

A preliminary approach to subsea risk management using sensor network information

M. Bucelli

Alma Mater Studiorum—University of Bologna, Bologna, Italy
Norwegian University of Science and Technology NTNU, Trondheim, Norway

I.B. Utne & N. Paltrinieri

Norwegian University of Science and Technology NTNU, Trondheim, Norway

P. Salvo Rossi

Kongsberg Digital AS, Trondheim, Norway

V. Cozzani

Alma Mater Studiorum—University of Bologna, Bologna, Italy

ABSTRACT: During the last decade, increasing attention has been focused on environmental protection. For instance, the ecological effects of hydrocarbon releases in the sea are of paramount concern. One way to assess their environmental impact is to consider the amount of pollutant discharged. Effective early detection would help in revealing spills in advance and take the necessary mitigating measures to contain the released volume. Standards and guidelines are established for developing effective sensor networks in the subsea templates for monitoring purposes and data collection. Sensors provide a heterogeneous amount of information about the template they are monitoring. According to recent studies on risk assessment, the *level of knowledge* about a specific system is an intrinsic feature that should be considered during the assessment and evaluation phases for better managing potential increments of the risk level. The information provided by sensor networks may be used in this perspective. Sensors may be functionally placed in fault tree analyses and update the information about frequency deviation. The work in this paper is focused on risk management using such information from subsea sensor networks. A real reference case from the oil and gas industry located in an environmentally sensitive area on the Norwegian Continental Shelf is provided for testing the suggested approach. The case study refers to subsea monitoring of oil leakages from the wellhead templates. Insights from the case study highlight how sensor data analysis may improve risk management and support operational decision making.

1 INTRODUCTION

Dynamicity to risk assessment and management is a main challenge that today's researchers have to face. A quantitative assessment of the level of risk for a production installation is required by law, but it is usually performed during the design phase. Effective support during operations is missing (Villa et al., 2016). The chemical and petrochemical industry requires tools and methods to update the risk picture on a real-time basis and then improving risk management (Paltrinieri and Khan, 2016). Different approaches have been suggested to dynamically update the risk level. Some of these are based on Bayesian networks (Khakzad et al., 2016, 2014) while others are proactive approaches based on indicators (Paltrinieri et al., 2016).

In this perspective, the Dynamic Risk Management Framework (DRMF) has been developed (Paltrinieri et al., 2014). [Figure 1](#) shows the DRMF. DRMF focuses on the continuous systematization of information on new risk evidence. As shown in [Figure 1](#), its shape opens the process to new information and early warnings by means of continuous monitoring. Side information is an input to each step of risk management through communication and consultation.

The available information provided by different sources, such as monitoring and control devices, but also training reports and audits, should be included and exploited when assessing the risk level during operations. As suggested by Aven and Krohn (2014), a new dimension to the definition of risk from Kaplan and Garrick (1981) should be

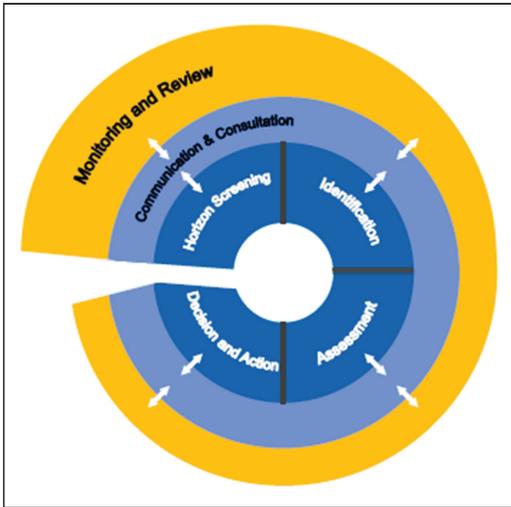


Figure 1. Dynamic risk management framework—clockwise (adapted from (Paltrinieri et al., 2014)).

added. As shown in Eq. (1), risk (R) is a function of the identified scenario (s), its probability (p), its consequences (c) and of what Aven and Krohn (2014) define as level of knowledge (k).

$$R = f(s, p, c, k) \quad (1)$$

The level of knowledge for a specific system is an intrinsic feature that should be considered during the assessment and evaluation phases for better managing potential increments of the risk level.

The information provided by sensor networks may be used in this perspective. Sensors may be functionally placed in fault tree analyses and update the information about frequency deviation. The current analysis in this paper refers to subsea detection networks.

Subsea leak detection is a considerable challenge for the oil and gas offshore industry, although the main concern for subsea templates is blow-out. As shown by Macondo (Deepwater Horizon Study Group, 2011) accident, the effect of a well blow-out due to the large amounts of spilt crude are catastrophic from human, environmental, economic and reputational point of views.

However, as oil and gas offshore production is moving north, towards sub-Arctic and Arctic areas, monitoring and control of crude oil spill are becoming critical issues. These areas are environmentally sensitive (Larsen et al., 2004) and specific requirements (DNV-GL, 2012) must be met during production. For instance, the Barents Sea area is recognized by the World Wildlife Fund (WWF) as

critically sensitive from an environmental point of view (Larsen et al., 2004) due to:

- Naturalness;
- Representativeness;
- High biological diversity;
- High productivity;
- Ecological significance for species;
- Source area for essential ecological processes or life-support systems;
- Uniqueness; and
- Sensitivity.

The current development of large oil and gas templates in the Barents Sea may lead to severe pollution and increased risks of large oil spill (Bioforsk Soil and Environment, 2006), constituting a major threat to the biodiversity of this particularly sensitive area.

Detectors are required to show high sensitivity to small amounts of leaking hydrocarbons and to detect a spill in a reasonable time interval. This is the basis for early detection systems. The threshold value of a leakage rate to be detected by the sensors is a critical parameter that influence the choice and the cost of the device. Furthermore, the detectors have to be available and reliable when in place to effectively provide information to the topside control room. Fault logs' information may be gathered to evaluate to which extent the measurement by the sensor is trustable.

Moreover, it would be preferable to locate the leakage source through the detection system. Collecting information about where the template is spilling oil is useful for both intervention and consequent maintenance activities.

The contribution in this paper addresses the main challenges related to subsea oil detection coupled with risk management for a real case of an oil and gas Floating, Production, Storage and Offloading (FPSO) unit located in the Barents Sea. Available sensor network information is used to support risk management.

The paper is organized as follows: [Section 2](#) provides some fundamentals of signal processing useful for a comprehensive understanding of how the subsea leak detector network works. The case study is extensively described in [Section 3](#). The legislative requirements and both the subsea template and sensor network characteristics are included in this Section. The results of the study and their discussion are provided in [Section 4](#) and [5](#). The paper ends with conclusions in [Section 6](#).

2 FUNDAMENTALS OF SIGNAL PROCESSING FOR OIL DETECTION

The detection system purpose is to reveal hydrocarbon spills in the sea from the subsea equipment.

For the sake of simplicity, this work addresses the oil leakage event in a binary way: the presence of release is associated with the state H_1 , while the absence with the state H_0 . Sensors detect the presence (H_1) or absence (H_0) of oil leakage from the wellhead. A sensor's local detection is performed by comparing the registered signal with a fixed threshold.

Typically, distributed multiple sensors are in place to detect the oil leakage. Their number is defined as K and everyone is equipped with an acoustic transducer. Every i -th sensor makes a local decision, y_i , and this signal is transmitted to a fusion center (FC), which takes a (theoretically more reliable) global decision, d , about the presence or absence of the binary event. The global decision is derived by appropriately combining the received information on local decisions from different sensors. This type of architecture is defined as centralized and it is represented in Figure 2 (Salvo Rossi et al., 2016; Salvo Rossi and Ciunozzo, 2015).

Referring to Figure 2, the present study considers that the local decision from the i -th sensor, y_i , does not suffer of disturbance and signal attenuation while it is transferred to the FC. The signal transmitted to the FC from the i -th sensor is named r_i . For the assumptions made, the value of r_i corresponds with y_i .

Locally, at sensor level, four different decision situations may result considering a binary leak event. Such decision situations are summarized in Table 1. The present analysis assumes that every sensor senses autonomously the environment in a defined space cell to detect the presence or absence of a target (which in this specific case is the presence of oil leaking from the template).

The probability of detection (P_D), false alarm (P_F) and missed detection (P_M) are defined according to the equations 2–4:

$$P_D = p(y = H_1 | H_1) \quad (2)$$

$$P_F = p(y = H_1 | H_0) \quad (3)$$

$$P_M = p(y = H_0 | H_1) = 1 - P_D \quad (4)$$

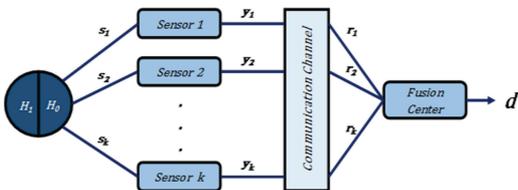


Figure 2. Distributed detection system (K sensors) with fusion center (adapted from Salvo Rossi and Ciunozzo (2015)).

Table 1. Detection and detection errors.

		DECISION	
		$d = H_0$	$d = H_1$
EVENT	H_0	Correct decision	Error type 2: False alarm
	H_1	Error type 1: Missed detection	Correct decision (detection)

The sensor local performance may be described by means of different parameters. The present work refers to P_D and P_F according to common practice in communication engineering studies (Salvo Rossi et al., 2016; Salvo Rossi and Ciunozzo, 2015). The present work assumes that sensors are independent from each other. Given this hypothesis, P_D and P_F are as well stationary and conditionally independent. The sensors within the network are assumed to have identical local performance (homogeneous network).

The detection system performance is evaluated in terms of the global probability of detection, Q_D , the global probability of false alarm, Q_F , and the global probability of missed detection, Q_M . They are defined according to the following equations 5–7:

$$Q_D = p(d = H_1 | H_1) \quad (5)$$

$$Q_F = p(d = H_1 | H_0) \quad (6)$$

$$Q_M = p(d = H_0 | H_1) = 1 - Q_D \quad (7)$$

The FC takes the final decision based on the received decisions and using a Fusion Rule (FR) (Javadi and Peiravi, 2013). This work applies the Counting Fusion Rule (CFR). The sum of sensor decisions is compared to a specific threshold at the FC to make the final decision (Javadi and Peiravi, 2013). The CFR is a simple and intuitive strategy to count the number of reported detections (Niu and Varshney, 2008), but it is far from the optimal performance (Javadi and Peiravi, 2013). However, it is suitable for the purpose of the current analysis as it does not require previous system knowledge and it provides a good basis for trade-off analysis.

3 CASE STUDY

As previously mentioned, this study focuses on the main challenges of subsea oil detection and risk management for a real case of an oil and gas Floating, Production, Storage and Offloading (FPSO) unit located in the Barents Sea.

For this reason, the study aims to evaluate if the facility detection system is able to:

- Improve subsea safety;
- Reduce environmental impact by controlling the released hydrocarbon quantities;
- Reduce the need for remotely operated vehicle (ROV) inspections.

In particular, the focus of this work is on early detection of oil releases in the subsea template on the seabed.

3.1 *Regulations and stakeholders*

Companies operating on the Norwegian Continental Shelf (NCS) are required to carry out environmental monitoring to obtain information about the actual and potential environmental impact of their activities (Norwegian Environment Agency, 2015). Different regulations set the requirements for the monitoring of petroleum activities. The regulations relating to conducting petroleum activities (The Activities Regulations) (Petroleum Safety Authority Norway, 2016a) dedicate Sections 52–57 to special requirements for environmental monitoring. These requirements include the monitoring of the water column and of the benthic habitats, as well as the establishment of an effective remote sensing system to detect and map acute pollution. The Management Regulations (Petroleum Safety Authority Norway, 2016b) require in Section 34 the operators to report the results obtained from monitoring of the external marine environment. These requirements have to be satisfied during oil and gas operations.

In 2014, a Joint Industry Project (JIP) led by DNV-GL was aimed at developing the best practices for designing and implementing detection systems (Leirgulen, 2014). Twenty key partners joined the project, including different operators, integrators and suppliers, as well as authorities, the Norwegian Ministry of Climate and Environment, and the Petroleum Safety Authority Norway (PSA) (Leirgulen, 2014). The JIP identified relevant functional requirements and general specification for a subsea detection system. The outcomes are included in the Recommended Practice F302 (DNV GL, 2016). The key functional requirements identified for the subsea detection system by DNV GL (2016) may be summarized as follows:

- Sensitivity to small releases;
- Responsiveness of the detection system;
- Availability and reliability of the leak detector;
- Ability to locate the leakage source.

Therefore, the detection system must satisfy the requirements set by the standard for oil detection in the subsea template RP-F302 (DNV GL, 2016).

The standard sets qualitative requisites to be fulfilled. First, the Best Available Techniques (BAT) approach for leak detection has to be selected. RP-F302 requires a two-step BAT process where the firstly single techniques are assessed and then different configurations are compared to identify the most efficient in cost and risk reduction.

Anyway, the analysis of the different standards does not provide straightforward guidelines for the positioning of subsea leak detectors. Different configurations have to be assessed and redundancy margins to be guaranteed. The main purpose of the subsea network is to strain the detection of oil releases to unit.

Different actors are involved in the response when a subsea leak is detected. The topside operators have to gather relevant information and start preliminary mitigation actions. Moreover, the offshore personnel have to consult experts from the onshore department, and notify the coast guard and to the airborne in case their intervention is needed. From the topside, it is possible to monitor and control the amount of oil released from the subsea equipment. The production system needs a detailed and reliable picture of the situation in the subsea template in case there would be a need for shut-down. The economic impact of unplanned shutdowns can be severe for oil and gas companies (Oil and Gas IQ, 2014). Assessing the risk in a detailed way may allow minimizing time (and costs) of unnecessary stops of production. Moreover, the effectiveness of the subsea detection system is also critical for limiting the number of unplanned ROV inspections. ROVs are operated by a crew on board dedicated vessels and are usually used for maintenance activities on the subsea templates. ROV inspections are extremely expensive and especially dedicated expert personnel is required. A reliable sensor network able to identify releases due to mechanical failures would be helpful in eliminating the costs of unnecessary ROV inspections. With a detection system that works effectively and identifies (and eventually locates) the leakage sources, the number of required interventions from the topside would decrease, leading to a subsequent drop in operation costs.

In addition, different environmental organizations have raised their concern about oil and gas exploration and drilling, particularly in the sensitive Arctic and sub-Arctic areas, which are critical for biodiversity and ecological significance (Greenpeace, 2017). These organizations may affect public opinion towards the environmental protection policy of a company. The impact on reputation of oil and gas operators may be severe. For this reason, implementation of advanced and effective strategies and technologies for environmental protection should be a main priority for the operator company.

For all these reasons, the stakeholders of subsea oil and gas activities within Arctic and sub-Arctic regions may be the following:

- Offshore operator;
- Production system;
- Onshore department;
- Coast guard;
- Airborne;
- ROV operator;
- Sensor supplier;
- Petroleum Safety Authority Norway;
- Environmental protection agency; and
- Non-Governmental Organizations (NGOs).

3.2 Subsea template overview

The subsea template on the seabed is a critical area of the oil production installation where a high number of valves and joint points are located. These critical connections may be potential sources of oil leakage due to pressure increments during production disturbances and/or mechanical failures.

Sensors are placed in the template structure to early detect oil releases. Although different types of sensors may be available, this analysis refers only to acoustic oil leak detectors.

Figure 3 shows the physical elements needed for the detection of hydrocarbon leakage at the subsea wellhead and X-Tree (adapted from Røsby (2011)).

3.3 Sensors characteristics and configurations

According to RP F302 (DNV GL, 2016), there are no unique guidelines to locate the sensors in the distributed detection network. The only relevant requirement concerns the use of BAT approach for early detection of oil releases.

Two types of sensors are considered named Type A and Type B, respectively. They are set to work with the same P_F (equal to 10^{-2}) as common

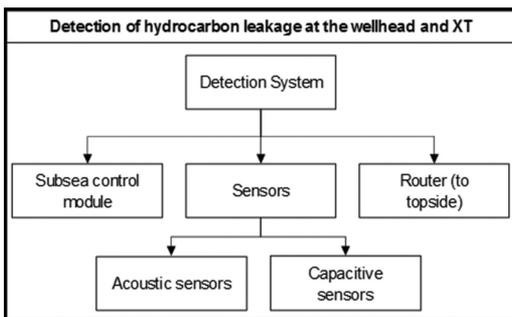


Figure 3. Detection system for the wellhead and X-Tree (adapted from Røsby (2011)).

practice in telecommunication engineering studies. However, the sensors have different Receiver Operating Characteristic (ROC) curves and this results in different P_D . The more performing sensor (Type A) has a P_D of 0.90 and the other (Type B) of 0.50 (Salvo Rossi et al., 2016).

Table 2 summarizes the characteristics of the sensors.

Detection and its reliability are key parameters during oil and gas operations. Reliably assessing that a mechanical rupture has happened and that the template is leaking is critical in efficient ROV intervention management.

The sensors are placed in two different configurations. The area of interest is organized in structured square cell grids, as shown in Figure 4. The first configuration considers one single sensor for each grid cell defined in the sensed environment (namely, single configuration). In the second configuration, redundant N sensors monitor the presence (or absence) of the target of interest (namely, redundant configuration). Figure 4 is shown as representative.

The case study compares the detection performance of the distributed sensor network in two cases. The first scenarios refer to the single configuration using high-performance acoustic sensors in terms of detection probability (Type A). The second considers the redundant configuration applying theoretically cheaper and less performance sensors (Type B). The detection performance of the two sensors are described in Table 2. The single configuration uses one sensor of Type A for each grid node described in Figure 4. The sensor covers the

Table 2. Description of detection performance for sensors Type A and B.

Sensor	P_D	P_F
Type A	0.90	0.01
Type B	0.50	0.01

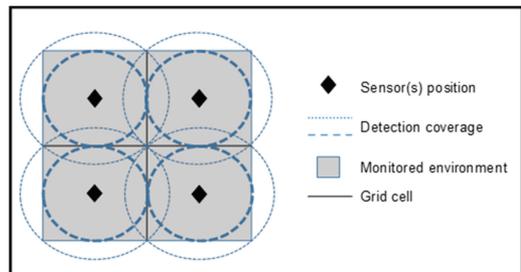


Figure 4. Sensor grid in the monitored environment.

entire grid cell and it sends its local decision about the presence or absence of oil release to the FC. The redundant configuration applies a number of N sensors Type B for each grid cells. The number N of sensors should be defined to approximately match the detection probability obtained with a single Type A sensor. The CFR is applied as fusion rule at the FC. The threshold is set conservatively to 1. This means that the FC conservatively takes a positive decision on the presence of oil leakage when at least one detector monitoring the grid cell sends a signal revealing the presence of the target.

4 RESULTS

The current analysis considers a release trend as the one shown in Figure 5. It is worth to noticing that the release behaviour has been adopted for demonstrative purposes. The sensors detect noises from the subsea template and they record them above a defined threshold. Some oscillations are recorded due to any pressure variation in the reservoir. In that case, the pressure is controlled and reset to its optimal value without any intervention from the topside (see the first 50 time steps in Figure 5). This trend may also be due to some slightly overpressure scenario developing in the first year of production, when the pressure in the reservoir is higher (Kansas Geological Survey, 2000). The oscillations may result in fatigue on mechanical components and induce a mechanical failure of some valve in the X-mas tree and well-head. The template is then continuously leaking and it needs dedicated inspections and intervention.

The detection and false alarm probabilities are calculated using the fusion rule described in Section 2. Table 3 shows that a number of Type B sensors equal to 4 in the redundant configuration has been found to approximately match the detection probability obtained with a single Type A sensor.

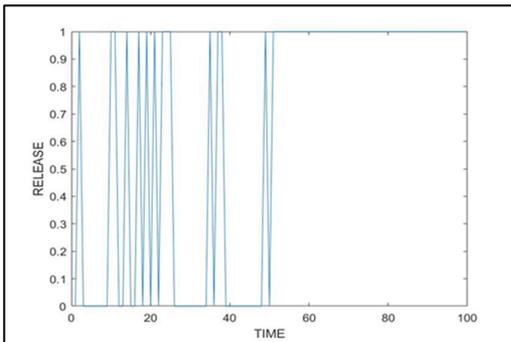


Figure 5. Assumed target trend for the present analysis.

Table 3. Detection performance of the subsea template system in two different configurations.

Configuration	SINGLE	REDUNDANT
Sensor type	Type A	Type B
Number for each grid cell	1	4
P_D	0.90	0.94
P_F	0.01	0.04

The P_D in the redundant configuration is slightly higher than the in the single configuration, while the P_F is four times increased.

5 DISCUSSION

Table 3 highlights a relevant increment of the detection system performance using redundant “cheap” sensors (Type B). The detection probability P_D for a single Type B sensor is 0.50 (see Table 2 in Section 3.3), but it is almost doubled in the redundant configuration (0.94). Moreover, this type of configuration slightly exceeds the single expensive Type A sensor P_D . Redundant configurations of Type A sensors may be also considered. However, the increment in detection performance would not be as relevant as in the case of Type B sensors as their performance is already high.

However, the redundant configuration as described in this work allows the increment of the false alarm probability P_F as shown in Table 3. This may have a negative effect on the organizational levels. False alarms may result in unnecessary unplanned ROV inspections and shut-downs with strong increments of operational costs. The fusion rule for the FC adopts a conservative approach with respect to leak detection for which the global decision is the presence of leak in case *at least* one detector emits a positive signal. That justifies a global P_F for the redundant configuration of four times the single value.

A more sophisticated decision rule should be implemented (Javadi and Peiravi, 2013). The sensor placement should be investigated and optimized to guarantee early detection and to track the oil spill movement in case intervention is needed.

The sensors detect noises from the subsea template and they record them above a defined threshold. Some oscillations are recorded due to any pressure variation in the reservoir. In such scenarios, the pressure is controlled and reset to its optimal value without any intervention from the topside. This trend may also be due to some slightly overpressure scenario developing in the first year of production, when the pressure in the reservoir is higher (Kansas Geological Survey, 2000). These oscillations may result in fatigue on

mechanical component and induce a mechanical failure of some valve in the X-mas tree and well-head. The template may then continuously leak, needing dedicated inspections and intervention.

According to the results of the performed simulations, the number of missed detections is lower in redundant configurations. It is possible to identify and distinguish if the release is due to well fluctuations or mechanical failures by coupling the signal from the FC and pressure data. This allows recording of early warnings and use them for risk assessment and management. The analysis of near-accident data is a fundamental step in the framework to forecast likely accident scenarios. The information from sensor networks may provide a basis to the reactive update the risk picture of the installation with respect to subsea leakage risk. For instance, the data from sensors may be used as evidence in Bayesian inference network for updating release probabilities (Paltrinieri and Khan, 2016).

Reliable information from the subsea may also improve communication between different stakeholders and decision making processes.

6 CONCLUSION

The threshold leakage rate for the sensors defines its sensitivity and therefore its cost. High sensitivity (detection of lower leakage rate) results in highly sophisticated sensors with substantial cost. A solution would be the application of low cost redundant sensors located in a specific network in order to perform early detection. The decision about the presence of oil leakage into sea from the subsea template determines the need of intervention from the topside. Different (internal and external) stakeholders are involved in oil and gas facilities. A reliable subsea detection system may help avoid unnecessary intervention and improve the overall company risk management. Moreover, every intervention to the subsea template from the topside requires substantial costs that may be reduced with a reliable basis of information.

The analysis suggests the investigation of different sensor placement configurations in order to enhance early detection and oil leakage tracking. Further studies should be considered applying different and more specific decision fusion rules.

The information from decision making may be used in updating the risk picture of the installation and in improving the decision making process.

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