Safety Barrier Management and Risk Assessment: integration for safer operations in the Oil&Gas industry

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Conventional risk analysis does not provide sufficient information to support the decision-making process in safety-critical systems, such as in the Oil&Gas industry. For instance, safety equipment deteriorates with time, operations may tend to delay or overlap and procedures may be disregarded in special circumstances. The development of such conditions has the potential to increase risk. Appropriate tools are needed to assess and monitor the risk trend, in order to allow for higher safety levels during activities. Potential benefits from iteration of risk evaluation are already well-known to authorities, academia and industry. Relevant regulations require reiteration of risk assessment every 5 years or in case of system changes. Most of the risk management frameworks mention the need for continuous update, but do not go into detail. Moreover, the topic of iteration of risk assessment is gaining momentum in the scientific community, assuming a number of forms and adopting different methodological approaches. This contribution focuses on the enhancement of existing approaches for systematic and quantitative analysis of safety barriers. Barrier management philosophy (as suggested by the Norwegian Petroleum Safety Authority) and quantitative risk assessment are integrated within the Risk Barometer methodology. Such technique aims to reflect how day-to-day status changes of barriers affect the risk level of an installation. Not only technical features of barriers are addressed, but also the whole series of operational and organizational activities aimed at establishing and maintaining them. A relevant case from the petroleum industry is considered for a demonstrative application: a FPSO (Floating, Production, Storage and Offloading) operating in the Norwegian continental shelf. A set of sensitivity analyses allowed evaluating relative influence of safety barriers on the overall risk level, outlining potential intervention priorities. Findings prove the importance of integrating effective and reliable barrier management in the oil and gas industry. The modelling of the safety barriers is a focal point of the methodology, which should be addressed comprehensively, considering not only the equipment but also related operators and organization. The highest criticality is found associated to the safety barriers preventing and mitigating the loss of containment of hazardous substances handled at the installation, resulting in human and environmental risk increase. For this reason, special attention should be dedicated to this class of barriers. Combining real-time information on safety barrier performance and risk analysis evaluations, the approach presented has the capability to provide detailed risk pictures, visualizing how risk trend changes over time. Drill-down capabilities allow the evaluation of the factors concurring to risk estimation. Performance of safety barriers are visualized and compared in order to define action priorities. For this reason, the results and the approach seem adequate to support operational decision-making.

Keyword: Risk assessment

Introduction

In the last three decades, major accidents in the oil and gas (O&G) industry, as the Longford gas plant explosion (U.S. Chemical Safety and Hazard Investigation Board, 2007), the Buncefield vapour cloud explosion (HSE, 2011), and the Deepwater Horizon well blowout (BP, 2010; Deepwater Horizon Study Group, 2011), point out the need of major safety improvements. For instance, from investigation about Macondo blowout conducted by Tinmannsvik et al. (2011), the failure in performing risk evaluation during operations and the inadequate verification of safety barriers are recognized as most important underlying causes.

Conventional techniques for quantitative risk analysis (QRA) suffer from a series of limitations highlighted by several studies and, in the extreme cases, by accidents (Hopkins, 2000; U.S. Chemical Safety and Hazard Investigation Board, 2007; BP, 2010). Risk quantification obtained using QRA techniques is normally static, failing to capture the variation of risks during the lifecycle of a production plant (Landucci and Paltrinieri, 2016).

Conventional QRA studies provide risk pictures showing the overall risk level of a production facility. They represent a good basis for making decision of significance, such as those related to design. However, on a long term basis, including plant modification is difficult. Nevertheless, on a short term basis, addressing risk fluctuation over time is challenging. Accidents aforementioned are good examples of these limitations. Understanding the risk picture is an important factor in managing, avoiding or minimizing the risk exposure. These risk variations over time may be evaluated on the basis of barrier performance variations. In turn, safety barrier performance are affected by degradation technical conditions and operational and organizational factors (DNV GL, 2014), as demonstrated by investigation on major accidents (Summerhayes, 2011).

These are features that are not effectively addressed in classical QRA, which presents the risk level as an average of all these factors. Notwithstanding, making operative decision relies on real-time data and this highlights the necessity of new risk assessment methods that are dynamically adaptable (Khan et al., 2016) and that may provide support during operations. To provide a good support basis during operations, risk assessment techniques should visualize effectively how safety barrier performance affect the risk level (Paltrinieri and Hokstad, 2015).

The Center for Integrated Operations (IO) in the Petroleum Industry aimed to develop new methods and tools for the integration of people, organizations, work processes and disciplines. In this context, the Risk Barometer concept was proposed for real time monitoring of major accident risk. This approach aims to support the process of decision making both in the engineering and operational phases, combining real time information about safety barriers with knowledge from risk analysis. The final output is the assessment of how the risk picture varies over time (Hauge *et al.*, 2015).

The analysis hereby proposed shows how the risk barometer approach applied to a barrier management framework could provide the user with a dynamic risk picture for daily decision support. In the next chapter, main definitions about barriers and barrier management adopted in this research work are described. Furthermore, a general overview of the risk barometer technique is presented and applied to a real case study from the offshore oil&gas industry. The case study is of particular concern since the facility considered is located in an environmentally sensitive area.

Barriers and Barrier Management

Main definitions about barrier

According to Sklet (2006) safety barriers are means planned to prevent, control or mitigate undesired events or accidents. They may be single technical units or complex engineered systems involving also human actions and interventions based on specific procedures or administrative controls (Andersen *et al.*, 2004). Safety barriers must be kept in a functional state and their use must be ensured by organizational measures (requirements for e.g. maintenance, inspections and qualifications) (Duijm *et al.*, 2003). The task or role of a safety barrier is described by the barrier function. Examples include preventing leaks or ignition, reducing fire load, ensuring acceptable evacuation and preventing hearing damage (PSA, 2013). The barrier system is designed and implemented to perform and maintain one or more barrier functions (Svenson, 1991). In a process plant, for instance, barrier systems related to fire and explosion are usually in place, as fire and gas detectors, emergency shutdown system, fire and explosion walls, passive fire protection, pressure relief systems, evacuation systems and training (Rausand, 2011). Figure 1 highlights the differences between the concept of barrier function and barrier systems.

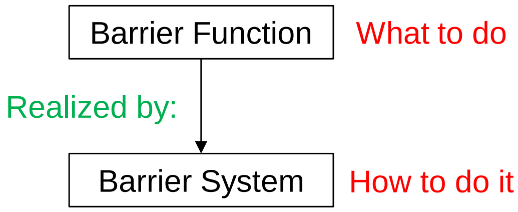

Figure 1. Barrier Function and Barrier System (adapted from Sklet (2006))

Several classifications have been defined for barrier functions. In the framework of ARAMIS project (Andersen *et al.*, 2004), barrier functions have been classified into four main categories described by four action verbs:

1. to avoid;
2. to prevent;
3. to control; and
4. to protect.

Category 1 aims at suppressing all the potential causes of an event by changing the design of the equipment or the type of product used. For instance, the use of a non-flammable product is a way to avoid fire (Duijm *et al.*, 2003). Category 2 aims at reducing the probability of an event by suppressing part of its potential causes or by reducing their intensity. For instance, better steel grades can be used to prevent corrosion. This is probably not sufficient to suppress an unwanted event, but it may reduce its probability (Duijm *et al.*, 2003). Category 3 aims at limiting deviations from normal situations. For instance, a pressure relief system performs a control function (Duijm *et al.*, 2003). Once an event has occurred, it is necessary to protect the environment from its consequences (category 4) (Duijm *et al.*, 2003). Considering a bow-tie approach and the ARAMIS classification aforementioned, barriers avoiding, preventing and controlling the occurrence of a hazardous event must be placed upstream, while barriers protecting it must be downstream (Figure 3 in Section 5).

Each barrier function is organized into a complex hierarchical structure, graphically represented by means of a "barrier tree", as shown in Figure 4 in Section 5. Barrier elements are the lowest level in the barrier function hierarchy. They are technical, operational or organizational measures or solutions which play a part in realizing a barrier function (PSA, 2013). Definitions (DNV GL, 2014) and examples are listed in Table 1. Barrier elements could be arranged in Safety Instrumented Systems (SIS). A SIS consists in one or more input elements (e.g., sensors), one or more logic solvers and one or more actuating (final) elements (e.g., valves or circuit breakers) (Rausand, 2011). According to IEC 61511 standard (Internationa Electrotechnical Commission, 2003), a SIS implements one or more functions intended to achieve or maintain a safe state for the process, with respect to a specific hazardous event. These functions are defined as Safety Instrumented Functions (SIFs).

Barrier Element Category	Definition	Example
Technical	Engineered systems, structures or other design features which can realize one or several barrier functions (DNV GL, 2014)	Fire Extinguisher
Operational	Tasks performed by an operator or by a team of operators which realizes one or several barrier functions (DNV GL, 2014)	Operating procedure for the (manual) fire extinguisher
Organizational	Personnel responsible for, and directly involved in, realizing one or several barrier function (DNV GL, 2014)	Fire fighter

Table 1. Definition of technical, operational and organizational barrier element.

Barrier management

Barrier management is an integrated part of Health, Safety and Environmental (HSE) management. Its principles were defined in 2013 by Petroleum Safety Authority Norway (PSA) for petroleum industry on the basis of the guidelines described in the risk management standard ISO 31000 (International Organization for Standardization, 2009).

According to PSA, barrier management involves and coordinates activities establishing and maintaining relevant, effective and robust safety barriers. The main purpose is to allow the barriers to perform their function. This, in turn, ensures risk mitigation by preventing undesirable events from occurring or limiting potential consequences (PSA, 2013). The rationale behind barrier management is to capture the complexity of major accident and to reduce the uncertainty (DNV GL, 2014). Figure 2 shows the barrier management model proposed by PSA. Detailed information are reported in (PSA, 2013).

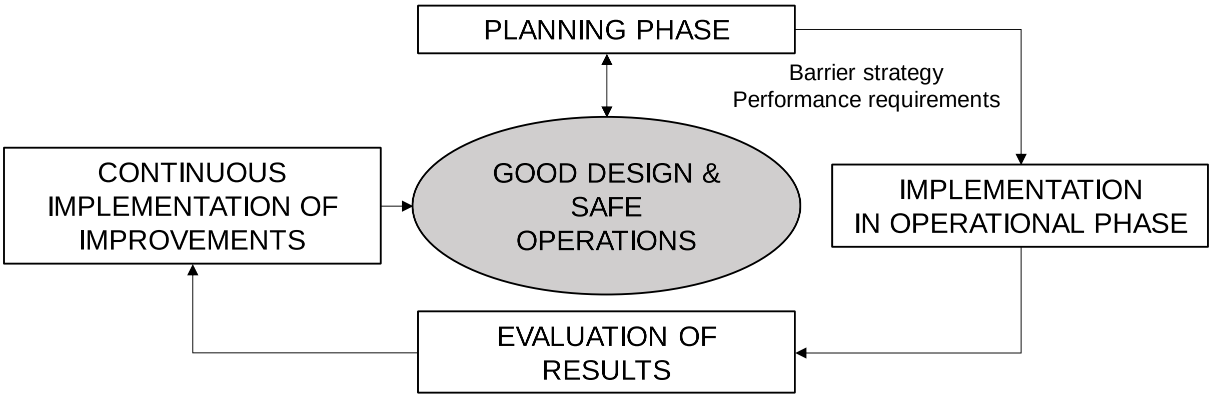

Figure 2. Barrier Management Model (adapted from PSA (2013a)).

To properly manage risk, the necessary barrier functions and barrier elements need to be identified in the planning phase on the basis of the risk picture, in turn based on QRA studies. The result of this process lays the foundation for barrier strategy, according to the PSA definition (PSA, 2013). Furthermore, performance requirements are established so that the barrier functions can be realized as intended. Generally, performance requirements are stated for barrier elements, but sometimes also for barrier systems and functions (Vinnem, 2014). According to the Management Regulation (PSA, 2001), personnel shall be aware of what barriers have been established, the functions they are intended to fulfil and the performance requirements that have been defined in respect to technical, operational and organizational elements.

Barrier management is not confined to the engineering phase, but it also involves follow-up and improvement of barriers throughout the entire life cycle of the facility, including the execution of every activity during operational phase. Barrier management implementation throughout operations is strongly dependent on the planning phase barrier analysis. However, a common critic (Vinnem, 2014) regards the limited connection between the risk (and barrier) management in the engineering and in operational phases.

To deal with risk over time, barrier conditions must be monitored (PSA, 2013) and therefore indicators are essential (Vinnem, 2014). They may represent early deviations from the ideal situation leading to further escalation of negative consequences (leading indicators) or may provide essential feedback from the system (lagging indicators) showing when a desired safety outcome has failed or has not been achieved (Paltrinieri and Khan, 2016). Suitable sets of indicators should be collected and evaluated. These should be able to describe not only technical factors affecting barrier elements performances, but also operational and organizational ones, as their importance has been recognized by several accident investigations (Lord Cullen, 1990; Hopkins, 2000). As suggested by PSA (PSA, 2016), industry should acquire a better understanding of operational, organizational, and technical barrier elements, and on their interactions and how these may affects the overall risk level. Once the established barrier strategy and performance requirements are actively implemented the operation phase through the monitoring of indicators, results may be evaluated and implemented in a typical control loop fashion (Vinnem, 2014), as shown in Figure 2.

The risk level of petroleum activities in the Norwegian continent shelf (NCS) is evaluated since 1999 within the PSA's RNNP project. This has become an important management tool for all stakeholders in the oil&gas sector. Its aim is to measure and improve health, safety and environmental conditions. RNNP Project focuses on personal risk and environmental factors, including major accidents, work accidents, working environment factors and acute discharge. The results are presented in an annual report. Risk data related to acute oil and chemical spills are provided in a separate report. The RNNP Project plays an important role in the industry by contributing to a shared understanding of risk evolution by companies, unions and government agencies.

Reference installation

Description of the facility considered

The O&G industry is focusing its attention on the Arctic and Sub-Arctic regions, as they represent promising production sources. According to the U.S. Geological Survey, 13% of global undiscovered oil and 30% of the world natural gas are located in the Arctic (Gautier *et al.*, 2009).

Technical, environmental and social features are challenges of exploring and developing oil and gas in the Arctic. The primary factors that make activities in the Arctic unique are ice, long periods of continuous darkness, cold, remoteness, very little infrastructure, vast distances at sea, and rich, important ecosystems (Norheim, 2010; Royal Dutch Shell, 2011). Due to such severe conditions, operability in the Arctic may be critical, maintenance ineffective and components may easily deteriorate.

The Norwegian Arctic shelf is unique in this respect: the ice does not involve operative problems due to Gulf Stream and the access to infrastructure is not remarkably remote (Norheim, 2010). This area is environmentally sensitive then offshore operations must be conducted with particular attention. The legislative framework for oil and gas industry in the Arctic regions in Norway is one of the toughest worldwide.

There are examples of geostationary Floating, Production, Storage and Offloading (FPSO) units in the subarctic region in the Barents Sea, an area climatically sensitive with increasing maritime activity and scarce onshore infrastructure.

There are advanced cylindrical oil platforms, consisting of multiple subsea templates and wells where oil may be completely treated and stabilized on board, then exported by tanker, while the associated gas re-injected (Rekdal and Hansen, 2015). Such examples of oil platforms are associated with the first oil fields developed in the area and representing the northernmost offshore production facilities worldwide. They are tailored for harsh arctic conditions and they are built for meeting high safety standards.

A representative facility from this area with these features is taken as reference case in the present research study. For this facility, risk of major hazards is qualitatively and quantitatively evaluated both for main areas and for the FPSO as whole. Specific barriers to prevent and/or mitigate risk are established and managed in daily operation. In order to monitor the status of the barriers in place on the installation, the Barrier Status Panel (BSP) was developed (Fornes, 2016). It is a planning, decision-making and risk management tool showing the status of barrier functions (and of each single barrier element) in their area of interest. BPS uses both real-time data from Safety and Automation System (SAS) (e.g. dangerous undetected fault signals, faults and blocking) and daily data from preventing and corrective maintenance. Information are provided both for main areas and for the FPSO as a whole. Examples are shown in Table 2. A total amount of 37 barrier functions has been identified for the considered FPSO (Rekdal and Hansen, 2015). The structure of each barrier function has a high degree of complexity because it may count several hundreds of barrier elements.

Safety Barrier	**Risk Influencing Factor**	**Indicator**
Limit hydrocarbon leak	Performance	Number of failures on demand
		Number of failed tests
	Operational support	Number of persons responsible for monitoring the related control panel
	Maintenance	Number of inspections/audits performed
		Number of functional tests performed
		Portion of maintenance personnel receiving training

Table 2. Examples of performance indicators.

Status of Safety Barriers

In the framework of RNNP Project, trends in the Norwegian petroleum activity for the year 2015 show a negative shift of the major accident risk level in several areas, in contrast with the industry stated focus on HSE (PSA, 2015b). Hydrocarbon leaks and well control incidents are the main significant contributors.

The report concerning environmental factors (PSA, 2015a) also highlights a steady number of large crude-oil spills in the period 2001-2015. However, the total number of acute oil spills and the number of near-misses that could have produced acute oil spills fell in that period. Moreover, the number of incidents has significantly increased in the Barents Sea, in line with the increased activity in that area (PSA, 2015a).

Results show also that some difficulties in meeting the industry requirements for barrier management are emerging (PSA, 2015b). The barrier management philosophy document is relatively recent and there is no commonly accepted practice that could be recommended by PSA (Vinnem, 2014). On the FPSO, barrier management using the BSP implements some simple rules of aggregation at system, barrier function and area levels, without any criticality consideration (Rekdal and Hansen, 2015). Quasi-real-time techniques for dynamic assessment of human and environmental risks may be considered. In particular, the application of the Risk Barometer approach may represent a valuable option in defining a more detailed aggregation structure (Hauge *et al.*, 2015).

Dynamic risk assessment: the risk barometer approach

In the framework of dynamic risk assessment, the center for Integrated Operations in the Petroleum Industry is developing the "Risk Barometer" technique. The technique is influenced by previous analogous methods, such as ORIM (Organizational Risk Influence Model) (Øien, 2001), and Risk OMT (Risk Modelling – integration of Organizational, Human and Technical factors) (Vinnem *et al.*, 2012). The risk barometer technique has been tested on a series of different case-study from the oil and gas sector (Hauge *et al.*, 2015), such as hydrocarbon release scenarios, impact between installation and visiting vessels, loss of containment (LOC) scenarios due to sand erosion-corrosion, well leak and blowout. The aim is twofold, first continuously monitoring the risk picture changes and second supporting decision makers in daily operations (Paltrinieri *et al.*, 2014). The focus is on the analysis of critical safety barriers, allowing for the evaluation of possible risk deviations due to performance fluctuation.

Information about barrier status are provided by means of appropriate sets of performance indicators. Each barrier element is described by technical, operational and/or organizational indicators and, for each of these, measures are collected. According to REWI method (Øien, Massaiu and Tinmannsvik, 2012), examples of technical, operational and organizational indicators are provided in Table 3.

Technical Indicators
Number of overrides of safety systems last months
Number of changes/modifications of technical equipment last month
Average availability of critical safety systems last 3 months
Operational Indicators
Number of feedbacks on procedures tracked in the management system
Number of hours system training last 3 months
Number of internal audits/inspection covering operational safety during last 6 months
Organizational Indicators
Number of procedures not up to date
Number of hot work permits issued in the same time period last month
Number of cases with incorrect use/distribution of roles and responsibilities

Table 3. Example of technical, operational and organizational indicators according to REWI methods (from Øien et al. (2012)).

The impact of the status of safety barriers on the risk picture is evaluated by using a case-specific risk model. The aim is to capture early deviations within the organization which may have the potential to facilitate barrier failure and accident occurrence. Table 4 shows the aggregation model.

Level	Aggregation Rule	Description
Indicator	$Ind = \mathrm{X}$	For each barrier element measure, indicators are collected. They are ranked on a scale from 1 to 6.
Element	$S_{El,i} = \sum_{h=1}^{N_h} w_{Ind,\mathrm{h}} \cdot Ind_h$	For the generic i-th barrier element, the degradation status, $S_{El,i}$, is evaluated by weighted summation of N_h indicators. Weights $w_{Ind,h}$ are assigned by means of Zipf's law (Zipf, 1949).
Sub Function	$S_{SF,j} = \sum_{k=1}^{N_k} w_{El,\mathrm{k}} \cdot S_{El,\mathrm{k}}$; $w_{El,\mathrm{k}} = \frac{1}{N_k}$	The degradation status of the j-th sub function, $S_{SF,j}$, is evaluated by weighted summation of the degradation status of N_k barrier elements constituting it. Weights $w_{El,k}$ are assigned as uniform.
Barrier Function	$S_{BF,l} = \sum_{m=1}^{N_m} w_{SF,\mathrm{m}} \cdot S_{SF,\mathrm{m}}$; $w_{SF,\mathrm{m}} = \frac{1}{N_m}$	The degradation status of the l-th barrier function, $S_{BF,l}$, is evaluated by weighted summation of the degradation status of N_m sub functions constituting it. Weights $w_{SF,m}$ are assigned as uniform.

Table 4. Aggregation rules defined for the risk barometer application (adapted from Paltrinieri et al. (2016)).

According to the aggregation model defined in Table 4, the probability of failure of the k-th barrier function, $FP_{BF,\mathrm{k}}$, is estimated from the retrieved degradation status, $S_{BF,\mathrm{k}}$, considering a direct proportionality law.

The Risk Barometer is a stand-alone tool, it means that it does not modify the quantitative risk assessment of the installation under examination, but it shows how its risk level changes over time because of safety barrier performance variations and it supports critical decision making allowing risk-informed decision-making. Further information about the technique may the retrieved elsewhere (Hauge *et al.*, 2015; Paltrinieri and Khan, 2016).

Application of the risk barometer to the reference installation

The Risk Barometer procedure has been applied to the reference case described in Section 3. The bow-tie diagram shown in Figure 3 represents the overview of multiple plausible scenarios considered in the case study. Each barrier function represented in the bow-tie diagram in Figure 3 has a complex hierarchical structure, as widely described in Section 2.1. For instance, the structure of barrier function "Limit Size" of hydrocarbon leak is partially shown in the following Figure 4 (adapted from Rekdal & Hansen (2015)). The aggregation model shown in Table 4 could be applied to the structure described in Figure 4. The final element status is evaluated by weighted summation of collected indicator measures. The status of the higher level in the hierarchical barrier structure, as SIF and sub-functions, is fixed by considering a uniform weighting system. The barrier function status obtained according to this aggregation model is related to the probability of failure on demand (PFD) of the safety barrier. Then, it is possible to evaluate the effect of the new value of PFD on the overall risk level of the installation.

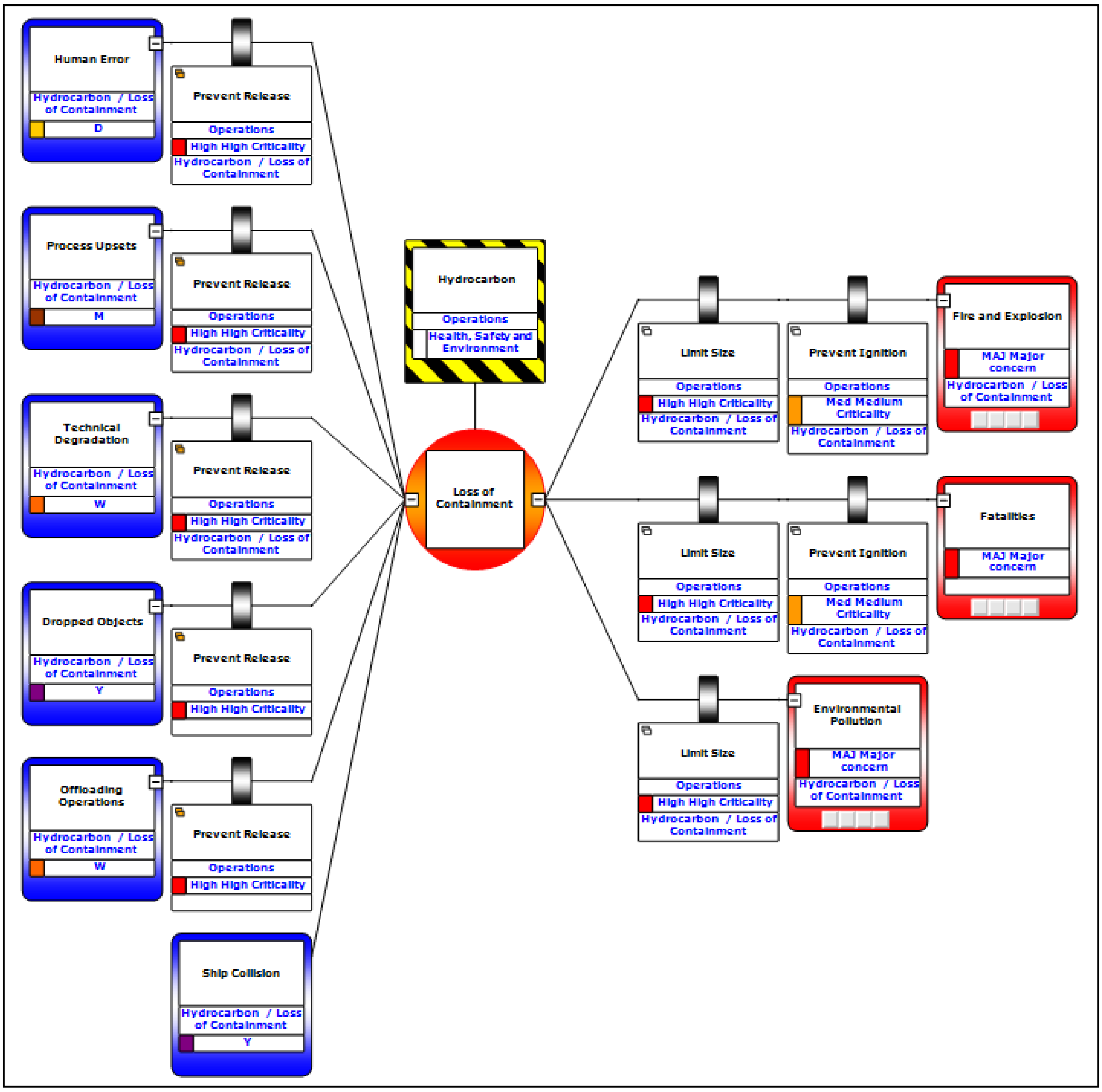

Figure 3. Bow-tie diagram concerning the case-study.

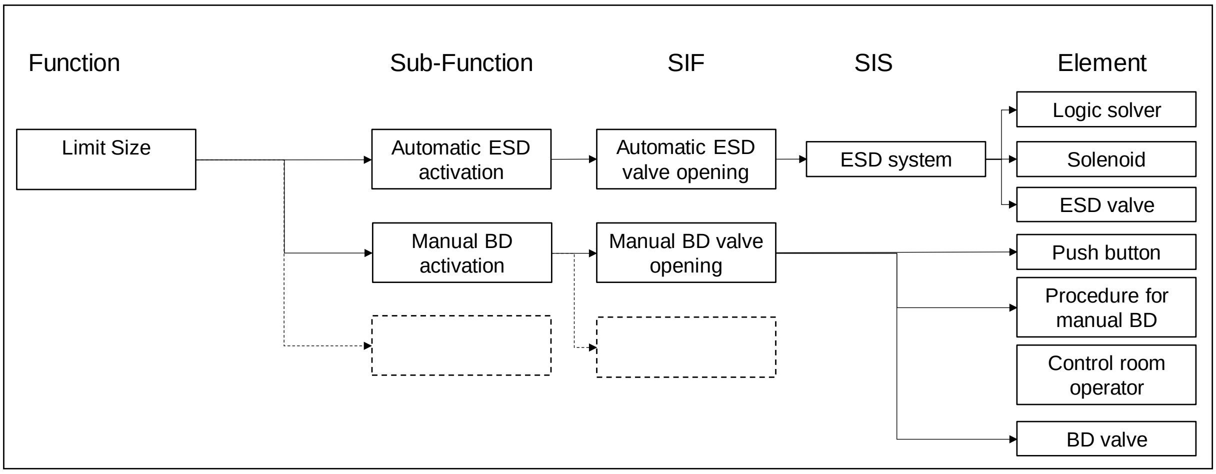

Figure 4. “Limit Size” of hydrocarbon leak barrier function (adapted from Rekdal & Hansen (2015)).

Results and Discussion

In the following, the results obtained from the application of the risk barometer approach to the reference case study are described. As highlighted in Section 2, each barrier function is constituted by some hundreds of barrier elements. Monitoring each one of them should be not possible as well as a waste of time and resources. Furthermore, measuring the status of a large number of non-critical barrier elements does not provide more information rather than measuring the status of a limited number of critical ones. These last are elements that severely affect the risk level of the installation. Then, firstly critical safety barriers have to be identified. In quantifying the effect of fluctuations of barrier performance on the risk level, at any level in the hierarchical structure, a series of sensitivity analyses has been performed.

Sensitivity analyses at the upper level in the barrier hierarchy show that the barrier function “Prevent Release” is the most critical for both fatalities and environmental pollution end consequences. This barrier is identified by the “high criticality” tag in the bow-tie in Figure 3. The same criticality level has been assessed for barrier function limiting the size of the hydrocarbon loss of containment.

Among the critical barrier elements, according to sensitivity analyses, the most crucial are the valves of the Emergency Shut Down (ESD) system. These components are shared by both barrier functions preventing and limiting the release of hazardous substances, according to the bowtie representation of Figure 3.

Performance of critical elements are collected by means of technical, operational and organizational indicators and aggregated according to the rules shown in Table 4 in the hierarchical barrier structure from the bottom until the top, represented by barrier function level.

In modelling of ESD valves performance both operational and technical barrier measures are addressed, due to the large influence they have on the overall performance. This influence could not be neglected especially considering that the valves of the ESD system are identified as critical from safety point of view by a series of sensitivity analyses.

The following Figure 5 shows the degradation status trend for a generic ESD valve considered in the modelling. Figure 5 also shows the trend of the operational and technical indicators collected. Their values are aggregated using the Zipf’s law, according to the model of Table 4. The model is tested using typical indicators trends retrieved for the oil&gas industry, as no real data were available.

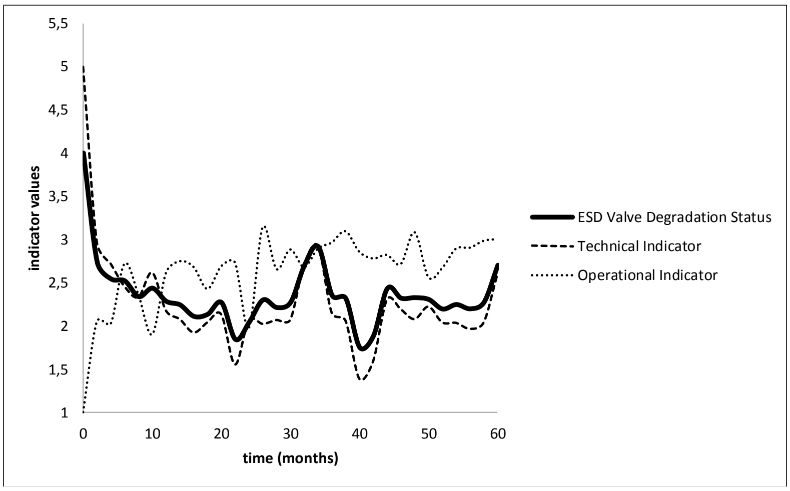

Figure 5. ESD Valve Degradation Status and Technical and Operational Measure Indicators Trend.

The risk picture obtained from the application of risk barometer method reflects the risk variations over time due to valves safety performance fluctuations, described in Figure 5. The ESD valve degradation status of Figure 5 is set in the aggregation model of Table 4. This allows the evaluation of variations of the degradation status of each barrier system represented in the bowtie of Figure 3 due to ESD valves performance. The probability of failure of the barrier is then set in the bowtie and the outcome frequency is evaluated.

The risk picture variations are shown using an easy-understanding format adopting traffic light analogy. In Figure 6 the risk trend variation over time is shown. Risk related to human fatalities is expressed in terms of potential loss of life (PLL), which represent the expected number of death per year. Findings are related to ESD valves performance variations, modelled addressing both technical and operational indicators as described in Figure 5. Analogous results are obtained for acute environmental pollution scenario. Figure 6 shows in the right hand the adopted risk barometer visualization format. It represents the simulated Risk Barometer indicating the risk level expressed as PLL for the last value of the simulation. The trend shown in Figure 6 proves that the Risk Barometer is a tool potentially capable in capturing the real-time information about the most critical safety barriers and translate them into variation of the overall risk picture. The Risk Barometer in this way provides the link between barrier elements status and installation risk level that was missing in the original BPS. In this way, risk trend and deviation are continuously monitored and these information could be exploited and used as a basis for decision support. Operators may evaluate the impact on the overall risk level by analysing the barrier conditions and take actions, if needed.

It should be worth noticing that the risk fluctuation represented in Figure 6 and due to the ESD valve system technical and operational performance are of 10^{-7} events per year magnitude order. This is reasonable as barrier systems count of thousands barrier elements as total. Performance variations of a limited group of them should not affect the risk level too significantly.

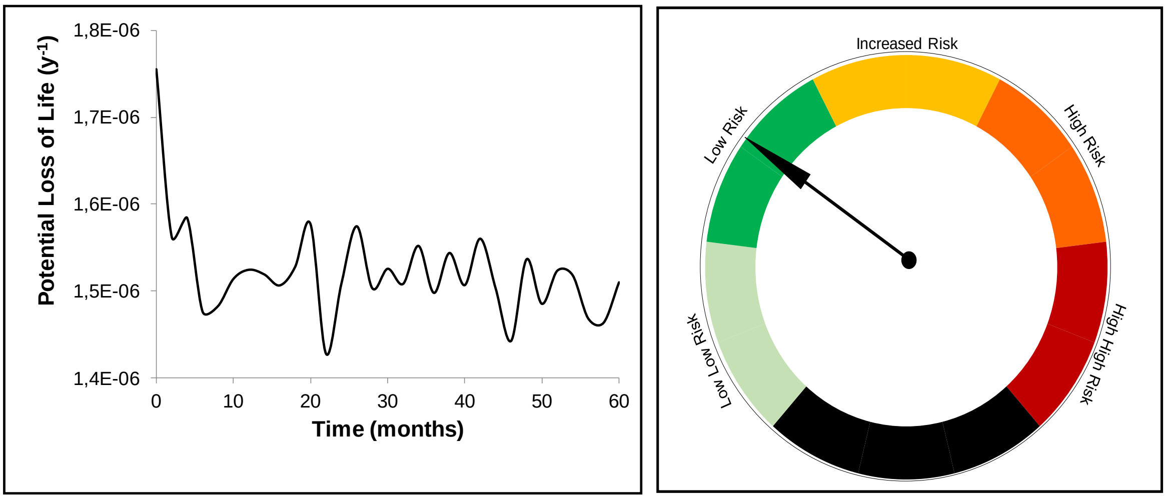

Figure 6. Risk trend related to potential loss of life (y^{-1}) and simulated Risk Barometer indicating the risk level for the last value of the simulation.

Conclusions

As stressed by PSA (PSA, 2013), the integration of risk and barrier management needs to be strengthened in the petroleum industry. The adopted BSP is a quite efficient tool to monitor the single barrier element in place on the installation. It provides a detailed overview of their single status, although the more attention has been on technical elements. In the first development however, simply monitoring the trend of barrier elements status does not provide enough information about the risk level trend. A decreasing trend, for instance, in the number of degraded elements (positive trend) does not necessarily imply a reduction in the risk level associated. That is the reason why additional information about the risk development should be supplemented.

The modelling of the safety barrier is a second main issues. The first phase of the BSP did not included the operational and organizational barrier element but it was limited to the technical ones. On the contrary, operational and organizational factors have a large influence on barrier performance and should be addressed in the risk picture. This is mainly important when modelling particularly critical safety barriers, as the ones preventing the LOC in the case study example. By combining real-time information on technical, organizational and operational safety barrier performance and risk analysis evaluation detailed risk pictures should be provided.

The BSP has no or only a limited link to the risk picture and this emphasizes the added value of using the risk barometer approach. Rules applied in the risk barometer technique and shown in Table 4 are a more sophisticated example of aggregation of data concerning the barrier element status than the BSP. Moreover, performance of safety barriers are visualized and compared in order to define action priorities. The results and the approach seem thus adequate to support operational decision making. However, the risk barometer data aggregation still lacks in addressing common cause of failures and redundancy of systems. These issues should be addressed considering also the high number of elements counted on the installation of the reference case. The large connection of information about element performance suggest the use of new tools and approaches for aggregation. For instance, further developments could be based on neural networks in aggregating information from performance indicators.

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