Building safety in the offshore petroleum industry: development of risk-based major hazard risk indicators at a national level

Xingwei Zhen[a,b,*], Jan Erik Vinnem[b,*], Sturle Næss[c]

a School of Naval Architecture and Ocean Engineering, Dalian University of Technology (DUT), NO-116024 Dalian, China

b Department of Marine Technology, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway

c Equinor ASA, Sandsliveien 90, NO-5254 Sandsli, Norway

ABSTRACT:

There has been an important controversy over whether the series of major accidents at Chinese Bohai Bay in 2011, i.e. the Penglai 19-3 and Suizhong 36-1 oil spills, are a sign of systematic safety problems in the Chinese offshore petroleum industry or a casual result of fortuities. It is hard to obtain the answer unless the national risk level of the offshore petroleum industry is monitored and measured. This paper describes an effort to propose and discuss an analytical approach for the development of major hazard risk indicators that can be used for monitoring, measuring and predicting national risk levels in the offshore petroleum industry. This study focuses on major hazards on offshore installations, hence personal safety hazards that affect individuals are not covered. Firstly, a risk-based approach for developing major hazard risk indicators on offshore installations is developed. Both leading and lagging major hazard risk indicators on offshore installations are suggested. After that, the proposed analytical approach is tested by the risk assessment results of the Norwegian Continental Shelf (NCS) in the latest ten years (2007-2017). This is followed by a discussion on suitability and challenges of the proposed risk-based approach. It has been demonstrated that the results of this study can provide a realistic and jointly agreed major hazard risk picture in the offshore petroleum industry.

Keywords: Major hazard; Risk indicator; Offshore petroleum industry; Risk assessment; Barriers; Precursor events

1. Introduction

1.1 Background

The Chinese Bohai Bay oil spills in 2011 at the Penglai 19-3 and Suizhong 36-1 fields (CNOOC, 2011; COPC, 2012; SOA, 2012) have brought a strong focus on the national safety level of the offshore petroleum industry. According to the official investigation report (SOA, 2012), more than 870 square kilometers of seawater were heavily polluted. In particular, the Chinese Bohai Bay is semi-closed and its own water exchange is abnormally slow. Hence, its eco-environmental system is hardly to bear any size of oil spills.

Over seven years, there has been an important controversy over whether the series of major accidents at Chinese Bohai Bay in 2011, i.e. the Penglai 19-3 and Suizhong 36-1 oil spills, are a sign of systematic safety problems in the Chinese offshore petroleum industry or a casual result of fortuities that the operations of the single company are in violation of industry standards. It is hard to obtain the answer unless the national risk level of the offshore petroleum industry can be monitored and measured (Skogdalen et al., 2011). In accordance with the in-depth investigations of major offshore accidents, it has been found that major offshore accidents result from a complex combination of deficiencies including technical, organizational and operational failures (Tamim et al., 2017; Zhen et al., 2018). Hindsight indicates that the major offshore accidents could have be prevented if early alerts can be

* Corresponding author.
Email address: zhenxingwei@dlut.edu.cn (X.W. Zhen); jan.erik.vinnem@ntnu.no (J.E. Vinnem).

provided (Øien et al., 2011a; Skogdalen et al., 2011; Olsen et al., 2015). Moreover, it has been recognized that defining risk indicators is an effective strategy to provide early warning signals of major accidents, as well as to measure how well safety is being managed on offshore installations.

Traditionally, in order to reflect the major hazard risk level on offshore installations, the operating companies in the offshore petroleum industry have been using HES (Health, Environment and Safety) indicators on personal safety for a long time. Nonetheless, indicators on personal safety provide very limited information on the overall safety performances, and hence can hardly provide a realistic picture to reflect the risk level for major hazards on offshore installations. The latest disasters, such as the BP Texas City refinery disaster (2005) and the Chemical industrial park blast disaster (2019), have created a high awareness that there are essential differences between major hazard management and occupational hazard management. Major hazard risk indicators provoke great concern.

1.2 Research purpose

This study describes an effort to propose an analytical approach for the development of major hazard risk indicators that can be used for monitoring, measuring and predicting national risk levels in the offshore petroleum industry. The objective of the research is to provide a more structured and systematic framework for developing two types of indicators, i.e. lagging and leading indicators.

1.3 Limitations and scope

This study has concentrated on major hazards on offshore installations, which consist of all offshore production facilities, mobile facilities and subsea facilities. The major hazards on vessel incidents associated with offshore operations are included only when the vessels are within the safety zone (500m) around the offshore installations. Hence, other hazards in the offshore petroleum industry are not included in this study:

- Hazards associated with occupational accidents are not covered.
- Hazards associated with offshore evacuation are not covered.
- Hazards associated with personnel transportation by helicopters are not covered.

1.4 Relevant work in the petroleum industry

1.4.1 Guidelines and recommended practices

Soon after the BP Texas City Refinery disaster (2005), several organizations, such as the UK HSE, the API, and the CCPS, etc., have been engaged in the recommendations or guidelines on the process safety indicators for the downstream petroleum industry in response to major accidents. In 2006, a guide for developing process safety indicators was published (HSE, 2006). Regarding the innovation of this HSE guide, it introduces the concept of 'dual assurance' that both lagging and leading indicators are set for each key risk control system. In 2007, the "Baker Panel" (Baker et al., 2007) and US CSB (CSB, 2007) each recommended in their final reports that dedicated process safety indicators should be developed in response to the major accidents. These recommendations have aroused great concern on process safety indicators. In the period of 2007-2011, a series of guidelines for process safety metrics were published by the CCPS (CCPS, 2007, 2009). Safety metrics are defined and classified into leading metrics, lagging metrics and near-miss metrics. In 2010, a recommended practice (RP) was firstly published by API (API, 2010) and was further updated in April 2016 (API, 2016). In the RP, process safety indicators are classified into four tiers. Thereinto, tiers 1 & 2 are intended for the public reporting while tiers 3 & 4 are for internal use within individual facilities. In 2011, CCPS has elected to update the CCPS metric recommendations with the aim to be consistent with the API documents (CCPS, 2011).

To ensure that the upstream petroleum industry can also benefit from the aforementioned studies, in 2011, a guideline (report No. 456) on key performance indicators (KPI) was published by IOGP (IOGP, 2011). The guideline builds a framework and definitions on the basis of the latest ANSI/API RP 754 as well as guidelines on metrics issued by HSE, CCPS and OECD (OECD, 2008). IOGP has spared efforts to provide further guidance to support the applicability of the API RP 754 for upstream activities. In 2016, a supplementary report (IOGP, 2016) focusing on leading key performance indicators was published for Report 456. The supplementary report provides further guidance on the tiers 3 & 4 levels based on good practice that has emerged in the industry.

1.4.2 Authority works

The International Regulators' Forum (IRF) initiated the IRF Performance Measures Project, which was undertaken to establish a framework of lagging indicators, i.e. number of fatalities/injuries, number/mass of hydrocarbon gas releases, number of collisions/fires and number of losses of well control (IRF, 2016).

The Risk Level Project (RNNP) was initiated by the PSA Norway in 1999. The major hazard indicators in RNNP can be divided into two categories as follows:

- Indicators based on occurrence of incidents and precursor events
- Indicators based on performance of safety critical barriers

1.4.3 Research institutes and Industry works

SINTEF conducted the "Risk Indicator Project" in collaboration with Equinor and NPD companies (Øien and Sklet, 1999). In the beginning, the study focused on developing technical indicators for process accidents and blowout. Soon, the study was extended to develop organizational risk indicators (Øien, 2001). After several years, SINTEF carried out the "Building Safety Project" in collaboration with Eni Norge As, IFE, and NTNU, addressing safety challenges in offshore petroleum activities in the Barents Sea. In this study (Øien et al., 2011a, 2011b), the proposed indicators in different approaches are classified into four groups as follows:

- Safety performance-based indicators
- Risk-based indicators
- Incident-based indicators
- Resilience-based indicators

1.5 Structure of paper

Section 2 presents the proposed risk-based approach for developing the national major hazard risk indicators on offshore installations. The proposed analytical approach is tested by the risk assessment results of the NCS in Section 3. Section 4 systematically discusses the suitability and challenges of the proposed approach used for these indicators. This is followed by the main conclusions in Section 5.

2. Risk-based approach putting forward

The risk-based approach for developing major hazard risk indicators on offshore installations at a national level is proposed and indicated in Fig. 1. The proposed risk-based approach consists of the following five main modules.

(1) Basis for the national risk level study.

(2) Development of the risk model.

(3) Development of national risk level indicators.

(4) Quantification of national risk level indicators.

(5) Establishment of the realistic major hazard risk picture.

The specific procedures are systematically presented in the following sections.

Fig.1 Main aspects of the proposed risk-based approach

2.1 Basis for the national risk level study

In the first step of the process, the study objectives, scope and relevant stakeholders need to be defined. Thereinto, the detailed study objectives and limitations have been presented in Sections 1.2 & 1.3 (and won't be repeated here). The relevant stakeholders in the offshore petroleum industry involve various 'parties', including employees on all levels, managers on all levels, employers and authorities.

2.2 Development of the risk model

The main principle of the development of major hazard risk indicators on offshore installations is that the status assessment of both technical and non-technical barriers shall be risk-based. Hence, the risk model needs to be developed, first and foremost.

2.2.1 Identify major hazard risk types on offshore installations

All major hazard risk types on offshore installations will be identified. Nonetheless, it can be noted that major offshore accidents are very rare during a limited time period even at a national level. This implies that there will be far too few major accidents to draw any conclusions on predicting trends. In view of this, a basis for expressing risk can be established in combination with monitoring and utilizing the precursor events as well as our knowledge on the possible accident scenarios.

Different categories of major hazard and accident conditions (DFU, Norwegian acronym) on offshore installations are identified and selected. The major hazard and accident conditions are unplanned events or conditions that may cause or have caused serious harm to human life, environment and substantial material assets.

2.2.2 Identify safety-critical barriers

It has been recognized that both technical and non-technical barriers are important measures or solutions to reduce the risk of major offshore accidents (Zhen et al., 2019). In this step, a set of safety-critical barriers consisting of both technical and non-technical barriers are identified for the possible major accident scenarios. The identified safety critical barriers lay the foundation for the subsequent development of corresponding leading indicators.

The identified technical barriers mainly deals with hydrocarbon (HC) leaks on offshore installations. The following technical barrier functions are included in this study.

- To prevent any fatalities.
- To prevent ignition.
- To reduce clouds and emissions.
- To prevent escalation.
- To maintain the integrity of HC production and process facilities on offshore installations.

With respect to identification of non-technical barriers, task analysis needs to be conducted for a representative selection of work tasks. In this study, the BORA (Barrier and Operational Risk Analysis) (Aven et al., 2006; Sklet et al., 2066; Zhen et al., 2018) and OTS (the Operational Condition Safety) (Kongsvik et al., 2010; Vinnem et al., 2007) projects lay the foundation of this work.

2.2.3 Establish performance standards (PS)

Performance standards are defined as the central risk influencing factors (RIFs), which affect the performances of initiating events and non-technical barriers. The basis for the definition of performance standards is as follows:

- Review, comparison and synthesis of the relevant existing models/approaches.
- Review, comparison and synthesis of the existing literature.
- Experience from accident and incident investigations.
- Structured interviews of relevant personnel on offshore installations.

•*2.2.4 Define checklists (specific indicators) and performance requirements (PR)*

Performance requirements are defined and can be used to assess the status of the performance standards on offshore installations (Vinnem et al., 2007). For each of the performance standards, performance requirements are defined with the following structure, as illustrated in Fig.2. Further, detailed checklists represent the specific indicators, which are used to measure the status of each performance requirement. It can be noted that the task follows the principle of the OTS concept (Kongsvik et al., 2010; Vinnem et al., 2007). A three-layer hierarchical structure approach is developed for the status measurement of the performance standards. The hierarchical structure, from top to bottom, includes the performance standards, corresponding performance requirements and corresponding checklists (specific indicators).

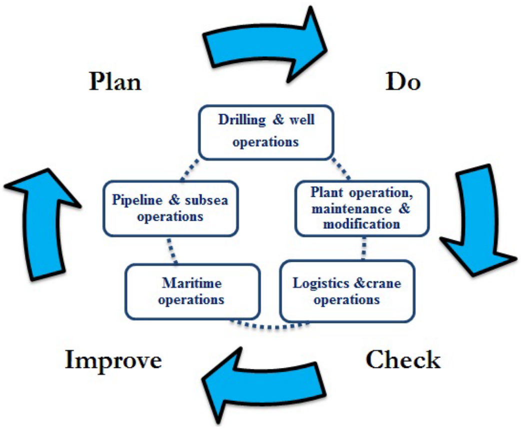

Fig.2 Main work processes and improvement circle for performance requirements adapted from PSA (2017)

2.3 Development of national risk level indicators

When the risk model has been developed, steps can be carried out for the development of national risk level indicators as follows: (1) set assessment criteria for the major hazard risk indicators; (2) define direct risk indicators; (3) define indirect risk indicators. Thereinto, the identification of lagging indicators and technical leading indicators is in line with the RNNP (PSA, 2018) and has been discussed in detail by Vinnem (2010). So it won't be repeated here for clarity. The main emphasis is on the non-technical leading indicators.

2.3.1 Set assessment criteria for the major hazard risk indicators

On the basis of the literature study (e.g. Haugen et al., 2011; Kjellén, 2000; Kjellén, 2009; Vinnem et al., 2003; Vinnem et al., 2006; Vinnem, 2010), a comprehensive set of assessment criteria for the major hazard risk indicators in the offshore petroleum industry is proposed and discussed as follows:

- *Observable:* The safety critical performance should be able to be observed and measured by the proposed risk indicators.

- *Quantifiable:* The quantitative measurement should be able to be given in a consistent manner by the proposed risk indicators.
- *Intuitiveness*: On the one hand, the proposed risk indicators should be regarded as intuitively by the experienced stakeholders to be of importance for the major accidents prevention. On the other hand, to ensure no confidence lost, it is intuitively preferable that complex calculations are not required by the proposed risk indicators.
- *Validity:* A valid status measurement of identified safety-critical barriers must be able to be given by the proposed risk indicators.
- *Regular monitoring:* The status of the proposed risk indicators should be able to be monitored on a regular interval, especially for the non-technical indicators, as under the comparable conditions, more resources and efforts are needed by the non-technical indicators in comparison to technical indicators.
- *Sensitive to change:* Changes in risk should be able to be reflected by the proposed risk indicators. Meanwhile, improvements aspects should be able to be identified.
- *Robust against manipulation:* On the one hand, reporting behavior for the proposed risk indicators is not allowed to change to ‘look good’. On the other hand, the reporting results should not be affected by safety competition activities.
- *Both types of indicators:* The proposed risk indicators should engage primarily in leading indicators, supplemented by lagging indicators.
- *Reflection on hazard mechanisms:* The hazard mechanisms should be able to be reflected as closely as possible by the proposed risk indicators.

2.3.2 Identification of lagging indicators

The following lagging indicators for major hazard and accident conditions in the offshore petroleum industry are identified and developed:

- Indicators based on occurrence of incidents and precursor incidents on offshore installations

The work on data collection for major hazard precursor events has been carried out in part on existing databases (DDRS, CODAM, etc.) in the PSA, as well as in cooperation with the operating companies. All the major hazard precursor events can be reported by the offshore petroleum industry in accordance with the corresponding channels.

2.3.3 Identification of leading indicators

The following leading indicators are identified and developed based on the identified safety-critical barriers on offshore installations, as has been discussed and presented in Section 2.2.2:

- Indicators that measure the status of technical barrier elements.
- Indicators that measure the status of non-technical barrier elements.

Thereinto, the technical leading indicators represent the availability and reliability of the technical barrier elements (Cai et al., 2012; Cai et al., 2013; Cai et al., 2018). They are reported by periodic tests.

A three-layer hierarchical structure approach is proposed for the development of non-technical barrier indicators, which measure the status of non-technical barrier elements on offshore installations, as illustrated in Fig.3. The development process is based on the experience from the IAEA project on “operational safety performance indicators" (IAEA, 2000) and OTS project (Kongsvik et al., 2010; Vinnem et al., 2007).

It can be seen from Fig.3 that the non-technical safety performance is established by different levels. The hierarchical indicator pyramid starts with the PS indicators, followed by PR indicators and specific indicators. It should be noted that in the hierarchical indicator pyramid only the specific indicators at the lowest level can be measured directly.

The non-technical barrier indicators, which are represented by PS indicators, PR indicators and specific indicators, can be developed in accordance with the established risk model, as has been presented in Sections 2.2.3 & 2.2.4. In this study, eleven PS indicators are structured in Table 1. Examples of PS indicator 'N2. Competence' with corresponding PR indicators and specific indicators are shown in Table 2.

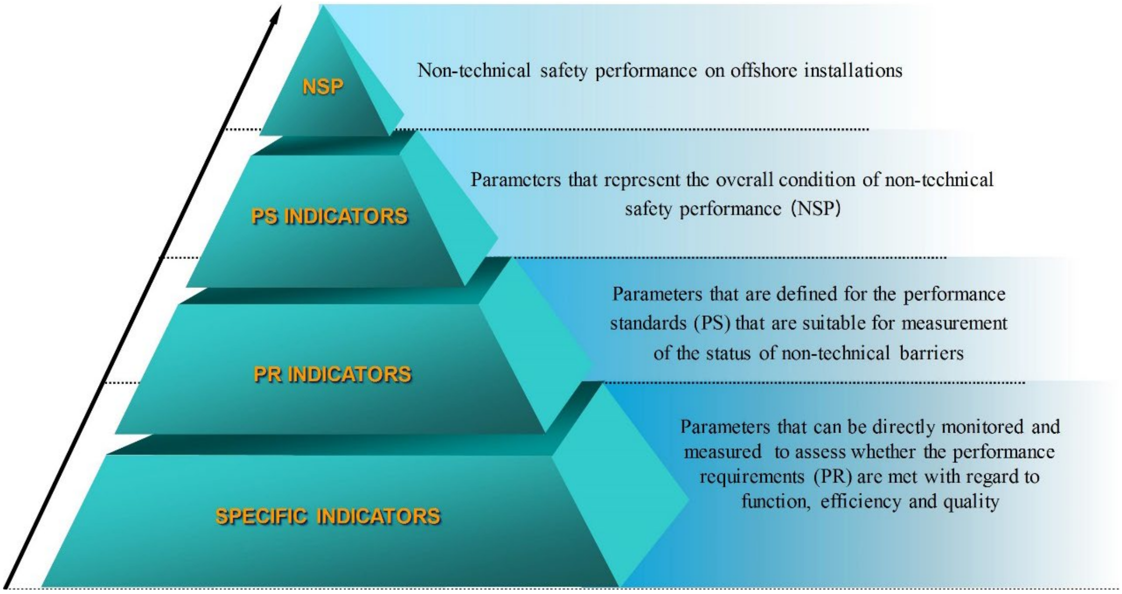

Fig.3 Hierarchical indicator pyramid for measuring the status of non-technical barrier elements

Table 1 Overview of PS indicators

PS Indicator NO.	Description
N1.	Work practice
N2.	Competence
N3.	Procedures and documentation
N4.	Communication
N5.	Work load
N6.	Physical environment
N7.	Task supervision
N8.	Risk awareness
N9.	Management
N10.	Management of change
N11.	Work schedule aspects

Table 2 Examples of PS indicator '2. Competence' with corresponding PR indicators and specific indicators

Indicator type	No.	Defined information
PR indicator	2.1	In order to handle major accident risk, the management and the executing team shall collectively have the capacity and knowledge of 1) major hazard risk, 2) activity, 3) process and plant, 4) handling of deviation situations.
Specific indicator	2.1.1	The teams have the necessary expertise and capacity to perform safety-critical tasks in a safe manner.
	2.1.2	Contractors are given the necessary training to be able to carry out their tasks safely.
	2.1.3	Training is sufficient for dealing with deviation and emergency situations.
	2.1.4	Expertise in process understanding, system knowledge and area knowledge is enough for the tasks that are performed.
	2.1.5	The management has sufficient capacity to control and follow up all safety-critical activities.

2.4 Quantification of national risk level indicators

In accordance with the established assessment criteria for the major hazard risk indicators, it indicates that the quantitative indicators can better build the basis for monitoring, measuring and predicting risk levels. Hence, quantification rules for both leading and lagging indicators need to be developed in this study, as follows:

- *Set quantification rules of direct indicators:* (1) lagging indicators; (2) leading indicators – status of technical barrier elements.
- *Set quantification rules of indirect indicators:* leading indicators - status of non-technical barrier elements.

The quantification rules of direct indicators have been discussed in detail by Vinnem (2010). It is noted that the development of lagging indicators consists of two types, i.e. individual lagging indicator (LagII) and overall lagging indicator (LagOI). The individual lagging indicator is the normalization of frequency of the DFUs while the overall lagging indicator aims at balancing the effects of individual lagging indicators. The technical barrier indicators ($LedI_{tot.}$) is represented by the overall failure fractions (PSA, 2018). Hence, the main emphasis is on the development of quantification rules of indirect indicators.

On the basis of the proposed hierarchical structure approach (see Fig.3) for the development of non-technical barrier indicators, the quantification rules are presented by the following four steps.

First step: establishment of the quantified scoring criterion for measuring specific indicators.

In this study, the principle of levels, and multipliers are adapted to establish the quantified scoring criterion for specific indicators, as presented in Table 3. The validity of this principle has been tested by the SPAR-H method (Gertman et al., 2005) in the nuclear industry and the Petro-HRA method (Bye et al., 2017; Taylor et al., 2017) in the offshore petroleum industry.

Table 3 Quantified scoring criterion for measuring specific indicators

Levels		Scale	Meaning of scale
A	Negligible weaknesses observed	0.1-0.5	1-5 out of 1000 will fail. There is little weakness observed in relation to performance requirements
B	Minor weakness observed	1-5	1-5 out of 100 will fail. There are only minor shortcomings observed weakness in relation to performance requirements
C	Apparent weakness observed	10-15	10-15 out of 100 will fail. It is clearly observed weakness in relation to

			performance requirements
D	Significant weakness observed	20-25	20-25 out of 100 will fail. It is observed significant weakness in relation to performance requirements
E	Critical weakness observed	50-75	50-75 out of 100 will fail. It is observed critical shortcomings in relation to performance requirements
F	Extremely critical weakness observed	90-100	90-100 out of 100 will fail. It is observed extremely critical shortcomings in relation performance requirements.

Second step: quantitative status measurements of specific indicators

As has been noted in Section 2.4.3, non-technical barrier indicators are established at different levels and cannot be measured directly. The non-technical safety performance is represented by a total of eleven PS indicators. Only specific indicators at the lowest level are directly measurable. For the illustration purpose, the hierarchical framework for the PS indicator 'F2. Competence' is presented in Fig.4.

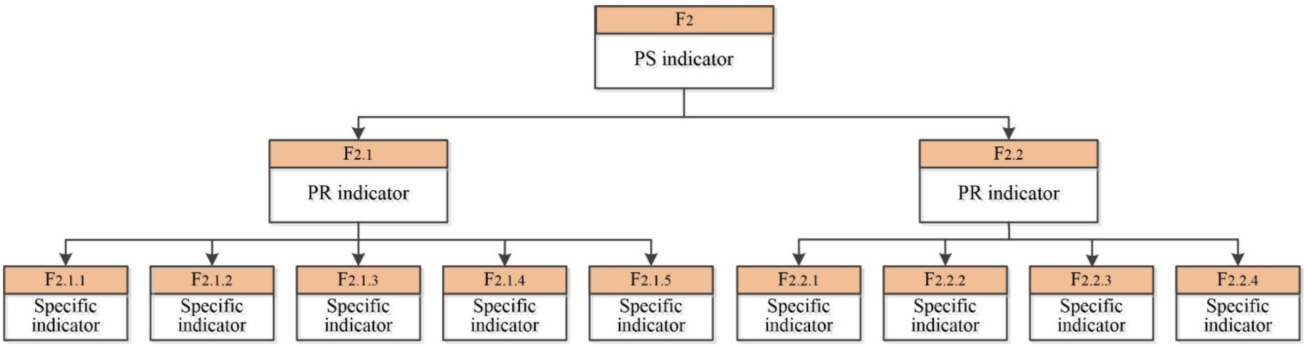

Fig.4 Hierarchical framework for the PS indicator 'F2. Competence'

The scoring responsible (SR) specialists are required to measure the status of each specific indicator according to the established scoring criterion (see Table 3). Each specific indicator will be assigned a numerical value.

Third step: multilevel weights measurements of indicators in the hierarchy

The weight represents the value importance of each indicator in comparison with the weights of other indicators at the same level. Multilevel weights in the hierarchy framework represent the weight assignment to PS indicators, PR indicators and specific indicators individually.

In this study, the analytic hierarchy process (AHP) (Saaty, 1990; Zhen et al., 2018) approach addressing the consistency is adopted. The following principles are applied as follows:

(1) Establish the judgment matrix in accordance with the pair-wise comparison. A comparison criterion of 1-9 scale is applied.

(2) Analyze the consistency of the established judgment matrix. The consistency ratio (CR) of 0.1 or less is considered acceptable. Otherwise, the judgments are considered less credible.

(3) Determine the weight of each indicator through the arithmetic averaging method.

Fourth step: system for aggregation

The aim of this step is to aggregate the quantitative score of each specific indicator into the corresponding PS indicator synthetically. The aggregation algorithm for PS indicators can be determined by the following equation.

$$\mathrm{LedI}_{\mathrm{PS}} = \sum_{i=1}^{n} (w_i \cdot Q_i) \quad (1)$$

Where w_i is the priority weight of the specific indicator in the hierarchical framework; Q_i is the numerical score for the specific indicator; $\mathrm{LedI}_{\mathrm{PS}}$ is the PS indicator.

2.5 Establishment of the realistic major hazard risk picture

In final, the realistic and jointly agreed major hazard risk picture in the offshore petroleum industry can be established in accordance with the suggested leading and lagging indicators for monitoring and predicting risk levels. Fig.5 presents a summary of the suggested risk-based major hazard risk indicators at a national level.

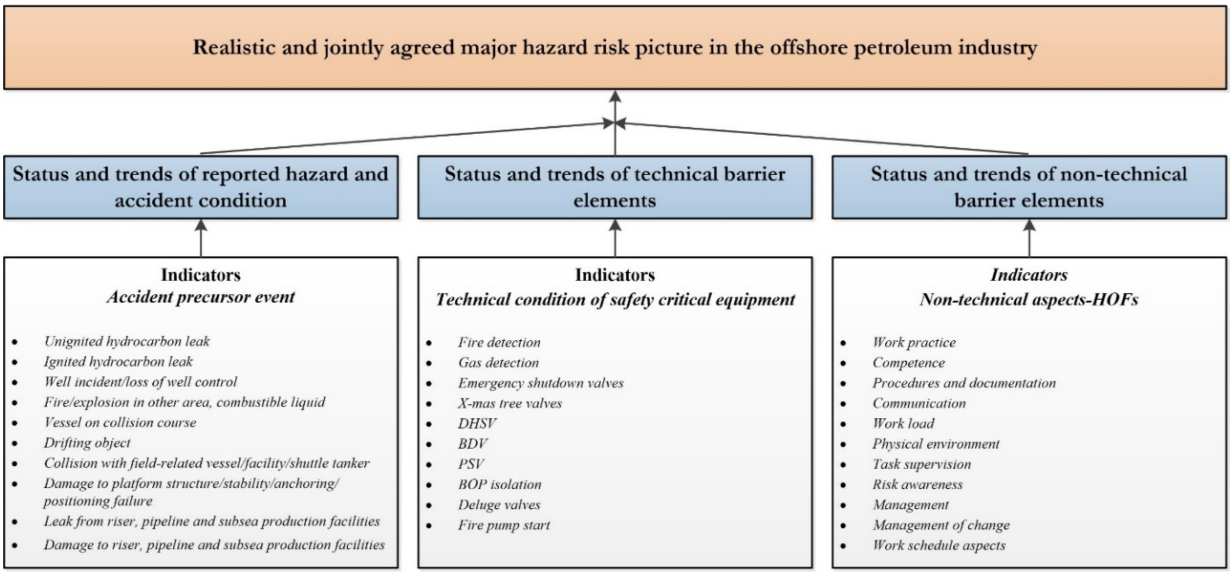

Fig.5 Summary of the suggested risk-based major hazard risk indicators in the offshore petroleum industry

3. Application of proposed major hazard risk indicators to NCS

This section exemplifies the application of the proposed risk-based methodology to NCS. It is necessary to stress that every finding in lagging indicators and technical barrier indicators is derived from the risk assessment results of the NCS in the latest ten years (2007-2017) (PSA, 2018). The findings in non-technical barrier indicators are derived from analytical calculations performed during the development of this study, based on the data and information obtained from the OTS project and expert judgments (Kongsvik et al., 2010, Næss et al., 2016; Olsen et al., 2015; Vinnem et al., 2007).

3.1 Lagging indicators

An illustration of the individual lagging indicator for major hazard and accident conditions is presented in Fig.6. It shows the trend of reported DFUs, normalized against installation years, in the period of 2008-2017. It can be seen from Fig.6 that there is a gradual reduction in the number of reported DFUs in the latest ten years. In addition, the diagram shows a relatively stable trend in the number of reported DFUs since the year of 2013. Both the gradual reduction and relatively stable trend in the frequency of reported DFUs are the noteworthy results of the initiative and purpose of the development of national risk level indicators in the offshore petroleum industry.

The overall lagging indicator for major hazard and accident conditions is presented in Fig.7. It shows the trend of the total indicator for all offshore installations, normalized against working hours, in the period of 2008-2017. It can be seen from Fig.7 that the three-year rolling average clearly shows a positive trend since the year of 2008. In comparison with the average for the period of 2008-2012, the diagram shows a significant reduction in the year of 2013 and 2014. This implies that the relevant stakeholders in the offshore petroleum industry have achieved better management of risk factors that affect major hazard and accident conditions. In addition, it can be seen that the annual values show larger variations. This is due to that there exists some severe precursor events with underlying fatalities. This can create high awareness that risk factors related to major hazard and accident conditions must be given keen focus and active management.

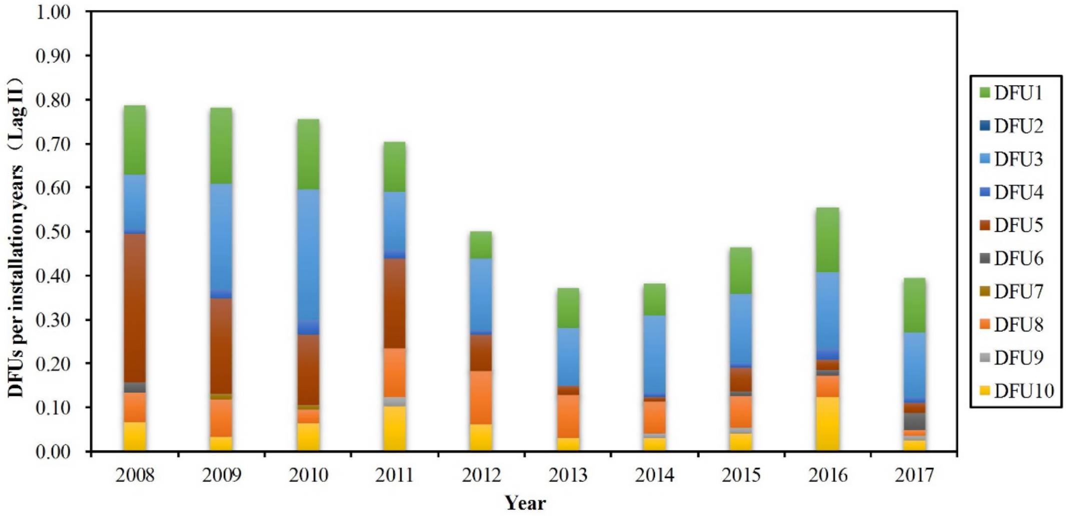

Fig.6 Individual lagging indicator for major hazard and accident conditions, normalized against installation years, 2008-2017

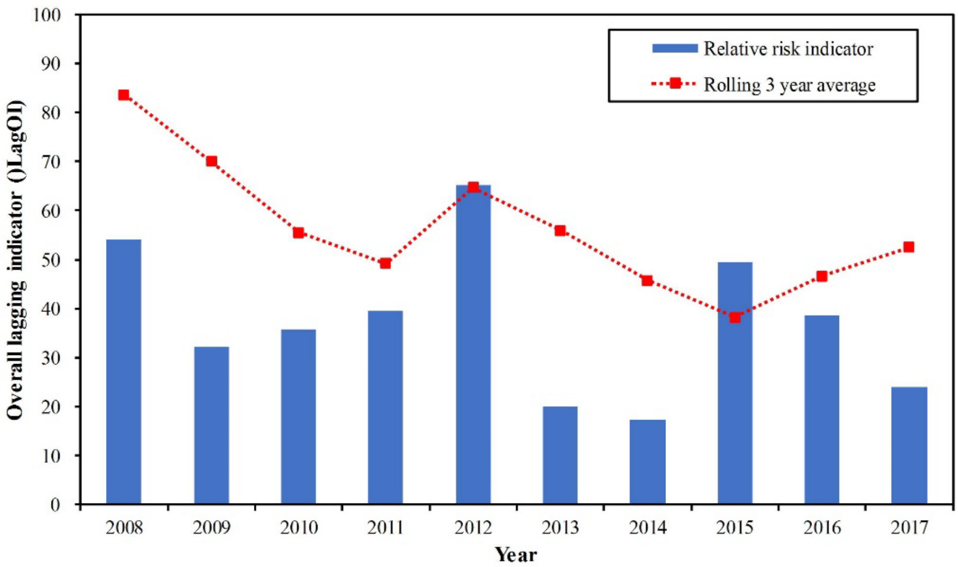

Fig.7 Overall lagging indicator for major hazard and accident conditions, normalized against working hours, 2008-2017

3.2 Leading indicators – status of technical barrier elements

An illustration of the technical barrier indicators for determined technical barrier elements is presented in Fig.8.

It shows the trend of the average values for all offshore installations on the NCS, in the period of 2008-2017. The industry norm for the associated technical barrier element is also shown in Fig.8. It should be noted that there is no comparable industry norm for isolation using BOP since this is not considered to be appropriate (PSA, 2018). It can be seen from Fig.8 that technical leading indicators show a considerable variation in average levels for some safety-critical barrier elements, such as riser ESDV, DHSV, PSV, etc. Thereinto, the technical leading indicator for riser ESDVs, which has exceeded the industry norm in recent years, shows a positive trend. The technical leading indicator for BDVs shows a fall from 2011 to 2015 and has a rising trend in 2016 and 2017. Nonetheless, the technical leading indicator for DHSVs shows a rising trend from 2012 to 2017. The technical leading indicators on the rest technical barrier elements are stably below their corresponding industry norms. This implies that the focus on barrier management within this area is yielding results in recent years.

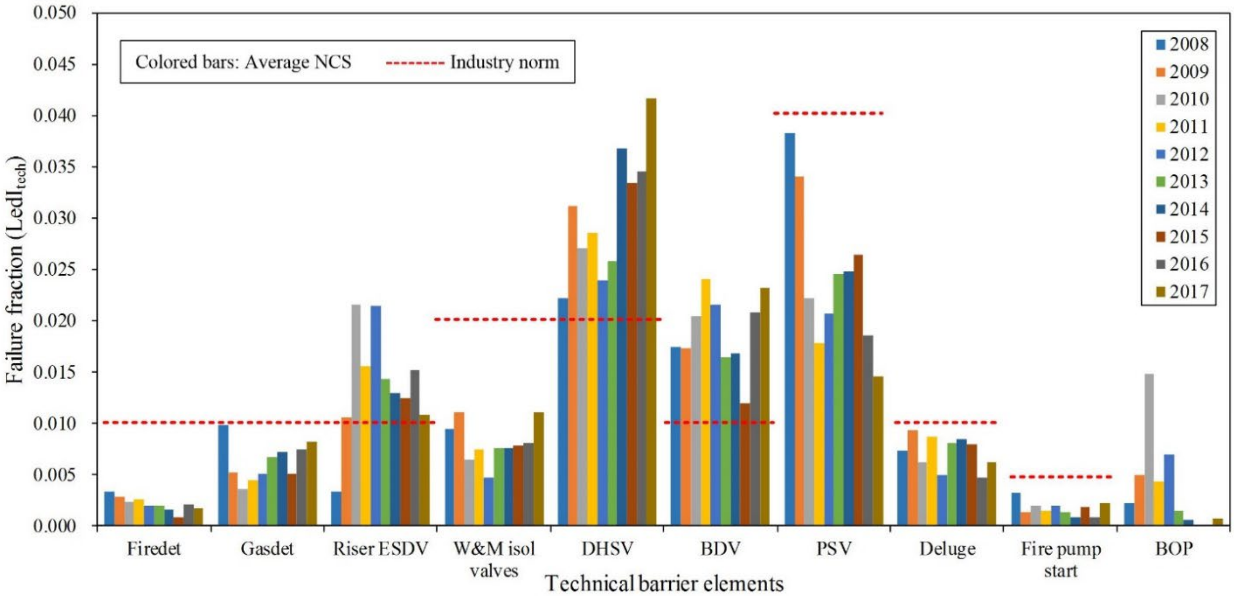

Fig.8 Technical leading indicator for selected barrier elements, 2008-2017

3.3 Leading indicators - status of non-technical barrier elements

An illustration of the non-technical barrier indicators is presented in Fig.9. It shows the trend of the average values on the status of non-technical barrier elements for all installations on the NCS, in four consecutive quarters. It is noted that it is an exemplification for monitoring the status of non-technical barrier indicators on a regular basis, i.e. quarterly. In practice, the monitoring period intervals can be year, half-year, quarter, month and day according to the consensus of relevant "parties". The presented results can be obtained in accordance with the quantification rules as presented in Section 2.4.3. It is noteworthy that the hierarchical structure approach that we have developed makes an attempt to critically measure the status of performance standards so as to provide early warning signals for non-technical elements at risk. This is our first step. What is needed now is a real case implementation as the prediction capability cannot be validated until the approach has been tested for a long-time. Further challenges for capturing non-technical conditions by indicators are discussed in Section 4.3. Some significant observations are obtained as follows.

(1) The testing of the approach confirms that the proposed hierarchical structure approach is a feasible and reliable

way to measure the status of non-technical barrier elements quantitatively.

(2) A relatively living picture of the status of non-technical barrier elements that affect major accidents can be established by PS indicators, which could provide better management of major hazard risk according to monitoring and predicting risk levels.

(3) The proposed non-technical barrier indicators are able to follow the key assessment criteria for the major hazard risk indicators, i.e. quantifiable, regular monitoring and sensitive to change. The non-technical barrier indicators could proactively identify the possible weaknesses in the non-technical barrier elements and then the major hazard risk can be decreased as practically as possible.

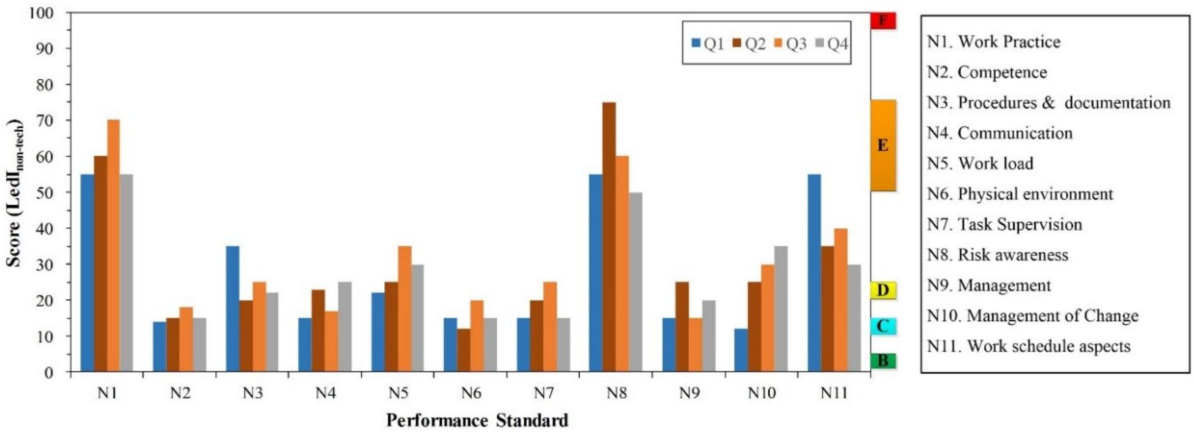

Fig.9 Non-technical leading indicator for performance standards, in four consecutive quarters (expert judgment values)

4. Discussion

4.1 Regulatory requirements and challenges

In order to build safety in the offshore petroleum industry, it is of great importance for developing the major hazard risk indicators. Prominent organizations on process safety have published relevant reports or guidelines on this topic (API, 2010, 2016; CCPS, 2011; HSE, 2006; IOGP, 2011, 2016; OECD, 2008).

It can be found that the instanced indicators in the issued regulatory guidelines have a much broader scope than major hazards, such as the number of reportable hydrocarbon releases without limitation on the leak flowrate (HSE, 2006). Some instanced indicators in these regulatory guidelines are somewhat alike parts of the RNNP, such as the percentage of safety-critical equipment that performs to specification (IOGP, 2011). In our perspective, the biggest challenge in the existing regulatory guidelines has focused obsessively on the ability to be capable of measuring (availability) while little attention is paid to the assessment criteria in relation to intuitiveness, validity, robust against manipulation and reflection on hazard mechanisms.

In the Norwegian safety regulations, there are no direct requirements on defining and monitoring major hazard risk indicators. Nonetheless, there are some certain requirements that can be related directly or indirectly to safety-critical barriers, addressing the major accident prevention. This implies that the indicators need to be developed for monitoring and predicting risk levels, as a basis for taking actions or not. As yet, Norway is the only country that seeks to measure progress in major hazard risk using a series of indicators at a national level around the world.

4.2 Suitability of the risk-based approach to major hazard risk indicators

The suitability of the proposed risk-based approach can be evaluated by its abilities as follows:

- The ability to provide a complete list of leading and lagging indicators, which involve all major offshore hazard and accident conditions.
- The ability to monitor and determine the status of major offshore hazard risk.
- The ability to predict the trends in major offshore hazard risk.
- The ability to identify safety-critical areas and the priority to be given to identifying causes.
- The ability to enhance the understanding and knowledge of the possible reasons of major offshore hazard and accident conditions.
- The ability to create a significant reporting volume for leading indicators.

It can be found that most of the abilities have been demonstrated by the proposed risk-based approach in a satisfactory manner. Thereinto, the list of suggested lagging indicators is complete, and it is capable of monitoring and predicting the major hazard risk levels, as well as identifying safety-critical areas. It is also capable of enhancing the understanding and knowledge of the possible reasons of major offshore hazard and accident conditions. In addition, it is considered that the technical leading indicators are suitable as a significant reporting volume has been created by testing of technical barrier elements (Vinnem, 2010). Table 4 presents an overview of reported data, which are generated by testing of technical barrier elements on an anonymous installation (A) in the period of 2013-2017. It can be seen from Table 4 that installation (A) has a significant volume of test data and fault data through testing of technical barrier elements in the specific period.

It can be noted that so far, in comparison to technical barrier elements, the non-technical barrier elements have not obtained equally strong focus in the offshore petroleum industry though non-technical factors are regarded as important root causes of some major offshore accidents. In this study, a hierarchical structure approach, which follows a top-down indicator scheme, is proposed attempting to develop non-technical barrier indicators, based on the OTS project (Kongsvik et al., 2010; Vinnem et al., 2007). The proposed non-technical barrier indicators allow to follow the key assessment criteria for the major hazard risk indicators, such as quantifiable, regular monitoring, etc. It is suggested to repeat the data collection on the specific indicators more frequently so as to lay a solid foundation for follow-up of non-technical barrier indicators. Further discussions on challenges for capturing non-technical conditions by indicators is presented in the next Section.

Table 4 Technical barrier tests (x) and faults (y) in (x-y), anonymous installation (A)

	2013	2014	2015	2016	2017
Fire detection	2457-0	1853-0	1101-0	940-3	892-2
Gas detection	587-2	1050-1	515-2	1310-7	402-0
Riser ESDV	26--2	18-0	15--2	15-0	11-0
BDV	28-9	56-4	56-2	53-1	52-5
Deluge	64-0	65-0	70-0	72-1	63-2
Fire pump start	104-0	104-0	104-0	56-0	52-0

4.3 Challenges for capturing non-technical conditions by indicators

The importance of organizational and operational conditions in relation to major offshore accidents has been highlighted in several latest accident investigation reports, such as Montara blowout (AU, 2009) (Montara Commission of Inquiry, 2010), Macondo blowout (US, 2010) (The National Academics, 2010), and Bohai Bay oil spills (CN, 2011) (CNOOC, 2011; COPC, 2012; SOA, 2012). Hence, there have always been wishes to establish indicators reflecting the status of non-technical barrier elements, but with little success (Vinnem, 2014).

In the RNNP project (PSA, 2018), a questionnaire survey research of perceived accident risk, safety climate, working environment and capacity for work has been conducted biannually. Nonetheless, the relationship between questionnaire-based survey results and major hazard risk is hardly established. Actually, the practical usefulness of questionnaire-based survey results has been questioned in designing interventions to improve safety (Guldenmund, 2000, 2007). This implies that the safety climate indicators in RNNP are insufficient of capturing the status of non-technical barrier elements.

In this study, a hierarchical structure approach, which follows a top-down indicator scheme (see Fig. 3), is proposed for the development of non-technical barrier indicators. Instead of the traditional qualitative scoring criterion (A-F), the principle of both levels and scales is adapted to establish a quantified scoring criterion for specific indicators. Then, a system can be established for aggregating the quantitative score of each specific indicator into the corresponding PS indicator so as to reflect non-technical barrier conditions. Hence, the proposed non-technical barrier indicators are able to follow some key assessment criteria for major hazard risk indicators, such as quantifiable, regular monitoring, etc. Particularly, the quantified non-technical indicators are sensitive to changes in organizational and operational errors, and hence assist in maintaining high awareness, motivation and emphasis on major hazards prevention on offshore installations.

The challenge of the present study is twofold. On the one hand, whether the proposed PS indicators meet the criteria for identifying good indicators or not requires a real case implementation as well as a long-term testing. For instance, it is recognized that competence is a very important PS, as it entails knowledge, skills and abilities that can contribute to adequate work performance and/or problem solving so that major accidents can be avoided. Nonetheless, as illustrated in Fig.9, the PS indicator 'N2. Competence' may not be a good indicator in practice as it is not sensitive to change in an industry with high qualification requirements. Hence, after a real case implementation as well as a long-term testing, some of the proposed PS indicators may need to be removed or replaced. On the other hand, we still get the challenge feedback from the offshore petroleum industry. The main challenge against the proposed approach is that the status assessment of the specific indicators is time consuming and resource demanding. They prefer to jump straight to measuring the status of PR indicators. It also implies that the industry always wants to find a "silver bullet" which will ensure that no major accidents occur in the offshore petroleum industry. The truth is that there are no apparent and easy ways to measure the status of such non-technical indicators as yet. In any case, the balance between costs and benefits needs to be maintained.

5. Conclusions

Aiming at building safety in the offshore petroleum industry, this paper proposes a risk-based approach for the development of major hazard risk indicators that can be used for monitoring, measuring and predicting national risk levels in the offshore petroleum industry. The proposed approach provides a structured framework for identification of both leading and lagging indicators on offshore installations. The suggested lagging indicators are built on a foundation of all categorized major hazard precursor events while the leading indicators are built on a foundation of the condition of safety critical barriers, which consist of both technical and non-technical barriers.

A total of nine assessment criteria for the major hazard risk indicators are defined. It can be concluded that a combination of leading and lagging indicators will be capable of meeting the defined criteria if the data collection and reporting schemes are carefully set up. A hierarchical structure approach is proposed for the development of non-technical barrier indicators. The central building block of the proposed approach is to set quantification rules of non-technical barrier indicators. Quantified scoring criteria and aggregation system for non-technical barrier indicators are developed.

The realistic and jointly agreed major hazard risk picture in the offshore petroleum industry can be established in accordance with the suggested leading and lagging indicators for monitoring, measuring and prediction risk levels. The proposed approach is tested and exemplified by the results from the risk assessment for the NCS. It can be argued that the series of major offshore accidents, such as Bohai Bay oil spills, can be avoided to a large extent if major hazard risk indicators have been developed and hence assist in maintaining high awareness, motivation and emphasis on major hazards prevention on offshore installations.

Declaration of conflicting interests

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Nomenclature

Abbreviations

AHP	Analytic Hierarchy Process
API	American Petroleum Institute
BDV	Blowdown Valve
BOP	Blowout Preventor
BORA	Barrier and Operational Risk Analysis
CCPS	Center for Chemical Process Safety
CR	Consistency Ratio
CSB	Chemical Safety Board
DFU	Reported Hazard and Accident Condition
DHSV	Downhole Safety Valve
ESDV	Emergency Shutdown Valve

HC	Hydrocarbon
HES	Health, Environment and Safety
HSE	Health & Safety Executive
IFE	Institute for Energy Technology
IOGP	International Oil and Gas Producers
IRF	International Regulators' Forum
KPI	Key Performance Indicator
NCS	Norwegian Continental Shelf
NPD	Norwegian Petroleum Directorate
NTNU	Norwegian University of Science and Technology
OECD	Organization for Economic Co-operation and Development
OTS	Operational Condition Safety
PR	Performance Requirement
PS	Performance Standards
PSA	Petroleum Safety Authority
PSV	Pressure Safety Valve
RIF	Risk Influencing Factor
RNNP	Risk Level Project
RP	Recommended Practice
SR	Scoring Responsible

Variables

LagII	Individual lagging indicator
LagOI	Overall lagging indicator
LedI_{PS}	PS indicator
$\text{LedI}_{\text{tot.}}$	Technical barrier indicator
Q_i	The numerical score for the specific indicator
w_i	The priority weight of the specific indicator in the hierarchical framework

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