Quantitative risk modelling in the offshore petroleum industry: Integration of human and organizational factors

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ABSTRACT:

In-depth investigations of major offshore accidents show that technical, human, operational and organizational risk influencing factors (RIFs) all have crucial effects on the accident sequences. Nonetheless, the current generation of quantitative risk analysis (QRA) in the offshore petroleum industry has focused on technical safety systems while applications and findings in the non-technical fields are to a large extent missing. There have also been parallel efforts to develop methods for the formal inclusion of human and organizational factors (HOFs) into QRA. Examples from the offshore petroleum industry include ORIM, BORA, Risk_OMT, etc. This paper presents a review of QRA models that have been developed for the offshore petroleum industry, allowing HOFs integrated in a systematical way. The main intention of this study is to summarize and evaluate how these QRA models effectively seek answers to the key questions in this line of research: (i) What are the RIFs that affect the risk? (ii) How do these factors influence the risk? (iii) How much do these factors contribute to the risk? Further, the weakness and challenges of the reviewed models are pinpointed based on a substantial data set of actual leaks that have occurred in the Norwegian sector. Following the close scrutiny of these models, their progress, limitations, validity and suitability are addressed and discussed in detail. Based on these insights, future work is suggested to enhance and improve the QRA framework for including the installation specific conditions of technical and non-technical RIFs in a more comprehensive and defensible way.

Keywords: Quantitative Risk Analysis; Risk influencing factor; Operational barrier; Bayesian belief network; Safety management

1. Introduction

The offshore petroleum industry is widely recognized as a leading industry within the field of safety engineering. Even so, the industry experienced several major offshore incidents and accidents, such as Piper Alpha (UK, 1988) (Cullen 1990), Montara blowout (AU, 2009) (Montara Commission of Inquiry 2010), Macondo blowout (US, 2010) (The National Academies 2010), CDSM explosion (BR, 2015) (Vinnem 2018) and a number of very serious near-misses in Norway in the period 1984-2004 (Sklet 2004), several of which involved serious hydrocarbon (HC) leaks with catastrophic fire and explosion potential. In-depth investigations of these major offshore incidents and accidents show that technical, operational, human and organizational RIFs all have crucial effects on the accident sequences. The current generation of QRA in the offshore petroleum industry, however, has been focusing on technical systems and capabilities, while the non-technical aspects are to a large extent missing (Aven et al. 2006b; Røed et al. 2009; Skogdalen and Vinnem 2011; Vinnem et al. 2012). During the past decade, a great amount of

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research efforts has been devoted to identifying HOFs and measuring their influence on the risk.

Meanwhile, in contrast to the design safety, the operational safety gains increasing attention in the offshore petroleum industry, in order to mitigate hazards and control risks. This can be mainly attributed to two reasons. On the one hand, the focus of the offshore petroleum industry is on safely operating of existing installations and extending the operational life of some of these installations. Authorities, such as the Petroleum Safety Authority (PSA) in Norway, Health and Safety Executive (HSE) in United Kingdom, etc., are also more focused on the risk reduction in the operational phase. On the other hand, the Risk Level Project by PSA (Vinnem et al. 2006a; Vinnem 2010) reveals that the trends of major accident risk for existing production installations in the Norwegian sector have been either constant or slightly increasing. The offshore petroleum industry may need a new initiative in order to turn the trends in the right direction. In response to this, special attention needs to be given to reveal how principles and requirements considering HOFs are included into QRA and thus, the updated risk picture can take the installation specific conditions of technical systems, operational conditions and HOFs into account.

There have been parallel efforts to develop methods to integrate HOFs into QRA. A total of five relevant QRA models (integration of HOFs) that were developed specifically for the offshore petroleum industry have been identified from the published literature. Among these are Organizational Risk Influence Model (ORIM) (Øien 2001a, 2011b; Øien and Sklet 2000), Barrier and Operational Risk Analysis (BORA) model (Aven et al. 2006a; Sklet et al. 2006; Aven et al. 2006b; Vinnem et al. 2006b; Vinnem et al. 2009; Haugen et al. 2007; Seljelid et al. 2007; Zhen et al. 2018), Operational Conditional Safety (OTS; this is a Norwegian acronym for Operational Conditional Safety) model (Vinnem et al. 2007; Sklet et al. 2010; Kongsvik et al. 2010), Hybrid Causal Logic (HCL) model (Røed et al. 2009), Risk modelling-integration of Organizational, Human and Technical factors (Risk_OMT) model (Vinnem et al. 2012; Gran et al. 2012a; Gran et al. 2012b). It is also interesting to note that all these leading-edge projects have been developed in a joint effort mainly by the Norwegian authority (PSA), universities (NTNU, UIS), research institutes (IFE, SINTEF, DNV-GL, etc.) and companies (Statoil, Safetec, Preventor, etc.). Nonetheless, it is certain that the importance and necessity of operational barriers, particularly non-technical, will be recognized gradually by other coastal countries, though the offshore petroleum industry in some other countries has for a long time invested considerable resources in engineering defenses against fire and explosion hazards on the installations.

Fig.1 presents the time series of reviewed models, benchmarked against their first published dates. The relationships among different models are also indicated. The OTS project is based on the modelling in the BORA project and provides a foundation for the Risk_OMT project. The main objective of OTS is to develop a system for monitoring the status of HOFs that influence major accident risk on oil or gas handling installations. Though the OTS model is not developed for the formal inclusion of HOFs into QRA, it truly plays an important role for the further development of the qualitative aspects of the Risk_OMT model. Hence, this review mainly focuses on the identified RIFs and their structures in the OTS model. It can also be noted that further tests and development of the Risk_OMT model have been carried out for Equinor (former Statoil). The updates mainly focus on the establishment of new human error probability (HEP) and activity data, alternative scoring of RIFs, adjustment of the leak frequency model, etc. The updated Risk_OMT model, which has not been published yet and is not in the public domain, is excluded from the present work. It is noteworthy that the Petroleum-Human Reliability Analysis (Petro-HRA) method (Bye et al. 2016; Taylor et al. 2017; Bye et al. 2017) was developed to analyze the human contribution to major accident risk in the offshore petroleum industry recently. Though HRA, which is used to estimate the likelihood of human failure events in post-initiating event scenarios, is not in this line of research for the formal inclusion of HOFs into QRA, the RIFs and their structures of the Petro-HRA method are of concern in the present work.

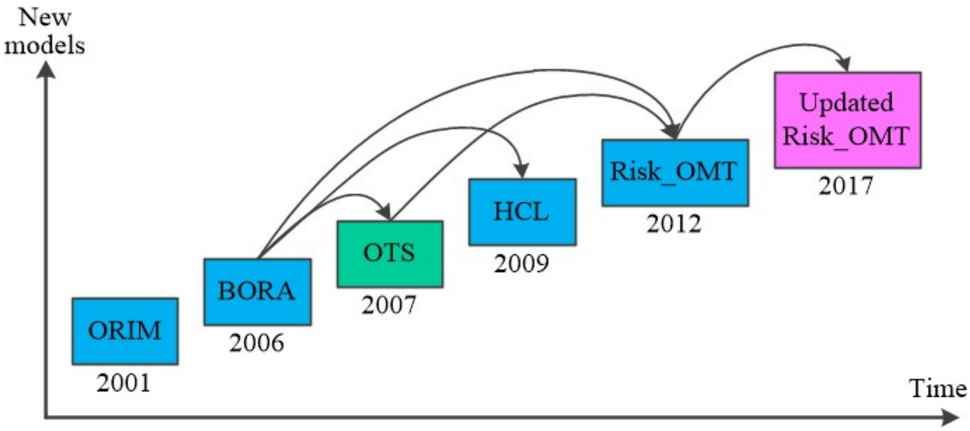

Fig.1. Time series of reviewed models developed for the offshore petroleum industry

This review article has four main objectives: the first objective is to provide a comprehensive and up-to-date picture of the existing QRA models that have been developed for the offshore petroleum industry specifically, allowing HOFs integrated in a systematical way. Following the close scrutiny of the reviewed QRA models, the second objective is to reveal the advantages, weakness and challenges of the reviewed models. On this basis, the third objective is to present and discuss the progresses, limitations, validity and suitability of the reviewed models. Based on all these insights, the last objective is to suggest the future work to enhance and improve the QRA framework to integrate the installation specific conditions of technical, human, operational and organizational RIFs in a more comprehensive and applicable way.

The main objectives are achieved by investigating how these QRA models effectively seek answers to the key questions in this line of research: (i) What are the RIFs that affect the risk? (ii) How do these factors influence the risk? (iii) How much do these factors contribute to the risk? The central elements of the answers to these questions are categorized as follows:

1. RIFs and their structures in QRA,
2. Link approaches to the system risk models,
3. Modelling techniques that are used to model the relationship between RIFs and the risk,
4. Measurement methods on how to quantify the relationship between RIFs and the risk,
5. The input data that is used as basic probabilities for all the failure events.

The paper is organized as follows. Section 2 presents the fundamentals of offshore QRA models integrating HOFs, mainly covering QRA, HOFs, safety barrier and safety indicator. The reviewed models are then systematically summarized and evaluated in Section 3. Section 4 pinpoints the weakness and challenges of the reviewed models based on a substantial data set of actual leaks that have occurred in the Norwegian sector. Progress, limitations, validity and suitability of reviewed models are discussed in Section 5. In final, Section 6 presents the main conclusions and recommendations for future work.

2. Fundamentals of offshore QRA models integrating HOFs

In order to understand the framework of extending QRA to include non-technical roots of risk in the offshore petroleum industry, the brief history and key analytic elements of QRA are presented at first. Further, some understanding on the expressions of human factors, organizational factors and RIFs are described. Thereafter, defining and modelling safety barriers, which are essential for analyzing the effects of HOFs, are presented.

2.1 QRA for the offshore petroleum industry

QRA is used as the abbreviation for 'Quantitative Risk Assessment' or 'Quantitative Risk Analysis'. The context usually has to be considered in order to determine which of these two terms is applicable. The difference between these two terms is that the former includes the evaluation of risk, in addition to the analysis of risk. QRA is applied frequently in the offshore petroleum industry. This technique is also referred to as Probabilistic Risk Assessment (PRA), Probabilistic Safety Assessment (PSA), Concept Safety Evaluation (CSE), Total Risk Analysis (TRA), etc. In spite of more than two decades of use and development, no convergence towards a universally accepted term has been seen (Vinnem 2014). QRA and TRA are the most commonly used abbreviations for the offshore petroleum industry. The term QRA will be concentrated on by this article as an abbreviation for 'Quantitative Risk Analysis'.

The use of QRA is central in the offshore petroleum industry to identify, analyze and evaluate risk, and dates back to the second half of the 1970s. A few pioneer projects were conducted mainly for research and development purposes, in order to investigate whether analysis methodologies and data of sufficient sophistication and robustness were available. In the year of 1981, the Norwegian Petroleum Directorate (NPD) issued guidelines for safety evaluation of platform conceptual design (NPD 1981). These regulations required that QRA should be carried out for all new offshore installations in the conceptual design phase. The next significant step in this development was the official inquiry, led by Lord Cullen in the UK, following the severe accident on the Piper Alpha platform in 1988. Lord Cullen in his report (Cullen 1990), recommended that QRA should be introduced into UK legislation in much the same way as in Norway nearly 10 years previously. In 1991, the NPD replaced the 1981 guidelines for risk assessment by Regulations for Risk Analysis (NPD 1990) which considerably extended the scope of these studies. In 1992, the offshore industry in the UK has been required to perform risk assessments as part of the safety cases for both existing and new installations. The use of QRA studies was rapidly expanded under the new regulations. The next step in this brief historical review is the blast and fire research carried out as part of the Blast and Fire Engineering for Topside Systems (BFETS) program (SCI 1998) which was undertaken in the period 1996–1998. This has focused attention on the high blast loads caused by possible gas explosion scenarios on the platforms. As a result of this work considerable attention is now being given to evaluating how explosion scenarios may be included probabilistically in QRA models. NPD published a new set of regulations in 2001, which replaced the risk analysis and technical regulations from 1st January 2002. The requirement for risk analysis and other analyses are stipulated in the Health, Environment and Safety (HES) Management regulations. These regulations have requirements for analysis of risk as well as requirements for the definition of risk tolerance criteria. The Safety Case regulations were modified in 2005 and these revisions came into force from 5th April 2006. The structure of the Norwegian regulations changes in 2007, due to the need to integrate more fully the regulations for offshore and onshore facilities. These changes were temporary and were superseded by permanent changes, when the structure of the Norwegian regulations was changed again from 1st January 2011.

According to the NORSOK standard Z-013 (Standard Norway 2010), QRA is a systematic methodology and has to be focused on identification of applicable hazards and description of applicable risks to personnel, environment and assets. The analytical elements of QRA are illustrated in Fig.2 in accordance with the bow-tie diagram, and mainly include the following steps (Vinnem 2014):

(1) Identification of initiating events

(2) Cause analysis

- qualitative evaluation of possible causes
- probability analysis in order to determine the probability of certain scenarios

(3) Consequence analysis

- consequence loads, related to physical effects of accidents
- response analysis, related to the response of the facilities, when exposed to accidental loads
- probability analysis, related to the probability that these loads and responses occur
- quantification of consequences in terms of injury to personnel, damage to the environment and to assets.

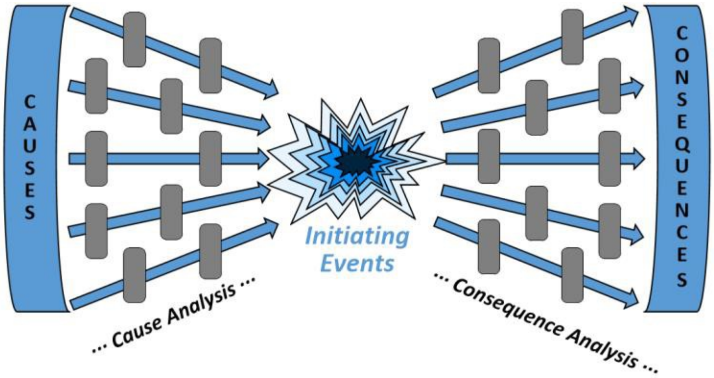

Fig.2. Model for representation of the analytical elements of QRA

The offshore petroleum industry has for a long time invested considerable resources in engineering defenses, or barriers, against fire and explosion hazards on the installations. Therefore, the current generation of QRA in the offshore petroleum industry has traditionally been focused on technical systems and capabilities. Nevertheless, some changes in the offshore petroleum industry have developed over the last few years, both in the UK and in Norway. The trend and focus are on the operation of existing installations, extending the operational life of some of these installations as well as using new subsea installations. This implies that operational safety is receiving more and more attention in contrast to design safety, in order to mitigate hazards and control risks. The need for understanding HOFs in all phases has also been pointed out by the HSE (HSE 2003). Hence, it is of great importance for QRA in the offshore petroleum industry to include an explicit representation of the effects of HOFs. Therefore, integration of HOFs into QRA is of great importance to the offshore petroleum industry. A conceptual model in regard to HOFs is illustrated in Fig.3.

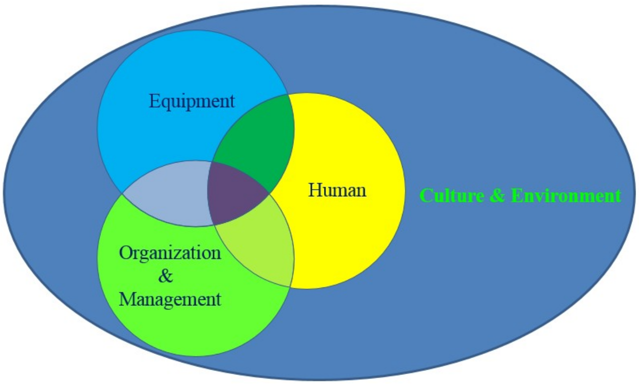

Fig.3. Conceptual model in regard to HOFs

2.2 Human and organizational factors (HOFs)

Human factors can be seen as a range of issues, including the perceptual, physical and mental capabilities of people, as well as the interactions of individuals with their jobs and the working environments, the influence of equipment and system design on human performance and, above all, the organizational characteristics that influence safety-related behavior at work (Skogdalen and Vinnem 2011). Other variations in the definition of human factors also exist (Dempsey et al. 2006). There are three areas of influence on people at work, namely: the organization, the job and personal factors. These are directly affected by (1) the system for communication within the organization and (2) the training systems and procedures in operation, all of which are directed at preventing human error (Stranks 2006). Human factors are understood as the branch of science and technology, which includes what is known and theorized about human behavioral and the biological characteristics that can be applied validly to the specification, design, evaluation, operation and maintenance of products and systems to enhance safe, effective and satisfactory use of individuals, groups and organizations (Goodwin 2007). It should be noted that the terms ‘human factors’ and ‘human error’ are often used interchangeably. However, it is important to distinguish between the underlying causes of accidents (human factors) and their immediate causes (human errors) (Gordon 1998; Schönbeck et al. 2010; Jacobs and Haber 1994).

Organizational factors are characterized by the division of tasks, the design of job positions including selection, training and cultural indoctrination and their coordination to accomplish activities. The main issues of organization and safety include factors such as complexity, size and age of the plant, and organizational safety performance shaping factors such as leadership, culture, rewards, manning, communications and coordination and social norms and pressures (Bellamy et al. 2008).

RIFs are introduced to model "soft" relations between HOFs and the parameters in the QRA model. A risk influencing factor may be defined as an aspect of a system or activity that affects the risk level of this system/activity (Øien 2011b). RIFs can also be understood as "a set of conditions which influence the level of specified risks related to a given activity or system" (Rosness 1998). The condition refers to a relatively stable property of the system or its environment (Rosness 1998; Hokstad et al. 2001). In principle, a RIF is considered as a theoretical variable and it may or may not be specified how to measure this variable. One hypothesis is that risk control can be achieved through the control of changes in the RIFs. Conditions for this hypothesis to be true are that: (1) all relevant RIFs are identified, (2) the RIFs are "measurable", (3) the relationship between the RIFs and risk is known (Vinnem et al. 2012). In a given context, the RIFs are considered as "true" underlying properties of the system being analyzed. It should be noted that a given RIF (denoted a 'theoretical variable') might not have a sufficiently unambiguous definition for empirical studies and thus it might not be directly measurable. Risk indicator, as a measurable representation of the RIF, is introduced as a measurable or operational variable of theoretical RIFs (Øien 2001a, 2011b). Parameter representations of the RIFs are shown in Fig. 4.

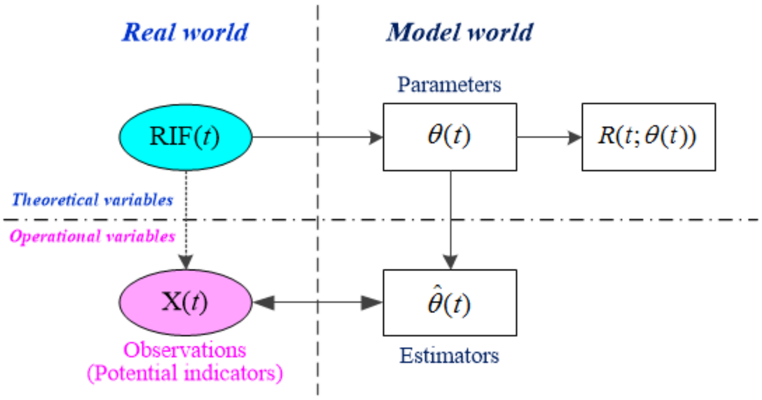

Fig.4. Parameter representations of the RIFs

2.3 Safety barrier

It is central to define and model safety barriers for the formal inclusion of HOFs into QRA. In accordance with the NPD regulations (NPD 2001, 2002), safety barriers shall be established which reduce the probability that any failures, hazardous situations and accidents will develop further, and limit possible harm and nuisance. It is further stated that safety barriers may be physical or non-physical, or a combination thereof. The concept of safety barriers can thus be defined as physical and/or non-physical means planned to prevent, control or mitigate undesired events (Sklet 2006; Sklet 2005). It indicates that the scope of the safety barrier may range from a single technical unit or human actions to a complex socio-technical system. In line with the ISO standard: 13702 (ISO 1999), the term 'prevention' means a reduction of the likelihood of a hazardous event and 'control' means limiting the extent and/or duration of a hazardous event to prevent escalation, while 'mitigation' means a reduction of the effects of a hazardous event. Undesired events may be technical failures, human errors, or a combination of these occurrences that may realize potential hazards, while accidents are undesired and unplanned events that lead to loss of human lives, personal injuries, environmental damage, and/or material damage (Sklet 2006; Sklet 2005).

In order to propose or unify definition used when applying the concept of safety barrier in the offshore petroleum industry in Norway [47], the terminology of safety barrier involves the following levels: barrier function, barrier system, barrier element and barrier influencing factor. The definition and differences between these levels are presented as follows:

- Barrier function: A function planned to prevent, control, or mitigate undesired events or accidents.
- Barrier system: Technical, human and/or organizational measures designed and implemented to perform one or more barrier functions.
- Barrier element: A component of a barrier system that by itself is not sufficient to perform a barrier function.
- Barrier influencing factor: Conditions that influence the performance of barrier systems.

The relationship among barrier function, barrier element and barrier influencing factor is illustrated in Fig.5. For more thorough discussion on the concept of safety barrier, one can refer to the literature (Sklet 2006; Duijum 2009).

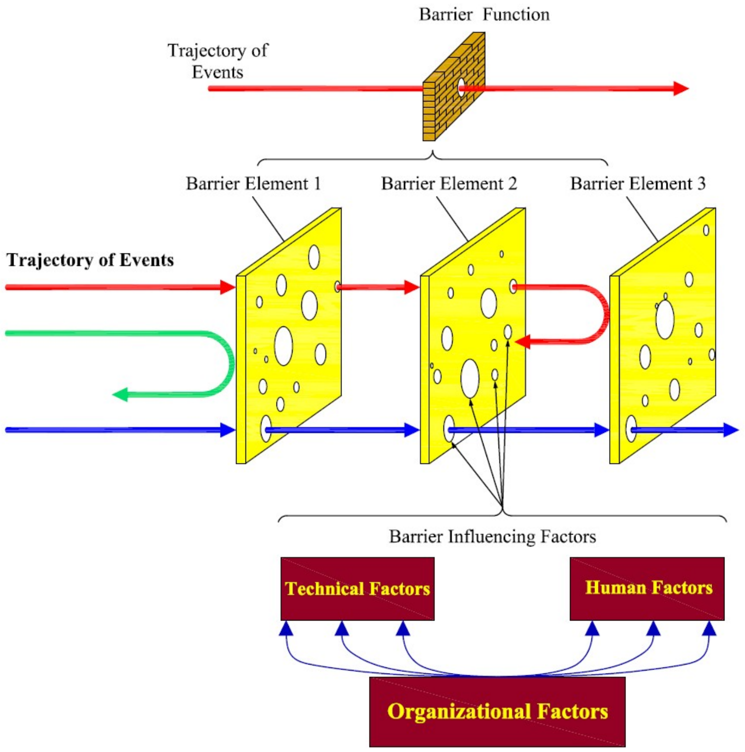

Fig.5. Relationship among barrier function, elements and influencing factors

3. Models review

The review focuses on both the qualitative and quantitative aspects of the different QRA models that formally include an explicit representation of the effects of HOFs. The qualitative aspects cover RIFs, RIF structures, link to the system risk model, modelling technique and input data. These elements demonstrate how RIFs interface with the QRA models. The quantitative aspects focus on the measurement methods, which cover the rating and weighting processes, propagation algorithm and the modelling of interactions between RIFs. These elements demonstrate how RIFs are integrated into quantitative estimation of risk. The results of the review are discussed from three aspects: the frameworks of QRA, the methodologies for the analysis, and the collation of the input data.

3.1 The frameworks of QRA

3.1.1 Risk influencing factors and their structures

The basis for identification of RIFs is the generic list of RIFs. The sources of RIFs of the models are mainly based on a review, comparison, and synthesis of several schemes of classification of human, technical, and organizational factors and experience from the case study. The schemes include classification of (1) causes in the accident/incident databases; (2) organizational factors in models for analysis of the influence of organizational factors on risk; (3) performing shaping factors (PSFs) in methods for human reliability analysis (HRA); (4) organizational and human failure theories.

Table 1

Generic RIFs and their structures from different models

Model	Generic RIFs and their structures					
ORIM	*1 level RIFs*					
	Individual factor	Training/competence	Procedures, JSA, guidelines, instructions	Planning, coordination, organization, control	Design	PM- program/ inspection
BORA	*1 level RIFs*					
	^{P}:Personal characteristics;	^{T}:Task characteristics;	^{C}:Characteristics of the technical system;	^{A}:Administrative control;	^{O}:Organizational factors/ operational philosophy;	
	Competence ^{P} Working load/stress ^{P} Fatigue ^{P} Work environment ^{P}	Methodology ^{T} Task supervision ^{T} Time pressure ^{T} Task complexity ^{T} Tools ^{T} Spares ^{T}	Equipment design ^{C} Material properties ^{C} Process complexity ^{C} HMI ^{C} Maintainability/ accessibility ^{C} System feedback ^{C} Technical condition^{C}	Procedures ^{A} Work permit ^{A} Disposable work^{A} description ^{A}	Programs ^{O} Work practice ^{O} Supervision ^{O} Communication ^{O} Acceptance criteria ^{O} Simultaneous activities ^{O} Management of changes ^{O}	
OTS	*1 level RIFs, associated performance requirements and a set of associated checkpoints* 1) Work practice; 2) Competence; 3) Procedures and documentation; 4) Communication; 5) Workload and physical working environment; 6) Management; 7) management of change					
HCL	The same to the BORA					
Risk_OMT	*2 level RIFs* (^{P}: Planning activities; ^{E}: Execution and control activities) *Level 2 RIFs—Influence on level 1 RIFs; Level 1 RIFs—influence to human error*					
	Mgmt_competence^{P,E}	Mgmt_information^{P,E}	Mgmt_general^{P,E}	Mgmt_task^{P,E}	Mgmt_technical^{E}	
	Competence^{P,E}	Disposable work description^{E} Governing documents^{P,E} Technical documentation^{P,E}	Communication^{P,E}	Supervision^{E} Time pressure Work load^{P,E} Work motivation^{P,E}	Design^{E} HMI^{E}	
Petro-HRA	*1 level RIFs* 1) Time; 2) Threat Stress; 3) Task Complexity; 4) Experience/Training; 5) Procedures; 6) Human-Machine Interface; 7) Attitudes to Safety, Work and Management Support; 8) Teamwork; 9) Physical working environment.					

The detailed taxonomy of generic RIFs and their structures of different models are summarized in Table.1. It can be found that the amount of similarities between the different models with respect to the RIFs is rather limited.

Nonetheless, there is no big surprise since the classifications and sources of generic RIFs between different models have significant differences (Øien 2001a; Wilpert 2000).

The ORIM covers a limited part of the risk model, focusing on one specific parameter (the leak frequency). Thus, the RIFs included in the model are only those that may contribute to leaks, which are much less than the total number of RIFs included in the loss causation model. It is emphasized that the ORIM is a balance between a theoretical, complete model and a practical, usable model. Thus, RIFs that are rarely involved (e.g. once in three years) or the most remote type (e.g. management commitment to safety) are not included in the model. The RIFs are mainly identified from the causal analysis of previous leak events and can be divided into three subsets. The first is the 'individual factor', covering a variety of reasons for slips and lapses. The second subset is 'training/competence', which represents some of the main responsibilities of the operational management. The third subset of RIFs is 'design' and 'preventive maintenance (PM) program/inspection', which represent constraints for the operation and management of the offshore installations. The RIF structure used in the ORIM modelling was a one level structure, where all RIFs were given the same structural importance.

The BORA model presents a generic risk model of quantification of the leak frequency, and a complete modelling and analysis of safety barriers on offshore production installations, including the installation specific conditions of technical, human, operational, and organizational RIFs. The RIFs are characterized into five groups, which are: (1) personal characteristics, (2) task characteristics, (3) characteristics of the technical system, (4) administrative control, and (5) organizational factors/operational philosophy. The RIF structure is a one level structure, where all RIFs are given the same structural importance. The proposed RIF framework and the taxonomy of generic RIFs are mainly identified from causes in methods for accident investigations (MTO-analysis (Bento 2001), TRIPOD (Groeneweg 1998)), organizational factors in models (I-RISK (Bellamy et al. 1999), WPAM (Davoudian et al. 1994; Jacobs and Haber 1994)) and performing shaping factors (PSFs) in methods from human reliability analysis (HRA) (THERP (Swain and Guttmann 1983), CREAM (Hollnagel 1998), SLIM-MAUD (Embrey et al. 1984)) and HRA database (CORE-DATA (Gibson et al. 1998)).

As indicated in Fig.1, the OTS project is based on the modelling in the BORA project and has given the opportunity to study the HOFs in a more detailed manner. The OTS model includes seven organizational factors condensed from the literature study: (1) work practice, (2) competence, (3) procedures and documentation, (4) communication, (5) workload and physical working environment, (6) management, (7) management of change. Each RIF is associated with a set of performance requirements and checkpoints that are used to verify to what extent these requirements are met. It can be noted that the RIFs are structured in one level in the BORA model while the OTS model has a three-level hierarchical structure. The total number of requirements that are considered is 50 and 291 checkpoints are applied in the verification process.

During the development of the HCL model, the main focus has been on the aviation industry at the outset (Wang and Mosleh 2005; Groen and Mosleh 2006). The applicability of the HCL model for the offshore petroleum industry was presented and discussed later (Røed et al. 2009;). The BORA model is used as a basis for the suggested application procedure. Thus, the identified RIFs are the same as the BORA model. Note that RIFs in the HCL model can interact with each other, which differs greatly from the RIF structure in the BORA model.

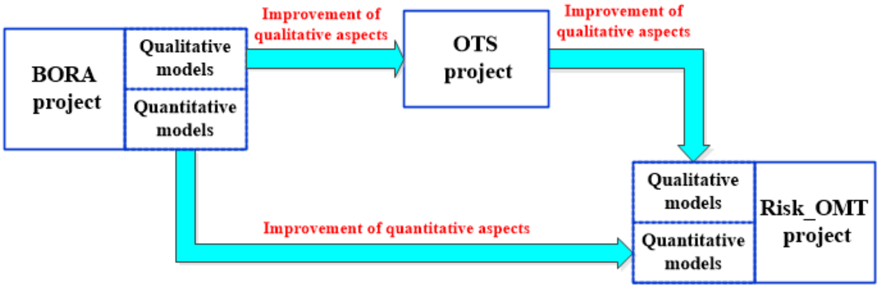

Fig.6. The relationship among the BORA, OTS and Risk_OMT projects (Vinnem et al. 2012)

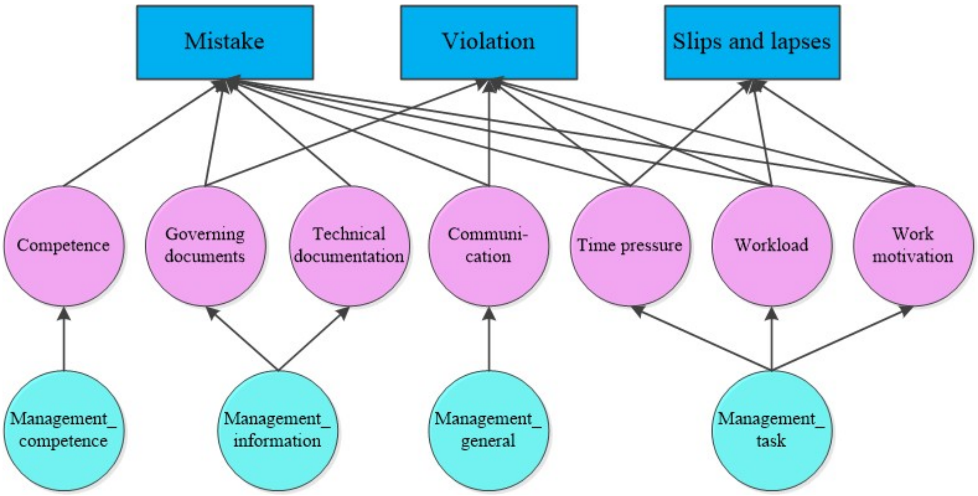

Fig.7. Generic RIF model for planning activities (Vinnem et al. 2012)

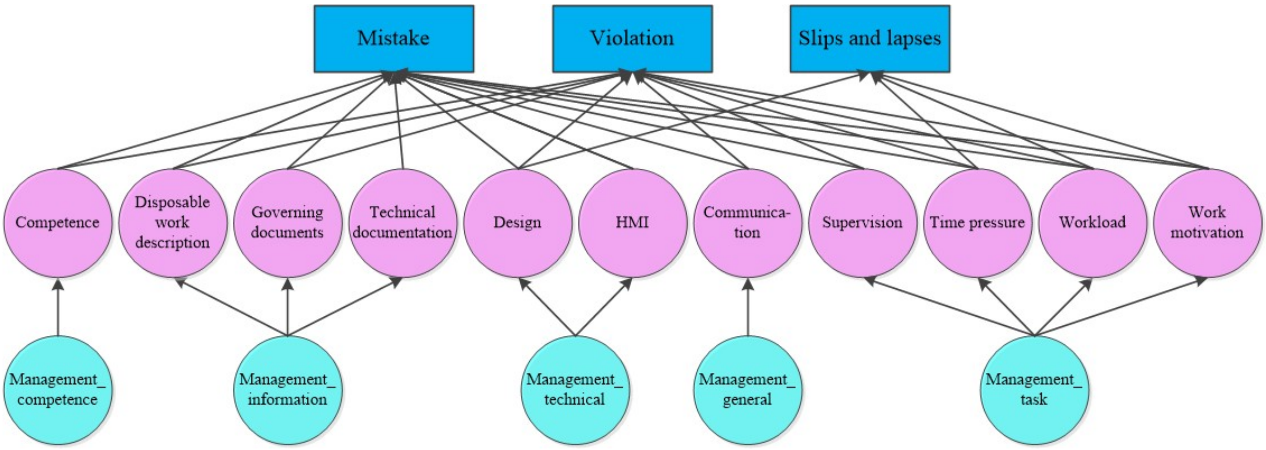

Fig.8. Generic RIF model for execution and control activities (Vinnem et al. 2012)

The Risk_OMT model represents a further development of the work in the BORA and OTS projects. The relationship among the BORA, OTS and Risk_OMT projects is illustrated in Fig.6. The Risk_OMT model examines eight scenarios and their associated activities, and two generic RIF models are proposed for 1) planning activities, and 2) execution and control activities, respectively. The RIFs are structured in two levels. Level 1 consists of RIFs with a theoretically and empirically justified direct influence on one or more of the error types.

Level 2 represents different aspects of management that have a theoretically and empirically justified influence on the RIFs on level 1. The two levels RIF structure were chosen to emphasize and elucidate the underlying impact of managerial decisions on the probabilities of human failure. It is worth noting that a three level structure of RIFs was considered initially, but was considered to be too complex, and therefore left. RIFs on Level 2 are considered only to influence RIFs on Level 1, and represent a means to reduce the uncertainty implied by observations of RIFs only on Level 1 with associated scores. Scores and influence from RIFs on Level 2 are used together in order to provide information about the true value of the RIFs. The generic RIF models for planning and execution activities and control activities are presented in Figs. 7-8, respectively.

As has been noted, though HRA is not in this line of research for the formal inclusion of HOFs into QRA, the RIFs and their structures of the Petro-HRA method are worthwhile to be considered in some detail. There are nine RIFs in Petro-HRA: (1) time, (2) threat Stress, (3) task complexity, (4) experience/training, (5) procedures, (6) human-machine interface, (7) attitudes to safety, wok and management support, (8) teamwork, and (9) physical working environment. These RIFs are identified via scenario walk-/talk-through, observation, interview and documentation review. Each RIF has several levels with corresponding multipliers, which are used to calculate the human error probability.

3.1.2 Link to the system risk model

With respect to the link from RIFs to the system risk model, the proposed approaches mainly rely on implicit functions relating RIFs to probabilities/frequencies. Hence, all reviewed models are developed for the formal inclusion of HOFs into QRA by updating the probabilities/frequencies of the failure events.

The ORIM employs the leak frequency parameter as the link to the system risk model. In the BORA and HCL models, the installation specific input probabilities/frequencies for the failure events are employed as the link to the system risk models. The Risk_OMT model links RIFs to the system risk model by updating the failure probabilities of basic events in the fault trees.

3.1.3 Modelling techniques

Though the modelling techniques differ between the reviewed models, it can be concluded that there are mainly two modelling techniques: (1) Influencing diagram and (2) Bayesian networks. The ORIM, HCL and Risk_OMT models make use of the Bayesian networks. Thereinto, in the ORIM, a regression-based technique is also used to model the relationship between the leak frequency and RIFs. In the BORA model, the influencing diagram is used to take the installation specific conditions of RIFs into account. More Bayesian networks related QRA articles in the domain of the offshore petroleum industry are reviewed in (Cai et al. 2013; Cai et al. 2018; Khakzad et al. 2013; Zhang et al. 2018).

3.2 Methodologies for the analysis

The measurement methods cover the rating process, weighting process and propagation algorithm. In particular, the review also pays close attention to how interactions between RIFs are treated in the models.

3.2.1 Rating of RIFs

Rating of RIFs means to assess the status of the RIFs. It is a measure of the state of the specific RIF. The aim is to assign a score to each RIF. It can be concluded that there are mainly five approaches for rating of the RIFs: (1) using indicators (measurable variables) (ORIM), (2) using RIF audit aided by behaviorally checklists and behaviorally anchored rating scales (BARS) (Jacobs and Haber 1994) (BORA, HCL, Risk_OMT), (3) using results from the Technical Condition Safety (TTS) project (Thomassen and Sørum 2002) (BORA, HCL, Risk_OMT) and OTS project (Risk_OMT), (4) using results from the RNNS (Risk Level on the Norwegian Continental Shelf) project (PSA 2005) (BORA). (5) using expert evaluation (HCL). It can be seen that these approaches can be used separately or combined for assessing the status of RIFs. Note that the credibility of the status assessment is one important aspect to consider when the approaches are selected.

3.2.2 Weighting of RIFs

The weighting of RIFs means to assess the effects that the RIFs have on risk directly or indirectly through intermediate factors or parameters in the risk model. The existing models suggest using expert judgment or a data-driven approach for the assignment of weights.

The ORIM and HCL models establish conditional probability tables for the dependent variables. Each single distributed value (i.e. a conditional probability) represents a weight. The weighting process of the ORIM model is illustrated in Fig.9. It can be seen that a Cox-like regression model is used in order to establish the conditional probability table, and maximum likelihood estimation (MLE) is used to obtain the regression coefficients. The covariate values are estimated based on the statistical model (92 leak events in the period 1997-1999). The HCL model presents a suggested method for determining the weights by considering the ‘distance’ and a few parameters assigned by the analysts. The weighting process is demonstrated by use of the example, as illustrated in Fig.10: (1) Determine by expert judgment the relative change in the expectation value $E(M)$ when K is changed from the state a to state f, and L is locked to state c. (2) This procedure is repeated to determine the relative change in the expectation value $E(M)$ when L is changed from the state a to state f, and K is locked to state c. (3) The resulting results are normalized and are applied as weights of K and L.

In the BORA and Risk_OMT models, the weighting of the RIFs is accomplished by expert judgement. Quantitatively, the RIFs are given relative weights. For instance, in the BORA model, “Compare the importance of the other RIFs with the most important one, and give them relative weights on the scale 10-8-6-4-2”. In final, the weights are normalized as the sum of the weights should be equal to 1.

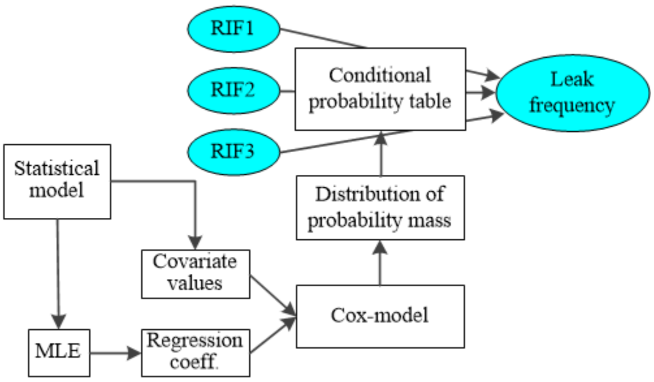

Fig.9. Weighting process of the ORIM model

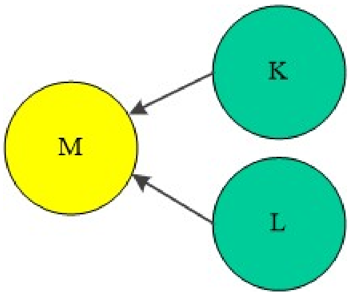

Fig.10. Illustration example of BBN

3.2.3 Propagation algorithm

When individual scores and weights are assigned to the RIFs, the scores and weights are combined and aggregated so as to reflect the total effect of RIFs on risk. This effect will be propagated through the model if the RIF structure has more than one level. It can be seen that the propagation algorithm is the way in which the scores and the weights of the RIFs are combined and aggregated.

It can be concluded from all the reviewed models that there are mainly two approaches of propagation. One approach is the sum of products (BORA), in which the scores and weights of the RIFs are multiplied and then added. It can be noted that this propagation algorithm is static, which means that the status and the weights of the RIFs can only be assessed for the present states. The other approach is to make use of the technique of Bayesian networks (ORIM, HCL, Risk_OMT). In this case, every possible combination of the status of the RIFs are given a score (unconditional joint probability) and a weight (conditional probability) that are multiplied and summarized.

3.2.4 Modelling of interactions between RIFs

Interaction effects among the RIFs imply that a RIF will have a different effect on the basic event, depending on the status of the other RIFs (Aven et al. 2006b). In the BORA model, a simple approach is suggested for analysis of interaction effects among the RIFs. If two or more RIFs are assumed to interact with each other and the states are worse than the average (D, E or F), the score of one of them will be reduced one category (e.g. from D to E), and similarly, if the scores of two interacting RIFs are better than the average, the score of one of them will be promoted one category. In the ORIM and HC models, the interactions between the RIFs are more accurately modelled automatically by use of conditional probability tables in the Bayesian networks.

Aiming to simplify the modelling of interaction effects, the Risk_OMT model introduces interaction effect factor W_I and sums the interaction effects for one subset of interactions to the original weighted sum in order to obtain the conservative results. Some critical aspects for modelling of interaction effects between RIFs should be noted: (1) Only negative effects where low values of two or more RIFs strengthened the negative influence on the basic event are treated. (2) Interaction effects are only modelled between the level 1 RIFs.

3.3 Collation of the input data

It is recognized that the choice of input data is of great importance as well as challenging to obtain. The total input data could be divided into two categories: the generic data and the installation specific data. The generic data include initiating event frequencies, basic event probabilities and weights of the RIFs. The installation specific data go into the quantification of the status of specific RIFs. More often than not, expert-based data are generated to compensate for lack of the generic data.

In the ORIM, the generic data basis for establishing leak frequency distributions has been 92 leak events from three installations in the same oil field in the period 1997-1999. The installation specific data for quantifying the status of the RIFs are obtained from indicator measurements. In the BORA model, the data basis for establishing leak frequency distributions has been 94 gas leaks that have been reported to PSA. The period is covered from 2002 to 2005, with some few leaks from the period before that. Regarding to the data basis for quantifying the effects of human error, the following data sources are reviewed: Swain and Guttman (1983), Reason (1997), Blackman and Gertman (1994), Kirwan I (1994), Kirwan II (1998). The data basis of the BORA model is used for the application procedure suggested by the HCL model. These data are also used as the basis for the assessment of generic HEPs in the Risk_OMT model. The generic HEP data presented in the SPAR-H (2004) and HEART (1988) methods are also considered in the Risk_OMT model. In addition, the observed data from the OTS project also provide a basis for quantifying the status of specific RIFs as well as the effects of human error.

It can be noted that how to collate a sufficient amount of the input data is a key in all reviewed models. Collation of the large database can be classified into three groups, namely collation of nominal human error probabilities, collation of data for scoring of RIFs and collation of data for weighting of RIFs. Thereinto, the collation of nominal human error probabilities is mainly based on recognized sources. As a general reflection, available human reliability data appear to be limited, when it is requested that the data shall be directly applicable for the specific project. Hence, the recommendation has always been made that human error probability data which is specific to the offshore petroleum industry should be collated. The way to collate sufficient amount of data for scoring RIFs can be summarized as follows.

- Collation of data specifically through work meetings collecting expert judgment.
- Collation of data specifically through questionnaire surveys.
- Collation of data specifically through MTO (Man, Technology and Organization) investigations.

With respect to collation of data for weighting of RIFs, there is little information available in practice. The relevant stakeholders are normally dependent on being able to arrange work meetings.

4. Development of failure models with major accident precursors (hydrocarbon leaks)

It can be noted that all the reviewed models are primarily developed for loss of containment on process equipment on offshore petroleum installations in the Norwegian petroleum sector. Thus, a detailed analysis of a substantial data set of actual leaks that have occurred in the Norwegian sector during 2006-2010 is carried out, in order to pinpoint the weaknesses and challenges of the existing models. It could be possible to use data from a longer period, but the advantage of using the selected period is that it is a period with a consistent level around 14-15 leaks per year for the entire Norwegian sector (Vinnem 2013). As has been noted, with respect to QRA in the offshore petroleum industry, the Risk_OMT model not only is the latest and the most comprehensive QRA model that includes an explicit representation of the effects of HOFs, but also represents a further development of the work in the BORA and OTS models. Given this, the emphasis in this work is placed on the Risk_OMT model while the same goes for other reviewed models.

4.1 Overview of hydrocarbon leaks

Fig. 11 shows an overview of the immediate circumstance of all leaks on the Norwegian Continental Shelf (NCS) with initial HC leak rate above 0.1 kg/s, which have escalation potential. The classification is on the basis of the BORA project (Haugen et al. 2007) with the following main categories:

- Technical degradation of the system (Category A)
- Human intervention
  - Introducing latent error (delayed release) (Category B)
  - Causing immediate release (Category C)
- Process disturbance (Category D)
- Inherent design errors (Category E)
- External events (Category F)

It can be seen from Fig.11 that the leaks associated with human intervention are dominating, with over 60% in the period 2006-2010. These interventions represent maintenance work, inspections and modifications. Actually, this percentage has been stable at between 50% and 60% for more than 15 years (Vinnem 2018) and indicates that human intervention is the most significant cause for HC leaks on offshore petroleum installations.

In Fig.12, a further breakdown of the category of human intervention (B & C) is performed. It is clearly shown that incorrect fitting of flanges or bolts (B2) and valves in the wrong position after maintenance (B3) are the two dominating causes, with a total of 60% of the HC leaks. Note that the ‘latent’ in the category B does not apply to the error, but to the conditions that will produce the leak. In addition, some leaks are associated with more than one error, and thus the number of leaks in Fig. 12 does not match the number presented in Fig.11.

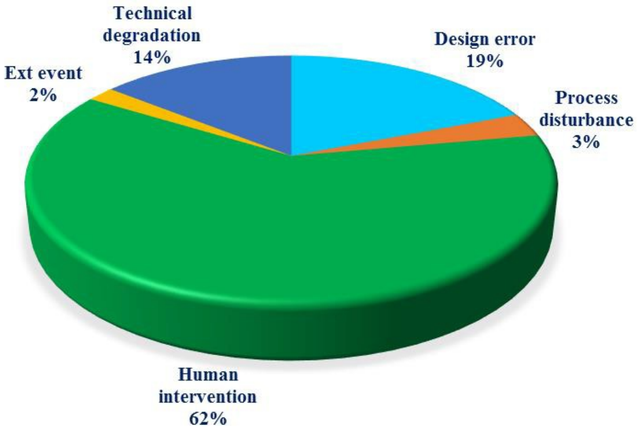

Fig.11. Hydrocarbon leaks distributed on operational circumstances, NCS, 2006-2010 (n=63)

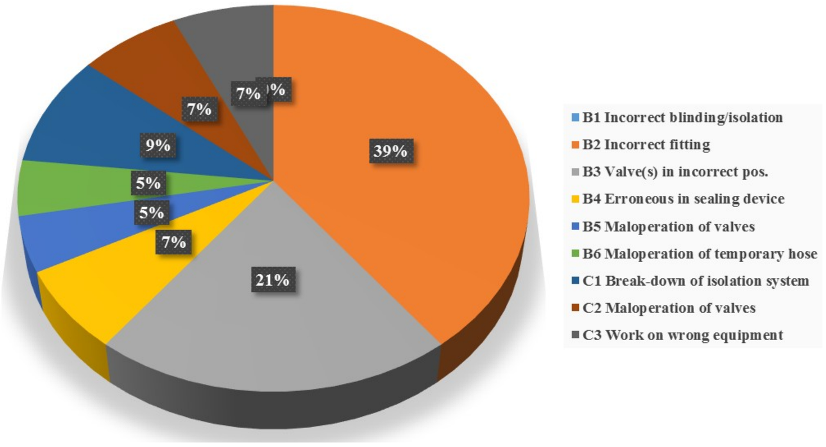

Fig.12. Distribution of detailed circumstances for errors during the manual intervention (n=43)

4.2 Modelling of leaks during work processes

Work processes are defined in procedures and involve a long list of steps. Different offshore petroleum companies have different work processes while common among these are the following steps:

1. Planning
2. Preparation
3. Execution
4. Reinstatement (resetting)

Fig.13 presents a model of the work process flow, where the steps of verification are explicitly marked. There will be differences between how different companies implement such a work process while not extensive, as a common system for Work Permits is used for all companies in the Norwegian sector. It is clearly shown that the planning, the implementation of the isolation plan, the execution and reinstatement are all subjected to verification activities, in order to reveal errors that have been made, either during the planning, preparation, execution or reinstatement phase.

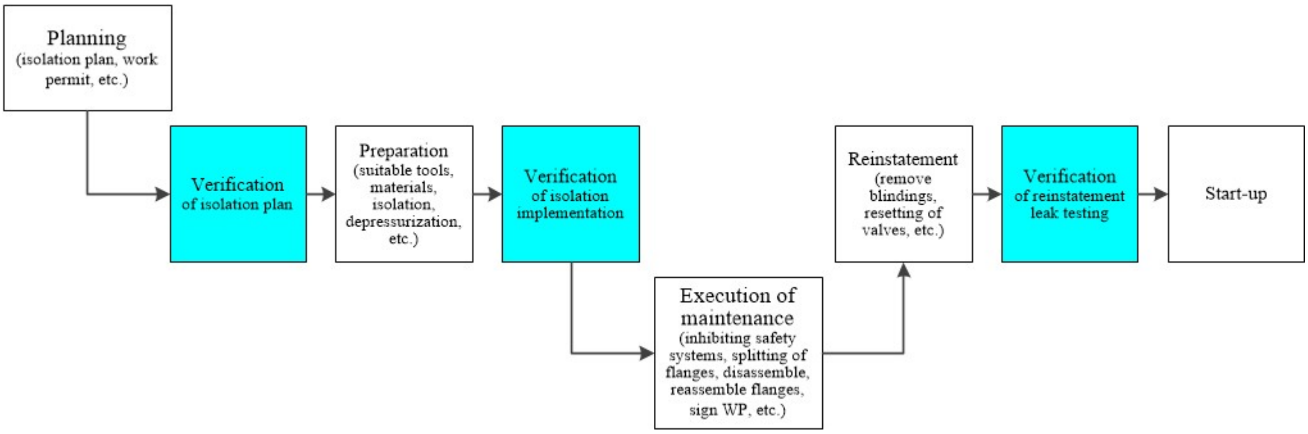

Fig.13. Overview of work process flow (Vinnem 2013)

4.3 Findings from leaks with respect to the operational barrier

In the Risk_OMT model, the modelling principle for operational barriers is illustrated in Fig.14. As presented in Fig.13, immediate causes B1-B4 for HC leaks during manual intervention account for nearly 70%. Hence, the discussion in this section is limited to the categories B1-B4. Fig.14 shows that there are two independent barrier elements; End control 1 and End control 2. The operational barrier elements are physical or non-physical actions taken by operators to carry out work or verification tasks in accordance with procedures and/or instructions. This indicates that a very reliable system can be achieved when two parallel verification barriers for the tasks are modelled. Hence, the HC leaks occur only when the following errors are combined:

- Error in the execution of the work task (Initiating events)
- Error during End control 1 (Independent verification)
- Error during End control 2 (Leak test)

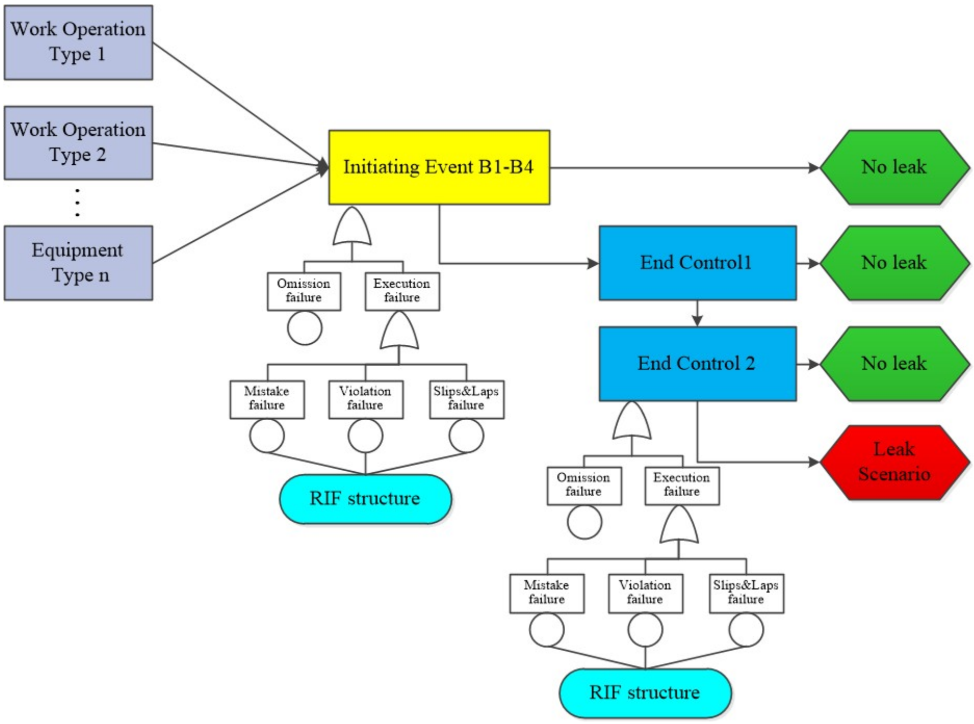

Fig.14. Modelling principle for operational barriers in the Risk_OMT model (Vinnem et al. 2012)

The question is however, is this a reasonable representation? Table 2 summarizes the number of leaks that resulted from the categories B1-B4 in different phases. It can be seen that only seven out of 22 leaks (total number of leaks that resulted from the categories B1-B4 is 29, but the information for seven leaks is unavailable.) occur after start-up of the process equipment in question. This implies that two-thirds of the HC leaks will occur before the leak test (End control 2) is carried out. This means that in most of the circumstances, the two parallel verification barriers as presented in Fig.14 are not available. Hence, a system which could be very reliable with three barriers (including the correct execution of the work tasks) is reduced to a maximum of two barriers in the majority of cases.

Based on the above statistical data and analyses, it is suggested that there is a need to improve the modelling for leak scenarios, where two additional barriers (not considering the correct execution of the work tasks) are available in one third of the leaks while for two thirds of the leaks, there is only one addition barrier available.

It can be noted that with respect to the improved modelling for leak scenarios, the verification of the work process steps will be of great importance as it is often that there is only on independent barrier available. More emphasis and focus should be placed on the performance of the work process steps and verifications.

Table 2

Summary of the number of leaks that resulted from the categories B1-B4 in different phases

Phase Fault	Preparation	Execution	Reinstatement	After start-up
Planning	0	1	4	1
Preparation	0	0	0	1
Execution	0	0	5	3
Reinstatement	0	0	5	2

5. Discussion

5.1 Comparisons and limitations among reviewed models

The overall comparison is performed by considering both the qualitative and quantitative elements of the reviewed models. These elements are categorized as follows: RIFs and their structures, link to the risk model, modelling technique, measurement method and input data. The comparison results are presented in Table.3.

It can be generally inferred from the comparison results (Table.3) that all the existing models have the same motivation to incorporate HOFs into the risk picture quantitatively. Applications of these models in the offshore petroleum industry can give a more detailed risk picture than the current generation of QRA where the analysis of non-technical RIFs are missing. It can also be found that the existing models have some similar steps and elements while different models also have their own unique features. The key questions in this line of research can be summarized as: (i) What are the RIFs that affect the risk? (ii) How do these factors influence the risk? (iii) How much do these factors contribute to the risk? It can be found from Table.2 that each model answers these questions in their own ways. The common lack from all the existing models is a fully implemented model for the underlying causal mechanisms linking measurable RIFs. In addition, the existing models still rely on implicit functions relating RIFs to frequencies/probabilities while insufficient theoretical and/or experimental basis can be provided for such relations (Skogdalen and Vinnem 2011). It can be concluded that a major problem that extends to all the existing models is that there is not an adequate basis to assess the validity or to build the confidence in these models in the absence of a comprehensive theory. Therefore, the studies in this line of research are focused on the possibility of improving the theoretical understanding of the relationships between the character of organizations and safety output (Mohaghegh and Mosleh 2009). The systematic principles and theoretical framework for incorporating HOFs into QRA should be further developed and validated specifically in the offshore petroleum industry.

Table 3

Comparison among QRA models integrating HOFs

Model		ORIM	BORA	OTS	HCL	Risk_OMT	Petro-HRA
RIFs and structures		1level RIF: Human factors; Organizational factors	1 level RIF: Human factors; Organizational factors; Technical factors; Operational factors	1 level RIF: Human factors; Organizational factors (associated with performance requirements and checkpoints)	Not specified. (Considered as the same to BORA)	2 level RIFs: Level 1-direct RIFs to human failures Level 2-indirect RIFs represents management	1 level RIFs: Each human factor has several levels with corresponding multipliers.
Link to the risk model		Leak frequency parameter	Failure frequencies/ probabilities of initiating events and basic events	NA	Failure frequencies/ probabilities of initiating events and basic events	Failure frequencies/ probabilities of initiating events and basic events	NA
Modelling technique		Bayesian networks	Influence diagram	NA	Bayesian networks	Bayesian networks	NA
Measurement method	Rating of RIFs	Indicator measurement	1) RIF audit 2) Results from TTS project 3) Results from RNNS project	NA	1) Results from TTS project 2) Expert evaluation	1) RIF audit 2) Results from TTS project 3) Results from OTS project	NA
	Weighting of RIFs	1) Data-driven method 2) Expert judgment	Expert judgment		Expert judgment	Expert judgment	
	Propagation algorithm	Bayesian networks	Sum of products		Bayesian networks	Bayesian networks	
	Interaction	Conditional probability tables (CPT)	Converting one category as for the score of one of interacted RIFs		Conditional probability tables (CPT)	Introduction of interaction effect factor W_I	
Input data		1) 92 leak events (1997-1999) 2) Observed data from indicators	1) 94 gas leak events (2002-2005) 2) Swain and Guttman 3) Reason 4) Blackman and Gertman 5) Kirwan I & Kirwan II	Literature study	Not specified. (Considered as the same to BORA)	1) 94 gas leak events (2002-2005) 2) Swain and Guttman 3) Reason 4) Blackman and Gertman 5) Kirwan I & Kirwan II 6) SPAR-H 7) HEART 8) Observed data from OTS project	1) Scenario walk-/talk-through 2) Observation 3) Interview 4) Documentation review

As a general reflection from the input data, it can be seen that available human reliability data appear to be rather limited and challenging, when it is requested that they shall be directly applicable for these models. In many cases, data are the result of expert elicitation using arbitrary scales (Skogdalen and Vinnem 2011; Mosleh and Chang 2004). Up to now, the latest study on quantitative assessment of human reliability in the offshore petroleum industry is the Petroleum-Human Reliability Analysis (Petro-HRA) (Bye et al. 2016; Taylor et al. 2017; Bye et al. 2017), which can be used to estimate the likelihood of human failure events (HFEs) in post-initiating event scenarios.

Moreover, advantages and disadvantages of reviewed models are compared and summarized in Table. 4.

Table 4

Advantages and disadvantages of reviewed models

Model	Advantages	Disadvantages
ORIM	1. The modelling technique is flexible and realistic causal relationships can be expressed. 2. A more precise quantitative link between the performance of RIFs is provided. 3. A comprehensive framework is provided. 4. Weighting process is data-driven	1. Remote organizational factors are not covered explicitly. 2. Risk-reducing measures are not focused on. 3. Only one specific parameter, the leak frequency, is covered. 4. The model is resource intensive. 5. The model is not tested and validated by the industry.
BORA	1. A more detailed risk picture is provided, reflecting the platform specific conditions of technical, human, operational, and organizational RIFs. 2. Event tree and fault tree are linked in one risk model. 3. The model is easy to apply. 4. The model is tested and recognized by the industry.	1. The model is relatively coarse. 2. The RIF structure is a one-level structure. Structural importance of certain groups of RIFs are not considered. 3. The focus is mainly on barrier functions that prevent the hydrocarbon release. 4. Analysis of the consequence reducing barriers is not included. 5. The uncertainties can only be captured by sensitivity analysis.
OTS	1. The model is based on the modelling of BORA, and studies the HOFs in a more detailed manner. 2. The status of operational barriers can be assessed proactively and independently. 3. Non-compliances to requirements and best practice at different levels in the organization can be revealed. 4. The basis for proposal, decision and implementation of risk reducing measures can be provided. 5. The model is tested and recognized by the industry.	1. The link to the risk model is not covered. 2. Only operational barriers influencing the risk of process leaks are covered. 3. The model is time consuming and resource intensive.
HCL	1. The model provides a good overview of risk model by combining event sequence diagrams, fault tree and Bayesian network. 2. A high resolution in the causal relationships is provided since RIFs are modelled in Bayesian network so the dependencies are well captured. 3. The modelling technique is flexible and detailed causal relationships can be expressed. 4. A multi-layered modelling approach is proposed so that the most appropriate techniques can be applied to different individual domains of the system.	1. The model is resource intensive. 2. Several simplifications are suggested. In particular, the suggested procedure for assigning the conditional probability tables including mechanistic aspects. 3. Analysis of the consequence reducing barriers is not included. 4. The model is not tested and validated by the industry.
Risk_OMT	1. The model is based on the modelling of BORA and OTS and represents a more comprehensive modelling of RIFs by integrating a simplified Bayesian network inference model (two levels RIF structure). 2. Two generic models for planning activities, and execution and control activities are proposed separately to consider different human failure mechanisms and influences from organizational factors.	1. To enable propagation of epistemic uncertainties of RIFs to the result, the event tree and fault tree have to be converted to Bayesian network to have one Bayesian network diagram. 2. The models of hazards and operational barriers are too simplistic and cannot identify the appropriate differences between hazards and barrier configurations. 3. The model is resource intensive to some extent. 4. Analysis of the consequence reducing barriers is not

	3. The score of the RIFs are explicitly modelled, so the epistemic uncertainties of RIFs due to lack of knowledge are considered in the model. 4. The modelling technique is flexible and detailed causal relationships can be expressed. 5. The model is tested and recognized by the industry.	included.
Petro-HRA	1. Human reliability in post-initiating events in the petroleum industry can be assessed. 2. The whole process of performing an HRA is comprised, including the qualitative and quantitative parts of the analysis as well as the integration in the overall risk analysis.	1. The link to the risk model is not covered. 2. Only post-initiator human errors are covered. 3. Specific conditions of technical, human, operational and organizational factors are not covered integrally. 4. The model is not tested and validated by the industry.

5.2 Are all models wrong?

All the existing models aim to extend the current generation of QRA modelling frameworks to incorporate the influences of HOFs as the more fundamental causes of accidents and incidents for offshore petroleum installations, which will result in an updated risk picture, ensuring the development and application of QRA in a more comprehensive way. Note that as part of the further development of the existing models, the pragmatic implementation in the offshore petroleum industry must be based on the validity of the models. Given this, in order to clarify the validity of the existing models, it is necessary to clarify what constitutes the probabilistic platform of the existing models first. In the ORIM and BORA models, the RIFs are assumed to be known and thus, the probability is interpreted as an objective probability to present the true likelihood of the occurrence of the failure event. In the Risk_OMT model, the RIFs are considered as "true" underlying properties of the system being analyzed. The RIFs are however not known, thus the RIFs are treated as random quantities. Yet the probability in the Risk_OMT and HCL frameworks, is considered as the subjective probability that expresses uncertainties, instead of the true likelihood of the occurrence of the failure event. In addition, the starting point of this line of research is that the current generation of QRA as a risk control tool is too static and unilateral (not allowing the integration of HOFs). The reviewed models have contributed to control risk on a plant level efficiently while to control risk on a "lower" level, RIFs and risk indicators come into play. The ORIM focuses on the leak frequency, the developed non-technical RIFs and associated risk indicators. The BORA and Risk_OMT models also focus on the leak frequency on the offshore petroleum installations. The primary difference is that the former focuses on operational barriers and relevant RIFs while the latter focuses on the failure of human intervention and relevant RIFs. From a quantitative point of view, one essential improvement is that the Risk_OMT model structures RIFs into two levels, which is more practical.

However, it is a highly complex problem for validation of QRA and there exist no simple solutions (Røed et al. 2009). Even so, the validity of the models can be evaluated according to a generic list of criteria concerned with the success at 'measuring' what one set out to 'measure' in the risk analysis (Aven and Heide 2009):

V1. The degree to which the produced risk numbers are accurate compared to the underlying true risk.
V2. The degree to which the assigned subjective probabilities adequately describe the assessor's uncertainties of the unknown quantities considered.
V3. The degree to which the epistemic uncertainty assessments are complete.
V4. The degree to which the analysis addresses the right quantities (fictional quantities or observable quantities).

The validity criteria for two types of approaches (relative frequency-based approach and the Bayesian approach) to QRA are investigated systematically, and summarized in Table.5. It can be noted that these two types of approaches are used separately (BORA) or combined (ORIM, HCL and Risk_OMT) in the existing models. There are some critical aspects that need to pay attention. In some cases, the frameworks (HCL and Risk_OMT) for assigning probabilities are hardly validated in the sense that it is impossible to check the results that are accurate relative to some true possibilities. This is because the probabilities in the HCL and Risk_OMT models are subjective in regard to expressing uncertainties. Hence, the stakeholders should have confidence in the process of transforming the analysts' knowledge and lack of knowledge into probabilities. In other cases, the validity of frameworks (ORIM and BORA) for assigning probabilities depends on the statistical data. The validity criteria can be met to a large extent if a large amount of relevant data is available.

Most importantly, it should be noted that the prediction capability can only be validated after an implementation of the proposed methodology (Øien 2001a). Up to now, the BORA, OTS and Risk_OMT models have successfully be implemented and recognized by the offshore petroleum industry while the rest frameworks still lack a real case implementation. The testing and validation of reviewed models are summarized in Table.6.

It is not difficult to be conscious of the limitations of the existing models while it is more important to acknowledge that the suitability and ability of the models to serve the specific scenarios. As stated by Røed et al. (Røed et al. 2009), all models are wrong but they can still be useful, to use a well-known phase.

Table 5
The validity of QRA under different approaches (Aven and Heide 2009)

Approach	Criterion			
	V1	V2	V3	V4
1. Tradition statistical analysis, a large amount of relevant data available	Y	NA	NA	Y/N
2. Tradition statistical analysis, in other cases	N	NA	NA	Y/N
3. The probability of frequency and Bayesian approaches estimating non-observable parameters	N	Y/N	Y/N	Y/N
4. Bayesian approaches that predict observables	NA	Y/N	Y/N	Y

Table 6
The testing and validation of reviewed models

Model	Testing and validation
ORIM	20 leaks during the time period 1997-1999 were used as the verification basis. Thus, an expected leak frequency equal to 1.7 leaks per quarter of the year was obtained. The expected value was assumed to correspond to the expected value used in the last updated QRA. There was no real case implementation.
BORA	The model has been tested in a case study on a specific offshore oil and gas producing platform on the Norwegian Continental Shelf. The basis for development of the basic risk model in the case study was 20 hydrocarbon leak scenarios.
OTS	The model has been tested in pilot studies at three plants.
HCL	The model was tested by the case study from the BORA project. There was no real case implementation.
Risk_OMT	The model has been tested through two main case studies called an "upper rand case" and a "lower rand case", which represents two installations with different scores on the RIFs.
Petro-HRA	The model has been tested by a detailed case study, with respect to the analysis of drive-off scenario for an offshore semi-submersible drilling unit. There was no real case implementation.

5.3 Are the most detailed models always the best?

As a rule of thumb, it is normally stated that the more detailed models are, the more credible are the results. A study (Skogdalen and Vinnem 2011) systematically investigated the existing QRA models, which were categorized according to the level at which the models included, analyzed, described, quantified and explained HOFs. As a result of the examination, the QRAs have been categorized into four levels, as shown in Table.7. It can be seen that the reviewed QRA models differ largely depending on the extent to which the models incorporate HOFs. All the existing models that extend QRA modelling frameworks to incorporate the influences of HOFs in the offshore petroleum industry can be considered as Level 3 analysis and none of QRAs fulfill the requirements to include HOFs such that they can be considered as Level 4 analysis. In this sense, more detailed models need to be further studied and developed for being able to fulfill the requirements of Level 4. Another motivation that calls for the more detailed QRA models is the lack of sufficient specific data. In order to approach the 'real' risk picture, the models try to capture as many details as possible. Hence, more detailed models with increased knowledge are expected to be developed so as to reduce epistemic uncertainties.

Nevertheless, it should be noted that the more detailed models always signify more resource demanding. In the overwhelming majority of cases, assumptions need to be made as a simplification, to avoid spending unmanageable time and resources on assessing uncertainty. Hence, the use of resources should be balanced against the argument from the representatives from the oil companies that it is important to use existing data in order to minimize the use of resources (Aven et al. 2006b). On account of this, in the BORA model, it is suggested to limit the number of RIFs for each event so as to keep the operational risk analysis in a manageable size. Likewise, in the Risk_OMT model, a three level structure of RIFs was considered initially, but was considered to be too complex, and therefore reduced to two levels. In practice, some assumptions are always required to establish the basis of risk assessment (Berner and Glage 2016). This can be due to lack of knowledge. In this case, it is hardly to develop more detailed models for certaining these assumptions. Therefore, the QRA models should be developed to serve certain purposes. How detailed the models should depend on how detailed we can keep the analyses in a manageable size. In the offshore petroleum industry, different QRA models at various levels as regards details are needed realistically. It should be a decision for the risk analysts to determine the most appropriate tool for each specific task, based upon the required level of details and the resources available.

Table 7
Levels and characteristics (Skogdalen and Vinnem 2011)

Level	Characteristics
Level 4	● The QRA is an integrated part of the safety and risk management system. ● Results from the QRA form the basis for daily risk management. ● The QRA is known and accepted at all levels of the organization. ● QRA is combined with risk indicators to reveal the status of the safety barriers.
Level 3	● Systematic collection of data is related to HOF. ● QRA models are adjusted according to findings from HOF. ● Identified causes of errors to support the development of preventive or mitigating measures. ● Includes a systematic procedure for generating reproducible qualitative and quantitative results.
Level 2	● Explains the importance of HOFs ● The HOFs' influence on different part of the system is partly described. ● Human error is calculated separately. ● Interviews with parts of the crew. The results are revealed but the models and calculation are not adjusted.
Level 1	● Analysis of technical and operational factors. ● Risk reducing measures are technical.

6. Conclusions and future work

In the offshore petroleum industry, some major accidents and incidents have demonstrated dramatically the potential catastrophic consequences due to human and organizational errors. Thus, HOFs must be modelled and formally included into QRA. This paper provides a comprehensive and up-to-date picture of QRA models that have been developed for the offshore petroleum industry, allowing HOFs integrated in a systematical way. In this work, the models are decomposed into different elements for a thorough review. These elements are categorized as: (1) RIFs and their structures, (2) link to the system risk model, (3) modelling technique, (4) rating of RIFs, (5) weighting of RIFs, (6) propagation algorithm, (7) modelling of interactions, (8) input data. Following the close scrutiny of the steps and characteristics of the reviewed models, a comparative study is undertaken to show the similarities, differences and limitations among the models from both the qualitative and quantitative aspects. Further, the validity and suitability of the models are addressed and discussed in detail. Based on these analyses, it can be concluded that:

- The existing models are primarily developed for loss of containment due to maintenance on process equipment on offshore installations in the Norwegian petroleum industry.
- The existing models consist of both the qualitative elements and quantitative elements. The qualitative elements demonstrate how HOFs interface with QRA models while the quantitative elements demonstrate how HOFs are integrated into risk prediction.
- The existing models reflect the non-technical conditions in accordance with a list of factors, which affect the performance of ‘front-line’ personnel and organization. The influence of HOFs is established through the rating and weighting of RIFs while the total influence is obtained by aggregating the rates and the weights of RIFs. The updated risk picture includes the influence of HOFs in accordance with implicit functions, which link relating RIFs to input probabilities/frequencies of the failure events in the risk model.
- Available human reliability data, which are used as basis probabilities for all failures that are modelled, are rather limited, when it is requested that these data shall be directly applicable for the purpose of the project.
- The indicators comprise an effective tool for risk control during operation of offshore petroleum installations, but very limited models use indicators for the purpose of measuring the status of RIFs.
- “Real” implementations of the BORA, OTS and Risk_OMT models have been carried out in the offshore petroleum industry and the prediction capability of the models are validated.
- In the existing models, two independent barriers (not considering the correct execution of the work tasks) are not always available in the dominating scenarios and in most cases, there is only one independent barrier (verification of the work).

It is certain that all the existing models provide an essential basis for further work on how QRA reflecting HOFs as far as reasonably practicable should be carried out in the offshore petroleum industry. Note that the offshore petroleum industry is an international industry, with international standards for equipment and operations. This implies that the proposed QRA models should also be usable in the petroleum sector in other countries, especially for maintenance operations on complex offshore installations. Some of the future work to complement some of the weakness and limitations of the existing models are presented as follows.

- The existing models are focusing on either frequency or consequence reducing barriers unilaterally while no holistic risk models that integrate both have been developed. A holistic risk model including preventive, controlling and protective barriers will make it possible to analyze potential dependencies among all relevant safety barriers.
- HOFs related indicators should be defined and applied properly as the indicators comprise an effective tool for risk control during operation of offshore petroleum installations. However, there are very limited methods available using indicators for measuring the status of non-technical RIFs. In particular, how to derive the most relevant indicators for RIFs and justify whether they are sufficient or close enough to show the “True value” of the RIFs are challenging.
- More data with respect to HOFs need to be collected as lack of relevant data is still the weakest point for QRA models integrating HOFs in the offshore petroleum industry.

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

BARS	Behaviorally Anchored Rating Scales
BFETS	Blast and Fire Engineering for Topside Systems
BORA	Barrier and Operational Risk Analysis
CSE	Concept Safety Evaluation
HC	Hydrocarbon
HCL	Hybrid Causal Logic
HEP	Human Error Probability
HES	Health, Environment and Safety
HFE	Human Failure Event
HMI	Human Machine Interface
HOF	Human and Organizational Factor
HRA	Human Reliability Analysis
HSE	Health and Safety Executive
MLE	Maximum Likelihood Estimation
NCF	Norwegian Continental Shelf
NPD	Norwegian Petroleum Directorate
ORIM	Organizational Risk Influence Model
OTS	Operational Conditional Safety
PM	Preventive Maintenance
PRA	Probabilistic Risk Assessment
PSA	Petroleum Safety Authority
PSF	Performing Shaping Factor
QRA	Quantitative Risk Analysis
RIF	Risk Influencing Factor
Risk_OMT	Risk Modelling-Integration of Organizational, Human and Technical Factors
TRA	Total Risk Analysis
TTS	Technical Condition Safety

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