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A system engineering approach to subsea spill risk management

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ABSTRACT

In recent years, environmental protection has received more attention in society. In addition to the ecological effect of a hydrocarbon release into the sea, its environmental impact is assessed by considering the amount of pollutant discharged. Therefore, limiting the impact of a spill consists in lowering the volume of oil released and effective early detection is necessary for implementation of mitigating measures. Standards and guidelines have been established for developing effective sensor networks in the subsea templates for both monitoring purposes and data collection. Sensors provide various and heterogeneous amount of information about the subsea template they are monitoring. According to recent definitions of risk, the *level of knowledge* should be considered during the risk assessment and evaluation phases for better managing potential impacts. The information provided by sensor networks indeed may be used in this perspective. For example, sensor functionality may be included in dynamic fault tree analysis in updating the information about system deviations' frequency.

The work in this paper is focused on risk management using information provided from subsea sensor networks. The study adopts a top-down approach inspired by systems engineering to analyse the communication patterns among the different stakeholders. A real reference case from the oil and gas industry located in an environmentally sensitive area on the Norwegian Continental Shelf is used for testing the suggested approach. The case study refers to subsea monitoring of oil leakages from the wellhead templates. Different sensor configurations are considered in order to identify the one able to provide the most reliable information. Insights from the case study highlight how sensor data analysis may improve risk management and support operational decision making.

1. Introduction

Subsea leak detection is a considerable challenge for the oil and gas offshore industry, although the main concern regarding subsea templates is blow-out. The detection and its reliability are key parameters during oil and gas operations. The early detection of a release is of paramount importance to limit environmental impact. Reliably assessing that a mechanical rupture had happened and that the template is leaking is critical in Remotely Operated Underwater Vehicle (ROV) intervention management. ROV inspections are extremely expensive and especially dedicated expert personnel onboard a surface vessel is required. A reliable sensor network able to identify releases due to mechanical failures contributes to eliminating the costs of unnecessary ROV inspections.

Assessing the leakage risk in a detailed way may be helpful in minimizing the time (and costs) of unnecessary stops or shutdowns of oil and gas production. The economic impact of unplanned shutdowns can be severe for oil and gas companies (Oil and Gas IQ, 2014). Moreover, the effectiveness of the subsea detection system is also critical in limiting the number of unplanned ROV inspections. ROVs are operated by a crew on board dedicated intervention vessels and are usually used for planned maintenance activities in the subsea templates. When the detection system works effectively in identifying (and eventually locating) any leakage sources, the number of required interventions from the topside decreases with subsequent drop in operational costs.

As oil and gas offshore production is moving north towards sub-Arctic and Arctic areas, monitoring and control of oil spills are increasingly critical. 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, as the absence of perturbation due to anthropogenic activities and of introduced and/or cultured species (DFO, 2004);
- Representativeness of the environment;
- High biological diversity;
- High productivity;
- Ecological significance for species;
- Source area for essential ecological processes or life-support systems;
- Uniqueness; and
- Sensitivity.

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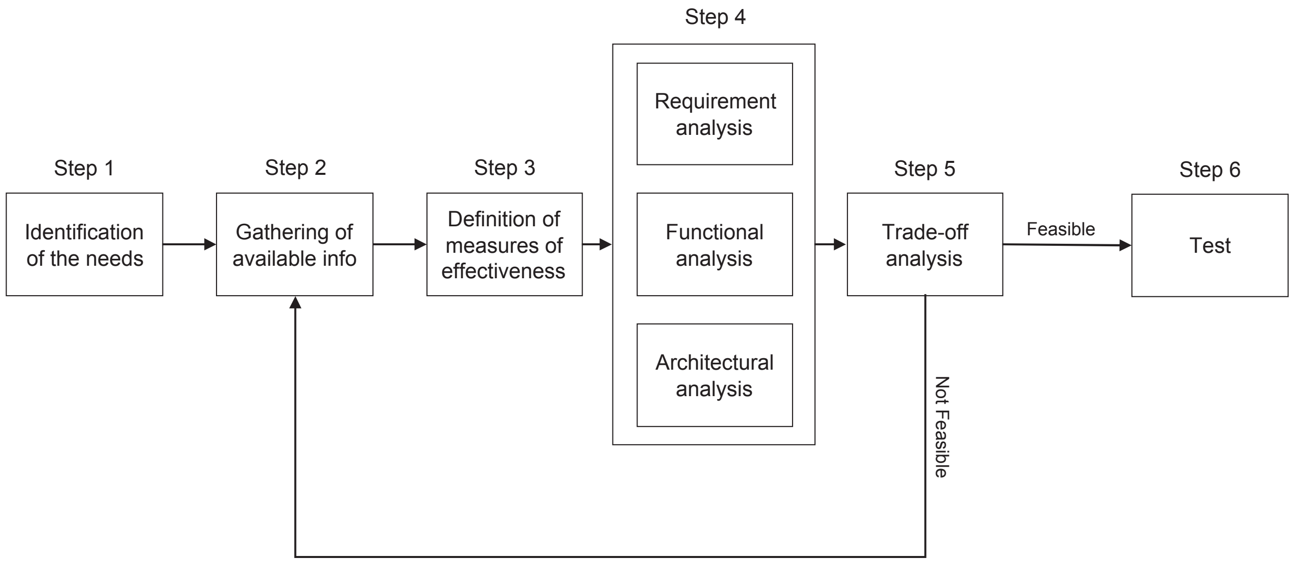

Fig. 2.1. SE process (Adapted from Olivier et al., 1997).

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

Dynamicity to risk assessment and management and validation of related techniques are important challenges that researchers today are facing (Paltrinieri and Khan, 2016; Lee et al., 2019). The systems approach may be helpful in that perspective for analysing complex systems. It allows for treating the different parts as black boxes and to focus on the interactions and interferences among them. Every single box may, of course, be exploited and analysed in detail, but the approach aims to highlight different, and sometimes unseen, characteristics (creatingtechnology.org, 2017).

A quantitative assessment of the level of risk for an oil and gas production installation is required by law and it is usually performed during the early design phase. Effective risk management support during operations is missing (Villa et al., 2016; Yang and Haugen, 2016). Therefore, the chemical and petrochemical industry requires tools and methods to update the risk picture on a real time (or quasi-real time) basis, improving risk management (Paltrinieri and Khan, 2016), particularly during operations. 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). For what concerns subsea leak detection principles and risk-based inspection, Bay and Bay (2014) represent an important starting point from which building advanced approaches for risk management.

The work in this paper focuses on the application of the systems approach in analysing the risk issues related to subsea oil and gas production, partially inspired by Jafarzadeh et al. (2017). The objective is to demonstrate early detection of oil leakages from subsea manifolds with lower cost sensors arranged in strategic networks with redundant configuration. The paper is partly a further development and extension of Bucelli et al. (2018). In addition to utilizing the systems approach, the current paper improves the rule for the aggregation of information from the subsea sensors at the fusion center (fusion rule) to achieve more reliable information from the subsea sensor network. A better level of knowledge about what is happening below the sea surface helps improving risk management and avoiding or mitigating emergency situations.

The Systems Engineering (SE) approach, as described in Bucelli et al. (2018), is adopted in this work, but with a different focus, meaning that the present emphasizes the interaction and use of SE to risk management. Further, the paper combines telecommunication engineering, SE and risk management to illustrate how the SE approach to the management of the information from subsea sensor networks can improve risk management for oil and gas installations.

Insights from the results of this paper suggest further investigations to improve the quality and reliability of data retrieved from the subsea network. This and its impact on improved risk management is discussed in the paper.

The paper is organized as follows: Section 2 provides the highlights about SE relevant for the present study, while Section 3 analyses the main challenges to be faced in subsea detection. In Section 4, the SE approach is applied to safe subsea production, and the different steps of the systems approach are described in detail referring to the case study considered. Section 5 provides the discussion, while the conclusions are stated in Section 6.

2. System safety engineering

A *system* is defined as a combination of interacting activities that transform inputs into outputs (INCOSE, 2006). The interdisciplinary approach meant to enable the realization of successful systems is defined as SE. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem. SE considers both the business and the technical needs of *all* customers with the goal of providing a quality product that meets the user needs (INCOSE, 2006).

To improve the understanding of their roles and interactions, the conventional engineering approach deconstructs a system into its formative elements. This approach is often referred as *reductionism* (Merriam-Webster, 1999). It allows to picture the system in its details in many different levels focusing on causality relationships (creatingtechnology.org, 2017). Focusing on individual elements, however, may result in missing some crucial characteristics that instead should be analysed by considering the system *as a whole*. This is the basic idea of *system thinking*. Considering the system as a whole and focusing on the interfaces of the different parts acting in it permits the analysis of emergent properties (Auyang, 1998). Specific standards for system approach have been developed in the last decades. They are summarized in the ISO/IEC/IEEE 15288 standard (ISO, IEC and IEEE, 2015). The set of interrelated or interacting activities that transform inputs into outputs is defined as process (INCOSE, 2006). Fig. 2.1 shows the SE process.

The systematic application of technical and managerial skills to the identification and control of hazards throughout the life cycle of a project, program or activity is defined as *system safety,* according to Roland and Moriarty (1990). Leveson (2011) defines the *system* in terms of hierarchical levels dominated by constraints. Accidents arise from the interaction of system components and violation of constraints. Safety is defined as an emergent property of the system and it should be determined in the context of the whole (Leveson, 2011). For instance, it is possible to assess the reliability of a valve in an industrial plant in terms of probability of success under specified conditions and in a given time interval. Contrariwise, the assessment of the safety of the valve by itself, estranged from the context and the system, does not provide any useful information. The safety of the valve is determined in terms of its relationships with other components. Therefore, safety is a system property should therefore be controlled at the system level.

The SE process is an iterative step procedure that starts with understanding the problem and its importance (step 1). This is a step of paramount importance in SE. In the V-model of SE, the stakeholderś analysis is at the top (De Weck, 2015). When the design of a system starts, a considerable amount of time is spent engaging with stakeholders to identify needs. Different definitions of *stakeholders* are provided in literature (Sharp et al., 1999). In the present approach, they are considered as groups or individuals who are affected by or that are accountable for the outcome of an undertaking, and they may be classified as (De Weck, 2015):

- Customers, which are organizations or individuals that have requested the product;
- Other interested parties, which provide constraints or have influence on the success of the system.

Relevant information about the system from different sources are gathered and made available in step 2 of the SE process. The third step consists in the definition of requirements the system has to satisfy and in their measurement. The fourth step defines uniquely the requirements, the behaviour and the structure of the system by applying a Model-Based System Engineering (MBSE) approach. The requirements are organized to guarantee their clear identification and traceability. Then, the functions the system must fulfil to satisfy the defined requirements are identified. The inputs and the sequence of each function are uniquely described. Finally, the functions are translated into components, both hardware and software. A top-down approach is therefore used to break down the system into its components and to organize them both physically and logically, as well as to define their relationships. This is a crucial phase, as the system hierarchy and structure are used to make the system traceable to the different stakeholders. The trade-off analysis in step 5 is used to evaluate different system designs and to identify the solution that best satisfies the stakeholders requirements. Finally (step 6), the optimal system design is produced.

The approach of the present work is focused on system safety during subsea operations in oil and gas offshore installations. It differs from Leveson (2011) approach, which is more focused on the design stage.

The SE approach and its steps are demonstrated for the subsea early detection system in Section 5.

3. Dynamic risk management

The Dynamic Risk Management Framework (DRMF) (Paltrinieri et al., 2014) is shown in Fig. 3.1. DRMF focuses on the continuous systematization of information on new risk evidence. As shown in Fig. 3.1, its shape opens the risk management process to new information and early warnings by means of continuous monitoring. Heterogeneous and various information is an input to each step of risk management through communication and consultation. Dynamic risk management can benefit from a SE approach as the one proposed in this study for the information gathering phase and for communication.

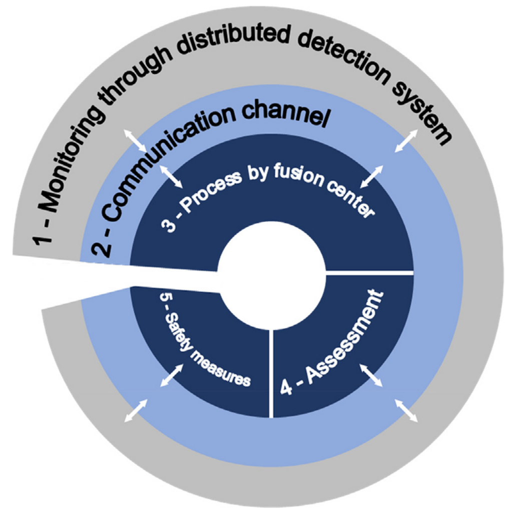

Fig. 3.1. Dynamic risk management framework - clockwise (Adapted for this study from Paltrinieri et al., 2014).

The available information provided by different sources, such as monitoring and control devices but also training reports and audits, should be included and exploited in the assessment of the risk level during operations. Hence, as suggested by Aven and Krohn (2014), a new dimension to the definition of risk from Kaplan and Garrick (1981) should be added. As shown in Eq. (1), risk (R) is a function of the identified scenario (s), its probability (p), its consequences (c) (Kaplan and Garrick, 1981) 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 in the risk level. Hence, information provided by sensor networks may be used. Sensors may be functionally placed in dynamic fault tree analyses to update the information about the frequency of system deviations. The current analysis refers exclusively to the subsea oil detection networks. Moreover, this analysis does not cover the functional placing on sensors in the fault tree structure, but this is considered further work.

The DRMF is an open, iterative, circular approach to risk management. The risk is updated according to the review of different steps, as shown in Fig. 3.1. The first step (clockwise) is the monitoring and review of the information and data available. This is realized, for this specific case study, by the distributed detection system. The information is continuously communicated (step 2) and it is gathered by the fusion center (step 3) and the related risk assessment is made (step 4). The safety measures to reduce and/or mitigate such risk condition are represented by the step number 5 in that approach.

Information gathered from continuous monitoring of the subsea template, such as wireless sensors, as proposed in this paper, might help in the updating of the following steps (2,3,4). Using this information, although the hazard identification would generally not change too much, the risk can be re-assessed and actions might be taken. These actions might be inspections using ROVs to assess the presence or absence of an oil release, maintenance activities, or in unfortunate cases, contact the authorities to notify an oil spill and start possible mitigation action towards environmental damage.

4. Challenges in the subsea detection system

4.1. Overview

A general summary of the major components included in a subsea

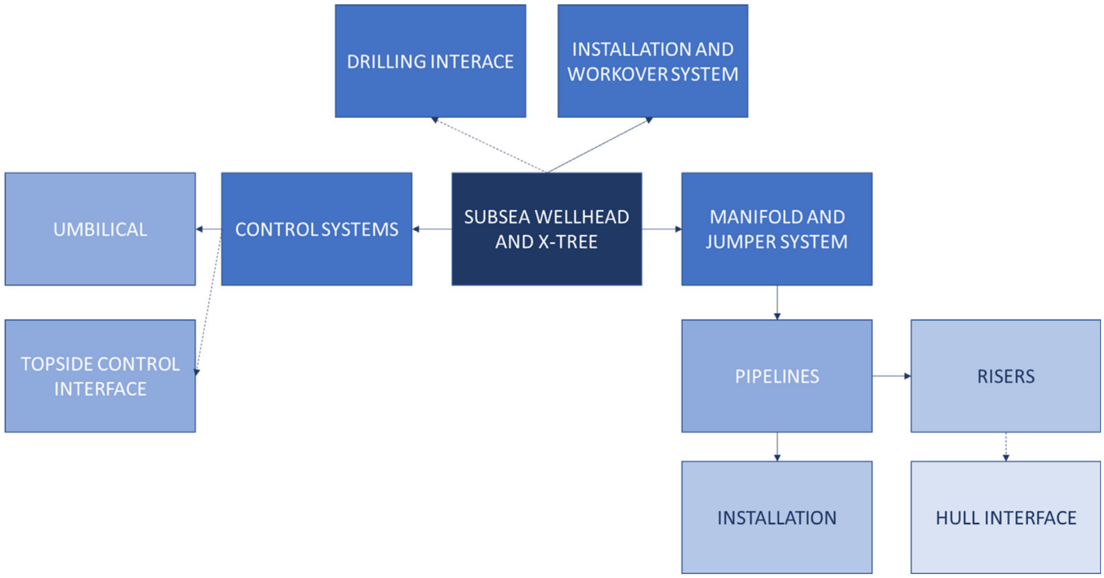

Fig. 4.1. Major components of subsea production system and their interactions (Adapted from Bai and Bai, 2010).

production system and their relationships are provided in Fig. 4.1 (Bai and Bai, 2010).

Subsea leak detection is a considerable challenge facing the oil and gas offshore industry. In 2014, a Joint Industry Project (JIP) led by DNV GL aimed at developing the best practices for designing and implementing detection systems (Leirgulen, 2014). Twenty key partners took part in the project, including different operators, integrators and suppliers, as well as the Norwegian Ministry of Climate and Environment and the Petroleum Safety Authority Norway (PSA) (Leirgulen, 2014). The JIP identified relevant functional requirements and developed a general specification for a subsea detection system. The outcomes are included in the Recommended Practice F302 (DNV GL, 2016), with the key functional requirements identified for the subsea detection system by 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 detectors should show high sensitivity to small amounts of leaking Hydrocarbon (HC) and be able to detect the leakage in a reasonable time interval. This is the basis for an early detection system. The threshold value of the 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 should be available and reliable. The information provided to the topside control room should be effective: fault logs information should be gathered to evaluate to which extent the measurement by the sensor is trustable.

Subsea detection systems should preferably locate the leakage source. Collecting information about where the spill is located in the template is useful for both intervention and consequent maintenance activities.

4.2. Measures of effectiveness

For the sake of simplicity and the stated purposes of this work, the oil leakage event is considered as binary: presence or absence of crude oil spilling from the subsea template. The sensors may detect the presence (H_1) or absence (H_0) of oil in proximity of the wellhead. The present study considers the acoustic detection network. Sensor detection is performed by comparison of an acoustic signal from the leaking source and fixed thresholds.

Typically, distributed multiple sensors are in place to detect an oil leakage. Their number is hereby defined as K. Every i-th sensor is equipped with an acoustic transducer. The local decision, y_i, made by the i-th sensor is transmitted to a Fusion Center (FC). The FC makes a (statistically more reliable) global decision, d, about the presence or absence of the binary event. The global decision is made by appropriately combining the received information about local decisions from different sensors. This type or architecture is defined as centralized. A summary is shown in Fig. 4.2 for the sake of clarity (Salvo Rossi et al., 2016, 2015). Fig. 4.2 refers to the DRMF described in Fig. 3.1.

Referring to Fig. 4.2, the present study assumes that the local decision made from the i-th sensor, y_i, on the basis of the sensed data, s_i, does not suffer from any type of disturbances or signal attenuation while it is transferred to the FC. The signal transmitted to the FC from the i-th sensor is named r_i. The value of r_i is assumed to be exactly the same as of y_i.

Locally, at sensor level, four different decision situations may result when considering a binary leak event, as shown in Table 1. The present analysis assumes that every K sensor autonomously senses the environment in a defined space cell to detect the presence or absence of a target (oil).

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

$$P_D = p(y = H_1|H_1) \tag{2}$$

$$P_F = p(y = H_1|H_0) \tag{3}$$

$$P_M = p(y = H_0|H_1) = 1 - P_D \tag{4}$$

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 studies (Salvo Rossi et al., 2016, 2015). Moreover, the present work assumes the independency of sensors from each other. Given this hypothesis, P_D and P_F are stationary and conditionally independent. The network is assumed as homogenous, i.e., the included sensors have identical local performance.

The performance of the detection system is evaluated in term 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 Eqs. (5)–(7):

$$Q_D = p(d = H_1|H_1) \tag{5}$$

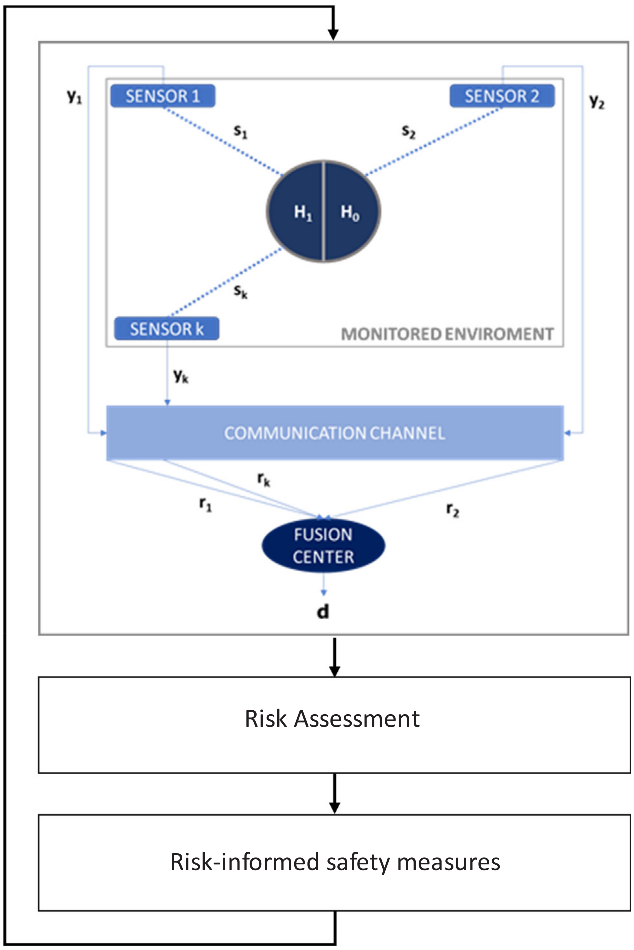

Fig. 4.2. Distributed detection system (K sensors) with FC.

Table 1
Detection and detection errors.

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

$$Q_F = p(d = H_1|H_0) \tag{6}$$

$$Q_M = p(d = H_0|H_1) = 1 - Q_D \tag{7}$$

The analytical expression for Q_D (and similarly for $Q_F andQ_M$) is as follows in Eq. (8):

$$Q_D = \frac{\int_0^{P_F} t^\gamma (1-t)^{K-\gamma-1} dt}{\int_0^1 t^\gamma (1-t)^{K-\gamma-1} dt} \tag{8}$$

where K is the total number of sensors, γ is the threshold (varying from $-1, \ldots, K-1$) and t is time.

The FC makes the final decision based on the received decisions and using a Fusion Rule (FR) (Javadi and Peiravi, 2013). The work in this paper applies the Counting Fusion Rule (CFR) as FR. The sum of the sensors' decisions is compared with a specific threshold at the FC to make the final global 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 gives far from the optimal performance (Javadi and Peiravi, 2013). More sophisticated rules other than CFR can be implemented to perform joint detection and localization of the release, see, for example, Niu and Varshney (2006) and Ciuonzo and Salvo Rossi (2017).

Nevertheless, CFR is suitable for the purpose of the present analysis since it does not require previous system knowledge. In addition, it provides a good basis for trade-off analysis.

The decision made at the FC is adopted as an input in risk assessment and it can lead to definion and triggering appropriate risk-informed safety measures. The process is iterative, as in DRMF.

The performance of the sensor network (represented as probability of detection, false alarm and missed detection) are directly related to the performance indicators (measures of effectiveness), as defined in Section 5.3.

The global probability of a false alarm and the global probability of detection are plotted giving the Receiver Operating Characteristic (ROC) curve for the FC.

$Q_D$and Q_{FA} represent the probability of detection and false alarm of the FC, respectively. If P_0 and P_1 are the a-priori probability of the hypothesis $H_0$and H_1, two other parameters are defined, namely *precision* (P) and *recall* (R), defined as:

$$P = \frac{P_1 x Q_D}{P_1 x Q_D + P_0 x Q_F} \tag{9}$$

$$R = Q_D \tag{10}$$

They can be plotted together giving the precision-recall curve for the FC.

5. SE approach applied to safe subsea production

The SE process described in Section 2 is demonstrated for the subsea release detection system in the following subsections.

The analysis refers to an existing oil and gas Floating, Production, Storage and Offloading (FPSO) unit located in the Barents Sea. The development of large oil and gas templates in the Barents Sea may lead to 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.

5.1. Identification of needs

The detection system's purpose is to reveal HC spilt in the sea from the subsea equipment. Companies operating on the Norwegian Continent 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 external marine environment. These requirements must be satisfied during oil and gas operations.

Subsea spill preparedness involves a large spectrum of actors; from national authorities to sharp end personnel. The onshore and offshore departments are fully prepared to provide the best response in case an oil spill 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 send the notification to the coast guard and to the air force in case their intervention is needed. From 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 a shut-down should be necessary. Supply and safety stand-by vessels are providing the unit with information about oil detection in the proximity of the subsea templates. Usually, these vessels are equipped with radar and cameras in order to reveal any release. The air force and satellites are involved in the response, in case of a large oil spill. They may provide critical information about the oil's movement on the ocean surface and they may be crucial in limiting its spreading.

Those that oppose oil and gas production in the Barents Sea should be mentioned within the stakeholderś list. Different Non-Governmental Organizations (NGO) have raised the concern about oil and gas exploration and drilling, particularly in Arctic and sub-Arctic areas where the sensitivity of the environment is critical for biodiversity and ecological significance (Greenpeace, 2017). These organizations are indirectly involved as stakeholders and they may increase the public interest in the environmental protection policy of a company. The impact of this on an oil and gas operator's reputation may be severe. Implementation of advanced and effective strategies and technologies for environmental protection should be a main priority for the operator company. A brief summary of the stakeholders identified in this analysis is listed in the following:

- Offshore operator;
- Production system;
- Onshore department;
- Coast guard;
- Air force;
- ROV operator;
- Sensor supplier;
- Petroleum Safety Authority (PSA)
- Environmental protection agency; and
- NGOs.

5.2. Gathering of available information for subsea risk management

In the SE approach, the necessary information has to be gathered and made available. Particularly, information about the detection system needs to be collected. According to recommended practices F302 (DNV GL, 2016), there are no unique guidelines to arrange and configure the subsea sensors in the detection network. The only relevant recommendation regards the use of the Best Available Techniques (BAT) approach, to early detect oil releases.

Therefore, the focus of this work is on early detection of oil releases from the subsea template on the seabed. This area of the subsea installation is critical as it is where a high number of valves and joint points are located. These may be a sensitive location to oil leakages due to both pressure increments during production disturbances and due to mechanical failures. Sensors should be located on the template structure strategically to detect oil releases early. Different types of sensors may be available. The analysis in this paper refers to acoustic oil leak detectors.

The two types of sensors are assumed to work using a fixed value of P_F and varying P_D values to facilitate comparison. This takes also into account the fact that the sensor threshold for a local decision is usually set according to P_F constraints (Ciuonzo and Salvo Rossi, 2017). The P_F is set equal to 10^{-2}. However, the sensors have different ROC curves and this results in different P_D. We consider sensors with different performance: type A, with P_D equal to 0.90; type B, with P_D equal to 0.50 (Salvo Rossi et al., 2016). As the detection performance determines the cost of a sensor, the study assumes that sensor type A is more expensive than B.

5.3. Definition of measures of effectiveness, according to the SE approach

In the present work, three indicators of effectiveness are defined, as follows:

- Number of true positive, i.e., number of small HC releases recorded (Ind_1);
- Number of false negative, i.e., number of HC releases not detected (Ind_2); and
- Number of false positive, i.e., number of false alarms (Ind_3).

These indicators measure the performance of the sensor network with the purpose to monitor the sensor performance and they are identified based on measurability of sensors characteristics.

The small HC releases that did not develop into a major release are defined as *near misses*. Their tracking helps the operator understanding how and why they have occurred, taking corrective actions and prevent similar – or more serious – incidents from happening in the future. Near-misses are recorded and stored in the Ind_1. The analysis of near misses provides an overview of both what happened and what could have happened. The sensors' duty is to react to small HC amounts leaking from the X-Tree and from the wellhead. Alarms have to be triggered immediately and notification has to be sent to the operator. Every time the release is stopped before developing into a major release, a record is tracked. Anytime the sensors fail at detecting the releases, the fault logs registers are updated with false negative records (Ind_2). This value, to some extent, represents the reliability of the sensor. For the same reason, the cases in which the sensors erroneously signal a HC release are tracked (Ind_3).

Indicators are furthermore grouped into three categories: outcome indicators, early warning indicators and resilience indicators (Thieme and Utne, 2017). Outcome indicators reflect failures of desired safety outcomes. Accidents, incidents and small leaks are included in this category. Early warning indicators reflect critical barrier element performance, and they complement the resilience indicators, whom instead are not related to safety barriers. Early warning indicators provide information on the quality of the adopted safety barriers. Ind_1 belongs to the outcome indicator category while Ind_2 and Ind_3 are classified as early warning indicators.

Table 2 summarizes the information about Ind_1, Ind_2 and Ind_3.

5.4. Definition of requirements, functions and system architecture

In the following subsections, the requirements, functional and architectural analyses are developed in detail.

5.4.1. Requirement analysis

The detection system must satisfy the requirements set by the standard for oil detection in subsea template RP-F302 (DNV GL, 2016). The standard sets qualitative requisites for the subsea leak detection system that must be satisfied. First, the BAT approach for leak detection has to be selected. RP-F302 requires a two-steps BAT process where firstly the single techniques are assessed, and then different configurations are compared to identify the most efficient, in terms of cost and risk reduction.

The F302 recommended practices does not provide straightforward guidelines for the positioning of subsea leak detectors. Different configurations have to be assessed, as well as redundancy margins. The main purpose of the subsea network is to strain the detection of oil releases to the unitary value.

5.4.2. Functional analysis

The main function of the subsea sensor network is early detection. Second, the system is required to locate the leakage source in the subsea template. The localization of the release is done by tagging the sensors. Two different areas may be identified subsea: the templates and the flowlines (including both the fixed line anchored to the seabed and the flexible risers). Every template includes more than one wellhead and X-tree. The detection is performed by exploiting different physical

Table 2
Indicators characterization.

	Ind_1	Ind_2	Ind_3
ID.	Number of small hydrocarbon releases recorded	Number of hydrocarbon releases not detected	Number of false alarms
Desired safety goal	Taking corrective actions and preventing similar, or more serious, accidents from happening in the future	Sensor monitoring the release of hydrocarbon from the X-Tree should work continuously during production and defect faults if they occur	Keep tracking of time the sensor was wrong in detecting a no leak scenario
Critical elements	Sensor sensitiveness and alarm responsiveness	Sensor adequateness and threshold value to trigger the alarm	Threshold value to trigger the alarm
Data requirements	Detection threshold	Definition of critical sensors and identification of associated faults	Detection threshold
Data sources	Manual identification of leakage and comparison with fault logs	Fault logs	Fault logs
Sampling intervals	Production phase	Production phase	Production phase
Actions	Identify causes to the release, implement necessary measures against reoccurrence and repair	Identify the contributors to decreased performance, identify causes, and implement measures against reoccurrence	Identify why the sensor is giving a false signal, turning off the alarms, stop emergency procedures
Resilience attribute	None (outcome indicator)	Information about barrier quality	Information about barrier quality

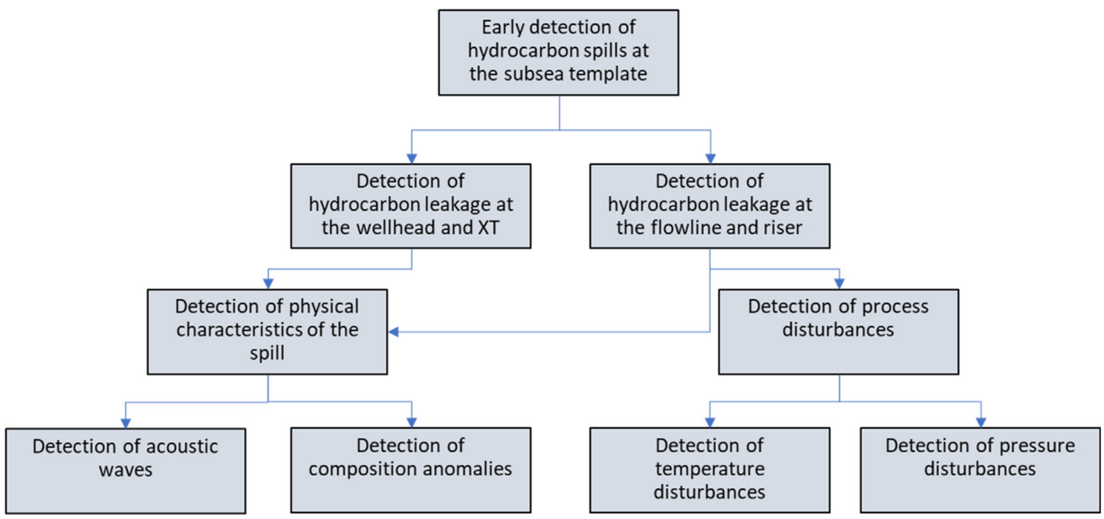

Fig. 5.1. Functional analysis for subsea detection system.

characteristics of the oil release. Particularly, different types of sensors detect different spill characteristics. Capacitive sensors are in place to reveal composition anomalies in the template area. Acoustic sensors detect the acoustic noise of the oil release in the subsea templates and flowlines. Process sensors, as pressure and temperature sensors, reveal possible disturbances in the process flow. The functions identified for the subsea detection system are summarized in the graph of Fig. 5.1.

Referring to Fig. 5.1, it is worth highlighting that the present work refers to the subsea wellhead and X-Tree (left side in the tree diagram). Moreover, the study focuses solely on the acoustic wireless sensors distributed on the template.

5.4.3. Architectural analysis

The functions identified for the subsea detection system described in Section 4.4.2 must be translated into hardware and software components. The physical elements needed for the detection of HC leakage at the subsea wellhead and X-Tree are different type of sensors, the subsea control module and the router to the topside. Fig. 5.2 (adapted from Røsby (2011) shows the basic elements of the subsea detection system.

As described in Section 4.1, the oil spill emergency response involves a large spectrum of stakeholders and therefore the definition of different roles and communication patterns is of paramount importance.

Fig. 5.3 shows the relationships between some of the different primary stakeholders (adapted from Bjørnbom (2011)).

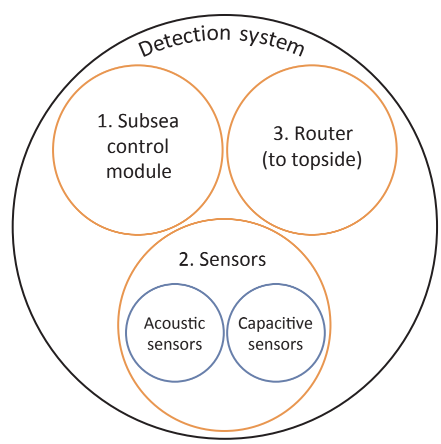

Fig. 5.2. Detection system for the wellhead and X-Tree.

5.5. Trade-off analysis: Application of SE to subsea risk management

Through the trade-off analysis the performance of the detection system is evaluated for different sensor configurations to determine if it is able to:

- Improve subsea safety by monitoring HC releases and reduce the risk of large oil spills by early detection;

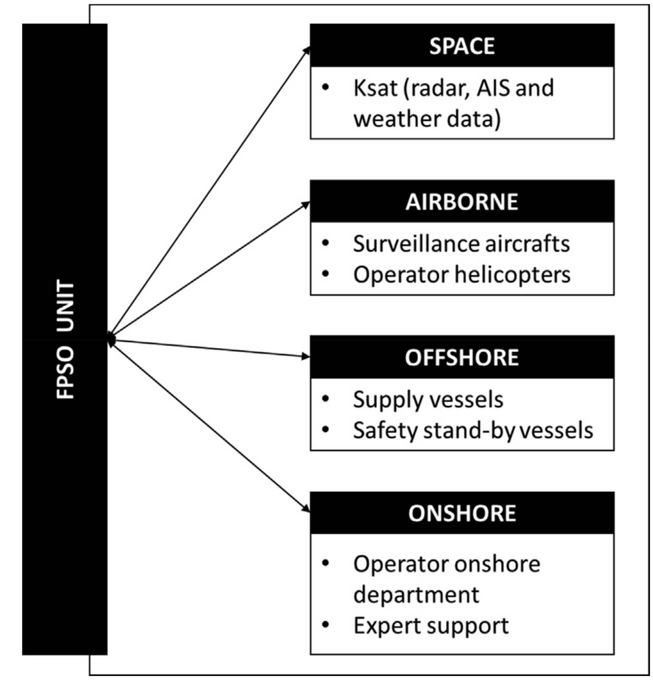

Fig. 5.3. Communication patterns for subsea leak detection preparedness (Adapted from Bjørnbom (2011)).

- Reduce the environmental impact by controlling the released HC quantities;
- Reduce the ROV inspections.

Two different configurations of sensors are considered for the network. The first configuration includes one single sensor for each grid cell defined in the sensed environment (namely, single configuration). In the second distribution, redundant N sensors monitor the presence (or absence) of the target (namely, redundant configuration). Fig. 5.5 is shown as representative. The case study compares the detection performance using acoustic sensors with different characteristics (type A and B, see Section 5.2). The subsea manifold and template is the monitored environment of this study. One single cell grid is assumed for the monitored environment.

The oil release trend considered in this analysis is shown in Fig. 5.4. The release behaviour has been adopted for demonstrative purposes. The release is considered as a binary event, and its value is set as 1 in case of presence and as 0 in case of absence. The transition between the two states is modelled as instantaneous. The sensors detect noises from the subsea template and they record them above a defined threshold. Some oscillations are due to random pressure variations in the reservoir. In those scenarios, the pressure is controlled and it is reset to its optimal value without any type of intervention from the topside. This trend may also be due to some slightly overpressure scenario developing during the early years of production, when the pressure in the reservoir is higher (Kansas Geological Survey, 2000). The oscillations may result in fatigue on mechanical components and they may induce the mechanical failure of some valves of the X-mas tree and wellhead. In that case, the template is leaking steadily and it needs dedicated inspections and interventions from the topside. From the generated release trend, it is possible to know the a-priori probability of presence or absence of the release.

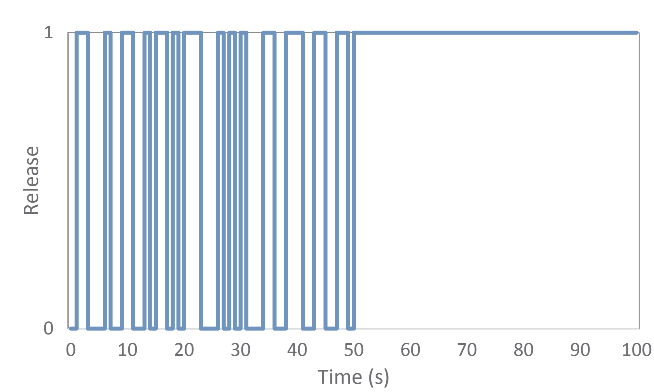

Fig. 5.4. Assumed target trend for the present analysis.

The detection performance of the two sensor types are described in Section 4.2. Referring to Fig. 5.5, three different configurations are defined, respectively, using 4, 8 and 16 sensors in a redundant scheme for each grid node. The sensors are located to cover the detection of the entire grid cell. Their local decisions about the presence or absence of oil releases are sent to the FC. The number of sensors for each grid cell is chosen to improve the network performance and to match (or exceed) the detection probability obtained with a single type A sensor. In the present analysis, the number of type B sensors equal to 4 guarantees the detection performance comparable to a single type A sensor (Bucelli et al., 2018).

The CFR is applied as fusion rule to the FC. The threshold for the CFR is set as 1, i.e., it is sufficient that the FC receives one positive signal about the presence of a release from the detection at the template, to give a positive signal transmitted to the control room. The detection performance of the three configurations are summarized in Fig. 5.6 Fig. 5.7 in terms of ROC curves.

Figs. 5.6 and 5.7 represent the ROC curves for the different sensor configuration and for the different sensor types, respectively. They describe the detection performance of the sensors/configurations. Fig. 5.6 shows the ROC curves for the three different cases using 4, 8 or 16 redundant sensors. They describe the detection performance of the different sensor configuration. Panel A refers to Type A sensors cases while panel B to Type B. The x-axis is logarithmic and represents the probability of false alarm while the y-axis is linear and shows the probability of detection for each case. Fig. 5.7 represents the ROC curves for sensors Type A and Type B. The three different panels show the detection performance of the two sensors in the three different configurations, specifically panel A represents the 4-sensor configuration, panel B the 8-sensorcase, and panel C 16-sensor case. The x-label is logarithmic, and it shows the probability of false alarm, while the y-label is linear and it represents the probability of detection for each sensor.

As shown in Fig. 5.6, the use of redundant configurations for the expensive (Type A) sensors does not result in a significant increment of detection performance. For the cheap (Type B) sensors, the findings define something different. Panel B of Fig. 5.6 demonstrates that the use of many redundant sensors results in improved detection capabilities. The increment in detection performance is more and more evident with the increment of the number of sensors in the network. The network constituted by 16 Type B sensors shows detection performance close to the redundant configurations of 8 and 16 Type A sensors (Fig. 5.6, panels A and B). Nevertheless, the use of redundant Type A sensors is not proven to be effective for improving the detection capabilities. From panel A in Fig. 5.6 it is evident that the detection performance change sensibly from the configuration of 4 sensors to the configuration of 8, but more than 8 detectors is demonstrated not to be more feasible. The ROC curves in these cases are saturated and they show a trend to fall on each other.

It is worth noticing the conservative approach adopted in the fusion rule. The FC makes a global decision about the presence of the oil leak in the case *at least* one single detector emits a positive signal. That justifies a global P_F for the redundant configuration four times higher than the single value.

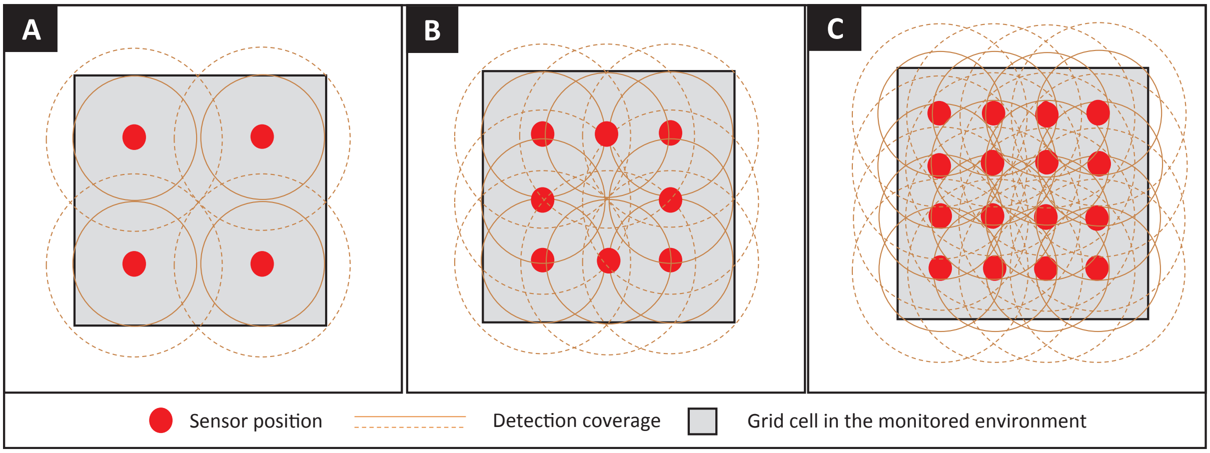

Fig. 5.5. Sensor grid in the monitored environment. Panel A: 4 redundant sensors per grid cell; Panel B: 8 redundant sensors per grid cell; Panel C: 16 redundant sensors per grid cell.

5.6. *Step 6 – Test*

The final step is to implement a feasible network configuration and test its performance. This is beyond the scope of this study and therefore not further discussed.

6. Discussion

SE has been used in the paper to identify the needs and interests of different stakeholders regarding subsea oil leaks and to transform these needs into requirements to subsea detection. Further, the process has been used as a systematic process to develop the sensor configuration alternatives, to analyse these options, and perform trade-off analysis focused on investigating the measures of effectiveness. The main advantage of using such an approach is that it covers the important steps that should be followed for developing relevant design options, perform analyses, and evaluate trade-offs. As such, the SE approach ensures that the relevant requirements to the sensor detection system were identified and formulated, with applicable measures of effectiveness, and that the sensor configuration alternatives were developed and analysed systematically.

Reliable detection systems are key in early detection and response to subsea HC releases. The increment in the false alarm probability may affect negatively the communication and relationships among the organizational levels described in Fig. 5.3. For instance, false alarms may result in unnecessary and unplanned ROV inspections and unplanned shut-down with high operational costs. Improving information management and gathering is fundamental for better risk understanding, risk management, and better operations.

Increasing the number of sensors in the network result in improved performance. For example, assuming that the value of Q_F is set to 1E-05 and referring to the ROC curves of Fig. 5.6, particularly panel A (but same conclusions could be made for the other panels), we can see that:

- For a sensor network made up of 4 sensors, the Q_D is 0.4 (circa);
- For a sensor network made up of 8 sensors, the Q_D is 0.8 (circa); and
- For a sensor network made up of 16 sensors, the Q_D is 0.99 (circa).

In other words, if the Q_F of 1E-05 is acceptable, with 8 sensors, the network will be able to detect a release in 80% of the cases.

The same discussion can be made considering a set value for Q_D. The more sensors in the network, the lower the Q_F.

The CRF adopted at the FC is a simple fusion rule that does not need any *a priori* knowledge of the system. It is not able to locate the release and therefore a more sophisticated decision rule should be implemented. The sensor placement should be investigated and optimized to guarantee early detection and to track the spilt oil movement.

According to the results of the performed analysis, the number of missed detections is lowered in the redundant configuration. Coupling the signal from the FC and pressure data it is possible to identify and distinguish if the release is due to well fluctuations or mechanical failures. This allows to record early warnings and to use them for risk management.

The coupling of information from acoustic sensors and other sources (for instance capacitive sensors, but also process ones) might be convenient to improve the subsea risk management, but it has not been considered in this study.

Increasing the Q_D by increasing the number of sensors should be considered over cost and maintenance, besides risk considerations.

The SE process is an iterative stepwise procedure that starts with understanding the problem and its importance, which thereafter forms the basis for developing requirements and specifications to system design, to perform analyses of the different design options, and to select the most optimal design configuration through trade-off analysis. The use of the SE process in this paper ensured a systematic and holistic approach to determining the needs for subsea leak detection for different stakeholders, to derive the alternative sensor configurations, and to analyze their performance in light of the measure of effectiveness.

A better level of knowledge about what is happening below the sea surface helps in improving risk management and mitigates emergency situations. The level of knowledge about a given system or operation is a key factor in the risk definition of Aven (2014) and in risk management.

Tracking of different configurations of sensors should be analysed in order to identify an optimal sensor configuration able to improve the detection performance. This would also result in more reliable information to provide the DRMF. The sensors' network performance characteristics can be used in updating dynamic fault tree to update the information about the frequency of system deviations.

The functional placing of the sensors in the fault tree structure is not covered in this analysis anyway, but it is considered further development of this study.

The modelling of the HC release constitutes an uncertainty of this study. Uncertainty is not investigated in the analysis but might be the subject for further work.

7. Conclusion

The cost of a sensor is driven by its sensitivity, i.e., for this specific case of subsea oil detection and the capacity of detection of small leakage ratio. The leakage ratio set as threshold for a sensor defines its

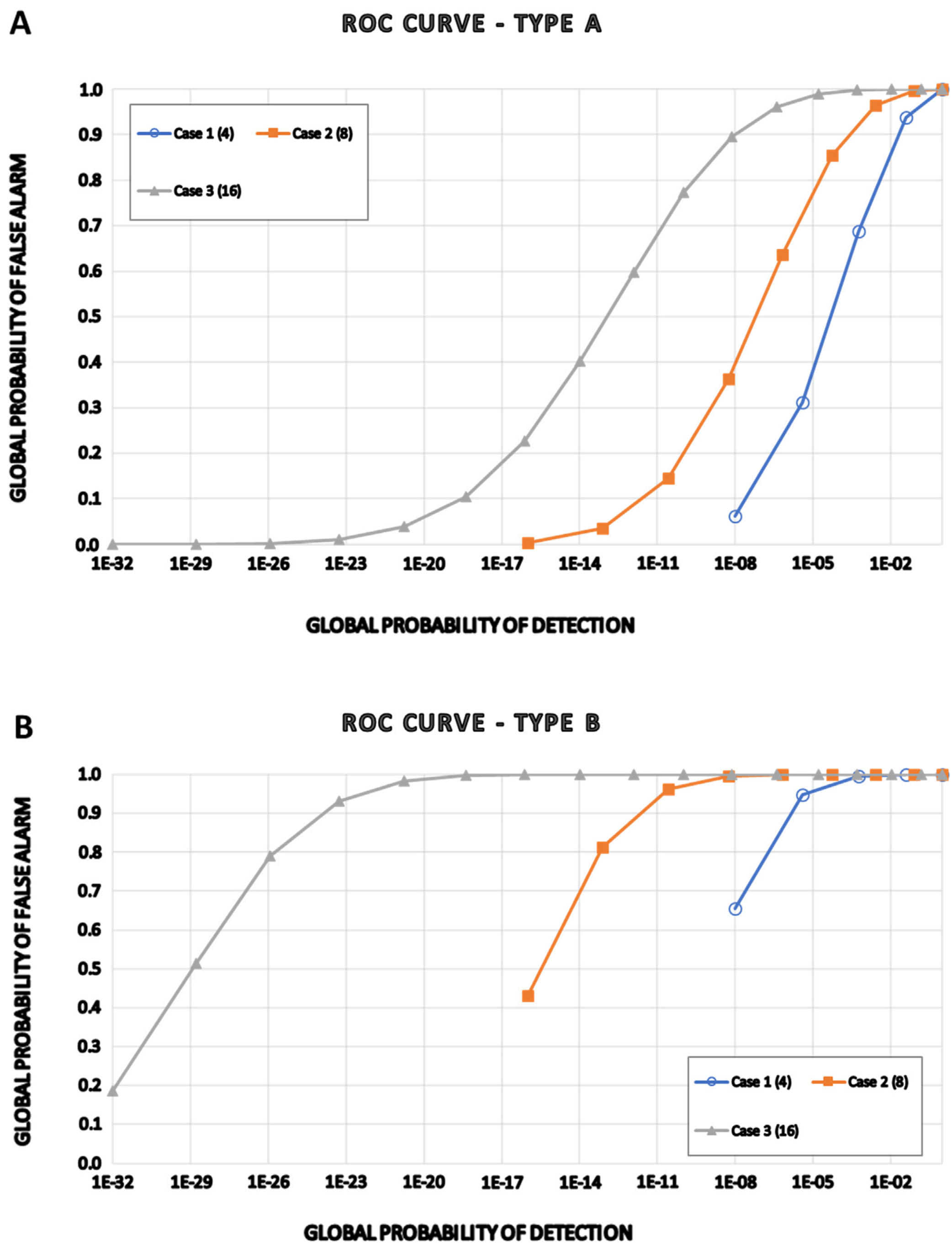

Fig. 5.6. ROC curves for the three different configurations (4-, 8-, 16-sensors). Panel A) refers to type A sensors, while Panel B) to type B sensors.

sensitivity and therefore its cost. Highly sophisticated sensors result in substantial costs but guarantee high performance and detection reliability.

This work demonstrates how the early detection of oil leakages from subsea manifolds can be performed using lower cost sensors arranged in strategic networks with redundant configuration in a defined monitored environment.

This study represents a further development and advancement of a previous study in this field (Bucelli et al., 2018). However, dedicated and specific studies applying different and more sophisticated decision fusion rules have been included in the present study to improve the reliability of the information from the subsea sensor network. The decision about the presence or absence of oil spilt into the sea from the subsea template determines the need for intervention from the topside. The communication patterns for oil and gas facilities are complex and they involve different stakeholders, internal and external. A reliable subsea detection system may reduce unnecessary interventions and management tasks of the company. Every intervention to the subsea templates from the topside requires substantial costs that may be reduced with a reliable basis of information.

The monitoring through the distributed detection system of the subsea template represents one of the key steps in the DRMF for the update of the risk.

Insights from the results of this paper suggest further investigations to still improve the quality and reliability of data retrieved from the subsea network. The transfer of information from the template to the platform represents the communication step in the DRMF and therefore a crucial gate in the process.

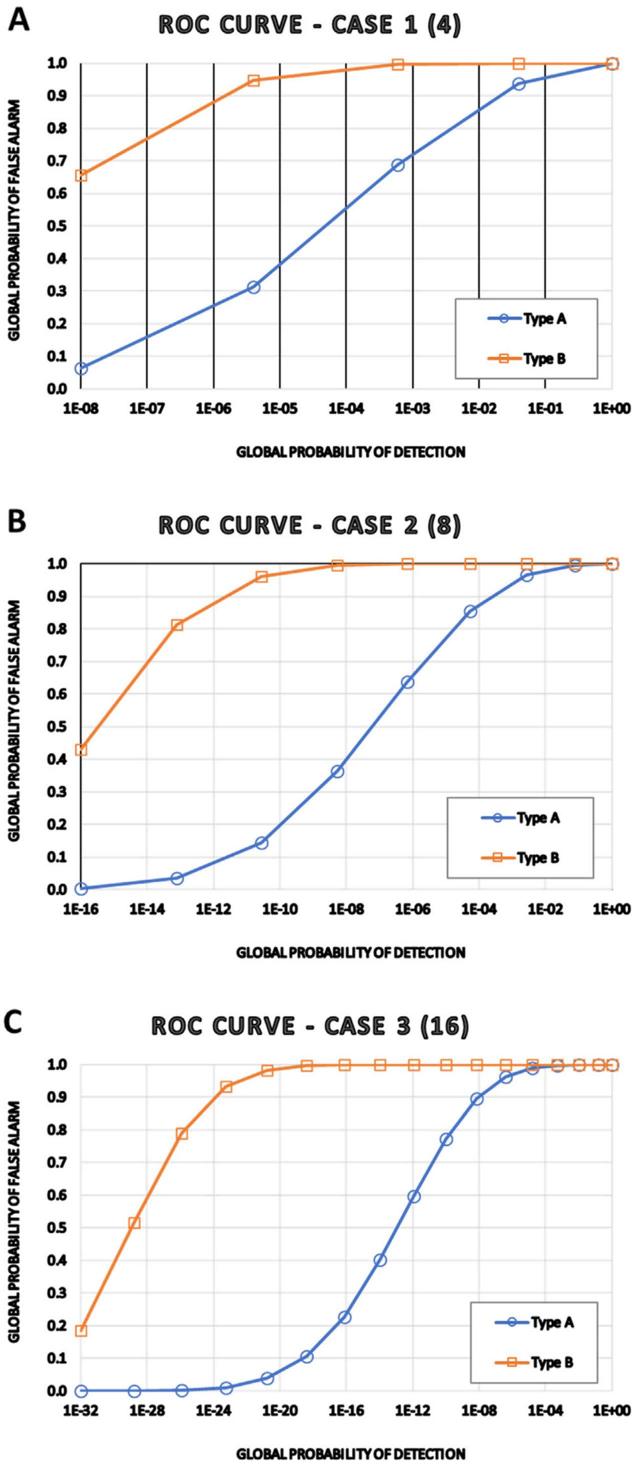

Fig. 5.7. Comparison of ROC curves for the three configurations for sensor Type A and B. Panel A) refers to 4-sensor case, panel B) to 8-sensor case and panel C) to 16-sensor case.

For instance, the FRC could be further developed by using machine learning or Bayesian approaches. The FC itself in this case would be able to recognize unusual signals and outliers that might be the insight of an oil release.

The analysis suggests the investigation of different sensor placement configurations in order to perform early detection and oil leakage tracking. Different configurations of sensors should be analysed in order to identify an optimal sensor configuration able to improve the detection performance. This would also result in more reliable information to provide the DRMF.

The use of more complex fusion rules able to reduce the false alarm situations has to be considered as further development of this study. This approach could be coupled with the one proposed by Paltrinieri et al. (2019) where a deep neural network approach is used in predicting rare events (for instance, major accidents) in drilling units.

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