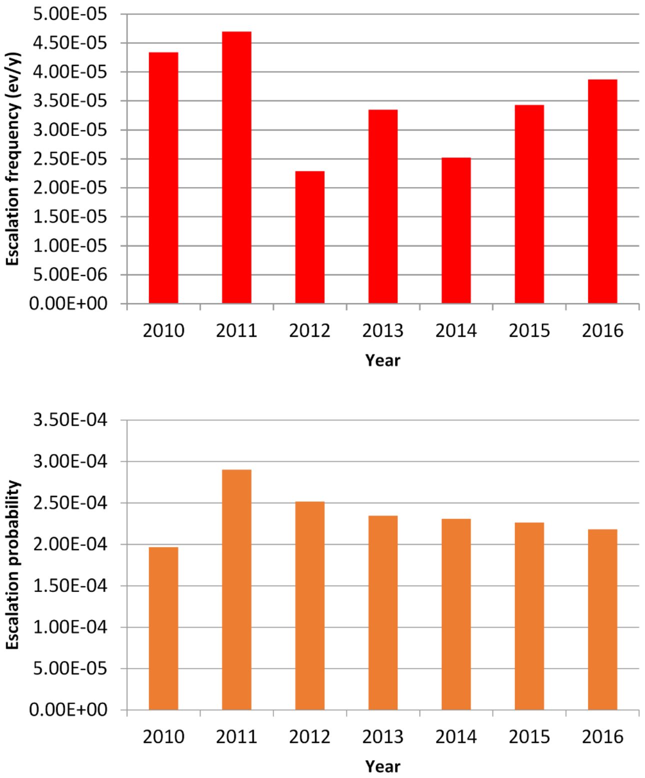

Fig. 5. Calculated escalation frequencies and probabilities within the period 2010–2016.

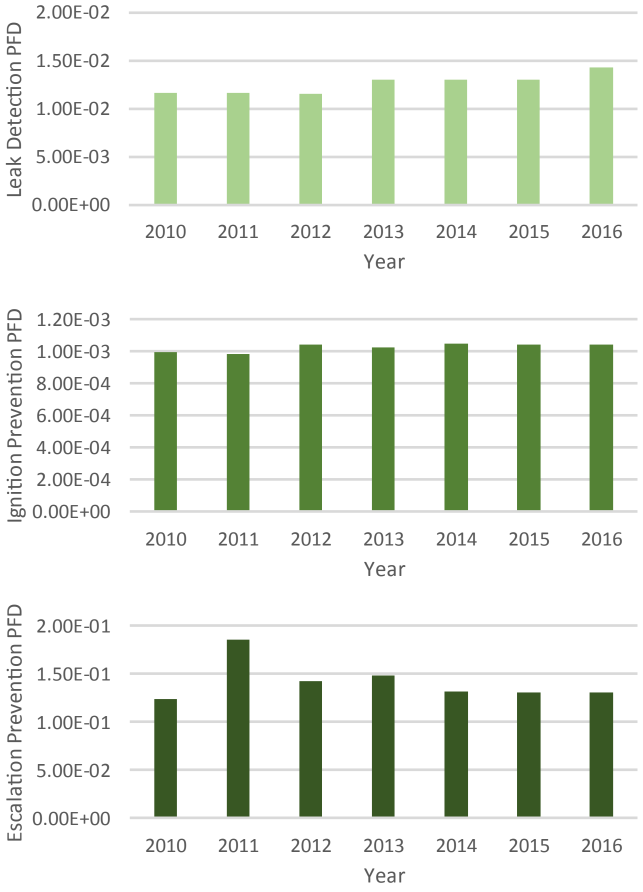

Fig. 6. Calculated safety barrier PFD values within the period 2010–2016.

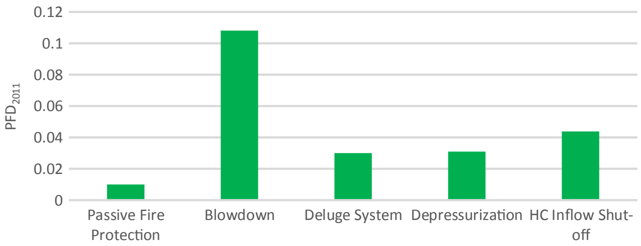

Fig. 7. Calculated PFD values of barrier elements for the safety barrier “Escalation Prevention in 2011.

presents the highest PFD. In particular, Escalation Prevention has record high in 2011. For this reason, Fig. 7 reports the PFD values of the Escalation Prevention barrier elements in 2011, from which we can evince that the Blowdown barrier element has the highest weight and its performance may relatively affect the overall escalation frequency.

6. Discussion

One of the first important results obtained from the study is represented by the BN itself. In fact, the network depicted in Fig. 4 is developed from the linear and simplified sequence of events and barriers in Fig. 3. BN unwanted events are described with an increased level of detail, which allows for more reliable modelling, but also for time-consuming analyses. “Process leak” is split in two BN nodes describing its size and physical state, while specific states are defined for “Fire/Explosion” to address the different physical phenomena that may occur in case of ignition. Interconnectivity among the BN nodes allows considering an increased number of dependencies. For instance, the “leak detection” barrier depends on “process leak” and affects “ignition prevention” in a linear scenario sequence, while a BN considers it as a child of “leak size” and “leak state” and parent of the “escalation prevention” barrier elements except “depressurization”. Such structure allows for definition of complex interdependencies existing in a real accident scenario (Weber et al., 2012).

As mentioned by Edwin et al. (Edwin et al., 2016), drill-down capability is an important feature for dynamic risk analysis tools. The overall risk is a function of the status and condition of the different safety barriers and associated barrier elements. Drill-down capability enables moving through the hierarchy of the model and its different barrier elements. If the risk underlying causes are traced, we can provide intuitive understanding of variation causes and support definition of priorities related to risk mitigation and control.

Fig. 5 shows the final result of escalation frequency for the Goliat platform throughout the years considered. Despite the fact that this overall value remains within the same order of magnitude, some fluctuations can be identified. In particular, the escalation frequency is at its highest point in 2011, while the lowest frequency value is experienced the year after (2012). It is worth reminding that the data used for the analysis are real data from the Norwegian Oil&Gas petroleum activities and such a value change may reflect an actual reaction from critical conditions imposed by PSA. Such effective improvement is possible only if the weak links are identified.

As the escalation frequency is calculated through equation 3, a potential user of a dynamic risk assessment tool would be interested in understanding whether it is the frequency of the initiating event (i.e. the leak frequency) or the escalation probability affecting 2011 overall result. For this reason, Fig. 5 shows also the escalation probability, which is at its maximum as well. This indicates relatively poor performance of the safety barriers mitigating hydrocarbon leak. Fig. 6 shows relatively stable values of PFD for the safety barriers throughout the years, except for the escalation prevention, which reports the maximum PFD in 2011. This highlights the influence of this barrier performance on the overall frequency of escalation. Finally, if the single

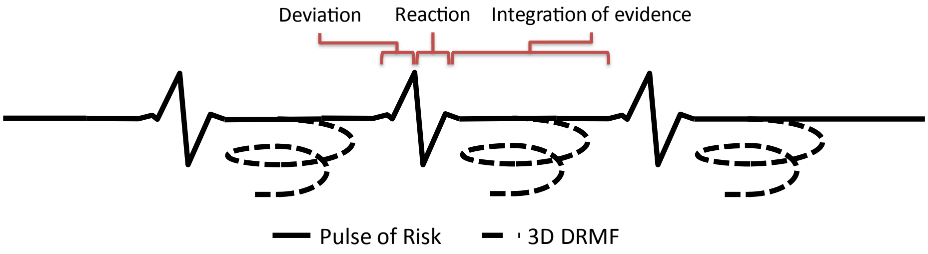

Fig. 8. DRMF as response to pulse of risk.

barrier elements are also studied, specific criticalities can be identified. For instance, Fig. 7 reports poor performance for the blowdown barrier element during 2011, and, consequently, indicates need for improvement.

Another aspect to consider is the quantity and quality of data used as input to dynamic risk assessment methods. In this case, the quality of data is (supposedly) high as the source is PSA, but they represent evidence that may sensibly affect the final analysis outcome. Moreover, it should be reminded that these statistics refer to a period preceding the start of Goliat productions and were used for the sake of demonstrating the effectiveness of such approach. Dynamic risk assessment would be hard to justify if little or no data are available, but this industry trend is in favour of data collection, as demonstrated by the ENI barrier panel project.

This study shows how dynamic risk assessment allows assessing risk variation also due to observed presence of resilience. Resilience is about dealing with the unexpected and the unprecedented and dynamism is the intrinsic premises for it (Grøtan and Paltrinieri, 2016). As discussed in Section 1, Oil&Gas production in arctic and sub-arctic regions may be characterized by the emergence of unexpected events, whose control assumes increasingly critical connotations due to the sensitive environment in which they occur. Continual performance variability due to intrinsic adaptations may be the norm rather than the exception. However, evidence on resilient episodes may be represented by barrier successes and may have various implications (Paltrinieri et al., 2017), such as positive effects in terms of evidence of enhanced processes of preclusion, mitigation or recovery. Even the opposite (series of failures) may signify a turning point due to accumulated learning.

Resilient episodes are better assessed within their context (Grøtan and Paltrinieri, 2016). For instance, the evidence collected for a single BN node eventually affects a larger portion of the network. A model such as BN is needed for the safety management process to identify and grasp such occasions. A “drift into failure” (Snook, 2002) might as well be a “drift into success” and a manifestation of resilience as a positive outcome of complex system properties. The drift metaphor is recurrent and recursive in the sense that technical revisions and redesigns, failures, incidents, accidents and recoveries may represent such occasions. BN analysis is used in this study to derive risk-related knowledge from resilient functioning.

Fig. 8 depicts how dynamic risk management (Fig. 1) may be performed as a response to a “pulse of risk” (Grøtan and Paltrinieri, 2016), i.e.:

- an expansion phase indicating a deviation from optimal system conditions, followed by
- a contraction representing the resilient reaction.

Examples of such pulses are provided by the near misses from the yearly PSA reports, such as leaks (expansion) that were successfully controlled (contraction). Collected evidence would trigger iteration of dynamic risk management. Newly assessed risk levels would call for overall re-organization and general improvement, as suggested for the blowdown barrier element after the analysis of its 2011 performance. This “Pulse of Risk” approach concurs into the shift of the DRMF perspective: from a two-dimension process designed to continuously integrate exogenous information, to a three-dimension process iterated to re-orient the overall risk management, for a flexible but comprehensive response to the challenges imposed by Oil&Gas production in arctic and subarctic regions.

7. Conclusions

A novel approach for dynamic risk assessment and management is suggested by this work. A method based on BNs and safety barrier assessment is used to carry out the approach indicated by DRMF (Grøtan and Paltrinieri, 2016). The method is applied to the Goliat Oil&Gas platform located in the Barents Sea and risk data on the Norwegian petroleum activities are used as evidence to simulate continuous update of risk assessment throughout the years. The case study showed the benefits and limitations of such an approach. Accurate modelling of potential accident scenarios is possible through BNs, but time-consuming. The approach allows for drill-down capabilities, which enhance support of operations and definition of risk mitigating measures. However, the data used for dynamic risk assessment has a pivotal role, as data quality and quantity may sensibly affect the outcome. Fortunately, the Oil&Gas industry is generally committed to improving collection of field data for the assessment of safety barrier performance. Finally, it must be mentioned that this approach represents a potential response to “pulses of risk”, in which system deviations and resilient reactions are processed by iteration of dynamic risk management for an effective strategy controlling risk in critical cases, such as Oil&Gas production in the arctic and sub-arctic regions.

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